Fuel 117 (2014) 259–268

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Further investigation into the mechanisms of asphaltene deposition and permeability impairment in porous media using a modified analytical model

S. Kord [a], O. Mohammadzadeh [b,*], R. Miri [c], B.S. Soulgani [d]

[a] Enhanced Oil Recovery Research Center, School of Chemical and Petroleum Engineering, Shiraz University, Iran
[b] DBR Technology Center, Schlumberger, Edmonton, AB, Canada
[c] Faculty of Mathematics and Natural Sciences, University of Oslo, Oslo, Norway
[d] Department of Petroleum Engineering, Petroleum University of Technology, Ahwaz, Iran

HIGHLIGHTS

- New mechanism was proposed for asphaltene deposition and permeability reduction.
- Existing mechanism(s) was modified based on experimental results.
- Existing analytical model was modified to better match the experimental data.
- The modified model predicts the experimental data more accurately.

ARTICLE INFO

Article history:
Received 28 May 2013
Received in revised form 10 September 2013
Accepted 11 September 2013
Available online 25 September 2013

Keywords:
Asphaltene
Experiment
Coreflood
Deposition
Permeability impairment

ABSTRACT

Asphaltene deposition in porous media and subsequent in situ permeability impairment is one of the main issues during oil production which damages the reservoir rock by clogging pore throats and pore bodies as well as by changing wettability of the formation. The major mechanism(s) under which asphaltene particles deposit and impair permeability are still under investigation as an active research topic in the literature. Recently, several dynamic and static asphaltene deposition tests were conducted by Kord et al. [4] in which live oil and core samples from target reservoirs were used. According to the experimental results associated with the coreflood tests, "surface deposition" was found to be the main mechanism of permeability reduction in porous media. In addition, all the experiments confirmed that "pore throat plugging" caused linear reduction of core permeability versus time up until the "pore throat opening" mechanism comes into effect in restoring core permeability and/or flattening out the decline rate associated with permeability versus time due to flow dynamics effects. Using a novel definition of "critical velocity in pore throats", this new mechanism was mathematically modeled. In order for precise demonstration and quantification of the "surface deposition" mechanism, a novel experimental apparatus was designed and constructed by Soulgani et al. [26] to measure mass of deposited asphaltene versus time. The results were used to present a new term describing the "surface deposition" mechanism. A three-phase, four-component black-oil simulator was then developed and coupled with the deposition model including two mechanisms of "surface deposition" and "pore throat opening". Subsequently, the simulator was verified using two sets of experimental results. A very good match between the values predicted by the model and those originated from the experiments were observed.

1. Introduction

Asphaltene deposition causes challenging operational/reservoir management difficulties including permeability reduction, changing the rock wettability and increasing the fluid viscosity. Developing a predictive tool could play a vital role in estimating the amount and location of asphaltene damage and subsequent treatment operations. However, developing physical and mathematical models to precisely describe deposition mechanisms and capture the true physics of deposition and impairment is still at initial stages of development.

Changes in pressure, temperature or composition would cause stabilized asphaltenes to precipitate from the oil solution [1]. Various models with different focal points have been developed using reversible and irreversible thermodynamics to model asphaltene

* Corresponding author.
E-mail address: OMohammadzadeh@slb.com (O. Mohammadzadeh).

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.09.038

Nomenclature

E_A	volume fraction of deposited asphaltene, dimensionless
E_a	attachment activation energy, J/mol
R_{Aso}	volume ratio of soluble asphaltene in the oil phase, dimensionless
C_A	suspended asphaltene saturation, dimensionless
W_{Sao}	suspended asphaltene, dimensionless
q_{osc}	flow rate, cm^3/s
S_g	saturation of gas phase, dimensionless
S_o	saturation of oil phase, dimensionless
$\dot{m}_d$	rate of asphaltene deposition, kg/m^2 s
u_o	velocity of oil phase, cm/s
v	interstitial oil velocity, cm/s
V_C	critical interstitial velocity for entrainment, cm/s
V_{CP}	critical interstitial velocity for entrainment in modified model, cm/s
V_{CT}	critical interstitial velocity in pore throats, cm/s
V_m	molar volumes of oil, m^3/kmol
B_o	oil formation volume factor, m^3/S m^3
B_A	asphaltene formation volume factor, m^3/S m^3
R	Universal gas constant, cal/mol K
T	temperature, K
ρ_g	density of gas phase, g/cm^3
ρ_o	density of oil phase, g/cm^3
ρ_A	density of asphaltene, g/cm^3
α	surface deposition rate coefficient, 1/s
β	entrainment rate coefficient, 1/cm
γ	instantaneous plugging deposition rate coefficient, 1/s
σ	snow-ball effect deposition constant, dimensionless
φ	porosity, fraction
φ_0	initial porosity, fraction
k_0	initial permeability, md
k_d	correction factor, $(m/s)^2$
f_p	permeability correction constant, dimensionless
t	time, s

Subscripts

A	asphaltene
cr	critical
o	oil
g	gas
m	molar
d	deposit
sc	standard condition

precipitation. In addition, scaling equations are recently proposed in the form of simple models to predict the asphaltene precipitation [2,3]. A new class of scaling equations was developed recently by Kord and Ayatollahi [4] which is capable of predicting asphaltene precipitation from live oil at reservoir conditions.

Asphaltene precipitation due to any thermodynamic instability cannot be considered as a unique criterion for asphaltene deposition. It is the rock morphology and flow hydrodynamics which govern the extent of permeability damage [5,6]. The model proposed by Gruesbeck and Collins [7] for migration of fine particles in porous media is the base for most of the asphaltene deposition models. Ali and Islam [8] used parallel pathways idea considering surface excess theory of Sircar et al. [9] and developed a mathematical model which was verified against experimental data. Minssieux et al. [10] conducted series of coreflood experiments with different core and fluid samples at reservoir temperature in order to investigate the effect of asphaltene deposition on permeability of core samples. Chauveteau and Nabzar [11] analyzed different mechanisms leading to permeability damage due to particle deposition based on different forces acting in various situations. They characterized deposition regimes by a few non-dimensional numbers. Considering parameters such as particle and pore size, shape and roughness, flow rate, concentration, viscosity, particle–particle and particle–pore wall interaction energies and pore surface physicochemical heterogeneity, they concluded that the deposition regime determines the deposition kinetics. Using Carman–Kozeny equation, Nghiem et al. [12] proposed a compositional simulator, which was coupled with an empirical linear correlation for the induced-damage factor.

Based on the Ali and Islam deposition model [8], Kocabas et al. [13] developed a near wellbore model which considers both mechanical trapping and adsorption which was analytically solved in the case of no adsorption and was then compared against some sets of experimental data. Almehaideb [14] developed a single well model to simulate asphaltene precipitation, deposition and well plugging during natural depletion. Based on this idea, Solaimany-Nazar and Zonnouri [15] used the same approach to examine the effect of production rate and initial permeability on asphaltene deposition behavior around the wellbore.

Zekri and Shedid [16] investigated the effect of fracture characteristics on its permeability reduction by asphaltene deposition. A single fracture with different properties (i.e. porosity, permeability and fracture angle), but with constant aperture was used to investigate the effect of different parameters on permeability damage. Moreover, the effect of asphaltene precipitation on the end point relative permeability values at S_{wi} was also studied in some experimental work [17,18].

Danesh et al. [19] presented three mechanisms contributing to entrapment of suspended asphaltene particles through porous media: surface deposition, entrainment, and pore-throat plugging. Wang and Civan [20,21] suggested a three-parameter equation for deposition rate of asphaltenes as a function of the mechanisms introduced by Danesh et al. [19], along with Gruesbeck and Collins [7] model. They also proposed a mass balance equation to calculate the amount of asphaltene ready for deposition. The whole sets of equations were incorporated into a three-dimensional, three-phase black oil simulator and were solved by finite-difference method. Surface deposition, entrainment, and pore throat plugging rate coefficients were estimated by regression analysis of the experimental data provided by Minssieux et al. [10]. Papadimitriou et al. [22] also performed some experiments to investigate the asphaltene deposition process and its subsequent permeability impairment in core samples under stimulant and realistic flow conditions.

Mendoza et al. [23] conducted coreflood experiments to investigate the processes of asphaltene precipitation and deposition during natural depletion and their effects on core permeability. Moreover, they developed a mathematical model based on the transport of stable particulate suspensions in porous media and validated it with experimental data. In their proposed model, asphaltene adsorption and trapping were considered as main causes of deposition. Lawal and Vesovic [24] implemented a simple one-parameter semi-analytic model for asphaltene-induced reduction of porosity, pore-radius and permeability in closed systems. They considered the sedimentation as the dominant deposition mechanism to demonstrate dynamics of asphaltene deposition under stagnant conditions. Results of this study showed that the damage rate depends on the size of asphaltene aggregates as well as on the rock and fluid properties.