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Modeling asphaltene precipitation and flow behavior in the processes of CO_2 flood for enhanced oil recovery

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ABSTRACT

This paper focuses on the idea for enhancing oil recovery by CO_2 injection into oil formation as well as reducing CO_2 emission into the atmosphere. The mechanism of asphaltene flocculation during CO_2 flooding in oil formations is analyzed and the regressive correlation between CO_2 concentration and the amount of flocculated asphaltene for an oil sample is set up for coupling with the flow governing equations for the flocculated asphaltene transport in porous media. A three-dimensional multiphase mathematical model describing CO_2 transport in oil reservoirs and asphaltene precipitation is presented for predicting CO_2 flooding performances for enhanced oil recovery. The finite difference method and preconditioned conjugate gradient algorithm are used to solve the discrete nonlinear equation systems. A numerical simulation software is developed to study CO_2 flooding performances and the effects of asphaltene precipitation on production behaviors. The numerical result indicates that water-cut decreases from initial 92.5% down to 40.3% after continuous CO_2 injection for 10 years. It is also shown that 0.130 million tons of crude oil is displaced by CO_2 injection in the 1 km^2 of the reservoir within 10 years. Asphaltene precipitation leads to the decrease in permeability, and the decline in production rates.

1. Introduction

Worldwide CO_2 emission is vast, and is regarded as a major factor leading to global warming (Akimoto et al., 2005; Radhi, 2009). Annual CO_2 emission in the 11 southeastern states (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia and East Texas), of U.S.A. is up to about 1045 million metric tons. Coal-fired electric power generation and other fossil-fueled plants account for 860 million tons (Petrusak et al., 2009). Depleted or mature oil and gas fields provide excellent sites for enhanced oil recovery (EOR) as well as CO2 geological storage in known porous and permeable reservoirs (Li et al., 2006; Gaspar Ravagnani et al., 2009). Many oil fields in main oil production countries offer good opportunities for CO2 injection into oil formations for EOR.

Previous experimental work on CO_2 displacement in long core (Moreno et al., 2011) and the field-trial history of CO_2 flooding for EOR purpose have verified that it can improve oil recovery to a larger extent. However, one adverse factor of CO_2 flooding for EOR is the asphaltene precipitation and deposition. This may not only lead to the formation damages (Monteagudo et al., 2001; Zekri and Shedid, 2004) for reducing porosity and permeability, but also have some adverse influences on production facilities such as well bore, tubing and pumps (Ruksana and David, 1990; Rashid et al., 2003).

The kinetic theory of aggregation of asphaltene is reported by Branco et al. (2001). It is critical to understand the asphaltene behaviors in petroleum production from oil reservoirs. Idem and Ibrahim (2002) studied experimentally the kinetics of CO_2-induced asphaltene precipitation. Their results show that the rate of asphaltene precipitation depends on the concentrations of asphaltene and CO_2 in petroleum. It provides a clue to set up a correlation between the amount of asphaltene precipitation and the concentrations of asphaltene and CO_2.

Nghiem et al. (2004) presented an asphaltene deposition model for CO_2 flooding for EOR. It includes reversible and irreversible asphaltene precipitation followed by surface deposition and pore-throat plugging. In the model, the authors gave two types of asphaltene solids to describe the transfer between small and large-size solids. The transferring rate depends on the concentrations of the two particles in the oil and two reaction coefficients. It seems feasible to describe asphaltene precipitation phenomenon caused by CO_2 injection. However, the methods to obtain the two concentrations of two types of solids are not reported in previous references. The objective of this work is to develop a numerical simulator to predict CO_2 injection performances, formation damage and their effects on the performances of oil production. In this work, a new mathematical model considering asphaltene precipitation is proposed, and a three dimensional numerical

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Nomenclature

a_1–a_4	correlation coefficients for asphaltene flocculated (dimensionless)
B	volume factor of fluid (dimensionless)
C_{ao}	volume concentration of asphaltene in oil phase (dimensionless)
C_{CO_2}	CO_2 the mole fractions in the oil phase (dimensionless)
C_{onset}	asphaltene flocculation onset of CO_2 concentration (dimensionless)
C_s	volume concentration of asphaltene dissolved in oil phase (dimensionless)
D	diffusivity of asphaltene in oil phase (m^2/s)
f	flow efficiency factor (dimensionless)
f_{vif}	mole fraction of component i (dimensionless)
f_{vCO_2f}	mole fraction of CO_2 (dimensionless)
f_{vgasf}	mole fraction of natural gas (dimensionless)
f_{vof}	mole fraction of dead oil (dimensionless)
h	distance from reference level (m)
k	transient absolute permeability of a porous media (m^2)
k_0	initial permeability of a porous media (m^2)
k_r	relative permeability of a porous media (dimensionless)
n	index for modifying permeability(dimensionless)
p_c	capillary pressure (Pa)
P_{WF}	bottom-hole flowing pressure (Pa)
q	production/injection rate (STM/D)
q_s	the rate of change of soluble asphaltene caused by a source/sink term (1/s)
Q_{ao}	the rate of change of flocculated asphaltene caused by a source/sink term (1/s)
R_{af}	the ratio of flocculated asphaltene to total asphaltene in oil (dimensionless)
R_{ao}	net asphaltene change rate on the pore surfaces and at pore throats (1/s)
R_{Loss}	flocculated rate of asphaltene (1/s)
R_{sio}	solution gas–oil ratio (dimensionless)
R_{siw}	solution gas-water ratio (dimensionless)
S	saturation (dimensionless)
t	time (s)
u	Darcy velocity of flow in porous media (m/s)
v	real flow velocity in porous media (m/s)
v_{oc}	critical velocity (m/s)
x	distance in x direction (m)
y	distance in y direction (m)
z	distance in z direction (m)
α_{dao}	rate constant for asphaltene deposition on pore surfaces (m^{-1})
α_{feao}	coefficient of flow efficiency (dimensionless)
α_{hao}	release rate of asphaltene by hydrodynamic forces (m^{-1})
α_{pao}	capture rate constant of asphaltene at pore throats (m^{-1})
β_{k12}	forward rate coefficient of formation of asphaltene aggregates ($\mathbf{s}^{-1}$)
β_{k21}	reverse rate coefficient of formation of solid asphaltene aggregates (m^3/s)
δ_{ao}	volume of asphaltene deposited on the pore surfaces per unit bulk volume (dimensionless)
δ^*_{ao}	volume of asphaltene trapped at throats per unit bulk volume (dimensionless)
ϕ	porosity of the porous media (dimensionless)
ϕ_0	initial porosity of the porous media (dimensionless)
γ	specific gravity of fluids (N/m^3)
λ_f	constant for fluid seepage allowed by the plugged pores (dimensionless)
μ	viscosity of fluid (Pa s)
ρ	density (kg/m^3)

Subscripts

0	Initial value
ao	asphaltene in oil phase
c	critical value or capillary pressure
d	deposition
e	entrainment
f_e	flow efficiency
g	gas
h	hydrodynamics
o	oil
omix	mixture of oil and gas and CO_2
w	water

simulator is developed to predict CO_2 flooding for enhanced oil recovery.

2. The mechanism and description of asphaltene flocculation

Asphaltene is defined as the fraction of the crude oil that is soluble in benzene or toluene but insoluble in liquid normal alkanes (Mitchell and Speight, 1973; Papadimitriou et al., 2007). It is generally in the soluble or suspended state under original conditions of oil reservoirs. The factors such as pressure, temperature and components of oil determine the flocculation onset of asphaltene. The change in any of the factors may lead to unbalance of asphaltene solubility and asphaltene precipitation, which is adverse to production and may lead to formation damage. Several models (Almehaideb, 2004; Huang et al., 2009; Jamialahmadi et al., 2009; Nghiem et al., 2004; Thanyamanta et al., 2009; Zahedi et al., 2009) have been developed to predict asphaltene precipitation. However, most of them (Almehaideb, 2004; Jamialahmadi et al., 2009; Zahedi et al., 2009) focused on the asphaltene precipitation problems in the primary recovery or deposition on the production facilities such as tubes and well bores.

Srivastava and Huang (1997) studied the deposition behaviors of asphaltene during CO_2 flooding by an experimental approach. In the operating conditions of 16 MPa and 59–61 °C, they gave the relations between the CO_2 concentration and flocculated asphaltene for Weyburn oil samples. More recently, an experimental approach and calculation method were given by Huang et al. (2009) to predict asphaltene precipitation induced by CO_2 injection. One of their important conclusions is that asphaltene precipitation starts to flocculate when CO_2 concentration reaches an onset value. Then asphaltene precipitation quantity sharply increases as injected CO_2 increases before a maximum precipitation reaches. Then, a further increase in CO_2 concentration leads to the decrease in asphaltene precipitation. Some of their experimental data are shown in Fig. 1.

The asphaltene precipitation onsets may be different from one oil sample to another for the different oil components. For an