Fuel 235 (2019) 239–248

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

A new model for permeability impairment due to asphaltene deposition

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ARTICLE INFO

Keywords:
Asphaltene deposition
Permeability reduction
Surface deposition
Pore plugging

ABSTRACT

The existing theoretical and empirical models to describe asphaltene deposition in porous media do not consider the complicated structure of pore network. Permeability reduction due to asphaltene deposition has been mainly attributed to pore volume shrinkage (porosity reduction). However, asphaltene particles can also block pore throats which will lead to severe permeability reduction even when a large fraction of total pore volume still remains intact. Thus, there is a need for permeability models that are explicitly function of pore/hydraulic connectivity. This paper provides a review of the existing models and examines a permeability model that explain permeability impairment due to asphaltene deposition.

In this study, we propose a new permeability model based on Critical Path Analysis (CPA) which is a function of average coordination number (average number of available/connected neighbor pores). Furthermore, experimental data in the literature related to limestone, sandstone and carbonate (dolomite) samples are utilized to understand combined effects of surface deposition and interconnectivity loss due to pore blockage on permeability reduction.

We observed that surface deposition is the dominant mechanism in the limestone samples studied here owing to large pore throat size compared to the particle size. In the sandstone samples, both the surface deposition and pore throat plugging mechanisms contribute fairly the same in the observed permeability reduction. For the carbonate (dolomite) samples, the pore blockage is the dominant mechanism, which results in rapid sharp decrease of the permeability. It is expected that the outcome of this work improves prediction of the asphaltene deposition in the near wellbore region.

1. Introduction

The issue of asphaltene deposition has plagued the oil and gas industry for decades since it has been identified and named as “asphaltenes” in 1837 [7]. Due to the huge costs associated with remediation, it is extremely important to understand the issue of asphaltene deposition and the factors affecting it [14]. Crude oil has several fractions, and asphaltenes essentially tend to be its heaviest, polarizable fractions. They are known as the “cholesterol of petroleum” due to their ability to precipitate as solids and subsequently deposit with changing pressure, temperature and oil composition [3]. Asphaltene precipitation is called the process when asphaltenes become a separate phase from the crude oil. They remain suspended in the liquid phase where the quantity and the size of the asphaltenes are relatively small. The precipitated asphaltenes clump together (aggregation) and form larger particles, also called flocs. The asphaltene aggregates are initially suspended in the crude oil. Subsequently, the flocs may attach to and accumulate on various surfaces, a process which is called asphaltene deposition [28]. In both up and downstream operations deposition may cause severe problems. Asphaltenes may precipitate and deposit on surface of pipelines, bottom of distillation column and heat exchangers as well, affecting efficiency and creating added economic costs to remediate [18,10].

Also, during production, asphaltene particles can deposit in reservoir, leading to possible blocking of flow, particularly in the near wellbore region. Asphaltene deposition problems encountered deep down in rock reservoirs are extremely problematic, and very challenging to tackle, as opposed to production tubing deposition problems. Minssieux [22] studied various core samples with different rock characteristics in core-flooding experiments, with regards to porous media. He concluded that porous sample plugging only seemed to occur after enough oil had flown through the sample, and that damage at earlier times was only observed in samples with a lower initial permeability [28].

The mechanisms through which formation damage due to asphaltene deposition can occur are surface deposition, and pore throat plugging. As asphaltene deposits accumulate on the pore surface, the pore surface area decreases leading to porosity reduction. Moreover,

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https://doi.org/10.1016/j.fuel.2018.07.079
Received 4 October 2017; Received in revised form 5 May 2018; Accepted 18 July 2018

when asphaltene deposits accumulate in front of a pore, they can plug them causing severe permeability reduction.

For modeling of permeability impairment in porous media due to asphaltene deposition, Deep Bed Filtration (DBF) models are often used [31,4]. Using DBF theory, Wang [31] modified Civan's model for near wellbore asphaltene deposition, assuming negligible capillary pressure and one dimensional horizontal flow:

$$\frac{\partial E_A}{\partial t} = \alpha C_A \phi - \beta E_A (v_L - v_{cr,L}) + \gamma u_L C_A \tag{1}$$

where, E_A is volume fraction of deposition asphaltenes; v_L is interstitial velocity ($= u_L/\phi$); $v_{cr,L}$ is critical interstitial velocity; u_L is superficial velocity; α is surface deposition rate coefficient; β is entrainment rate coefficient; γ is pore throat plugging coefficient. The first term in Eq. (1) represents the pore surface deposition rate which is directly proportional to the concentration of suspended particle concentration in the flowing fluid; the second term expresses the entrainment of asphaltene particles (removal due to drag force) that becomes dominant above critical interstitial velocity [8]; and the last term describes for the pore throat plugging rate, where the plugging rate is directly proportional to the superficial velocity. Wang [31] defined the pore plugging coefficient, γ as:

$$\begin{aligned} &\gamma = \gamma_i(1 + \sigma E_a),\ if\ 0 > R > R_c \\ &\qquad \gamma = 0,\ otherwise \end{aligned} \tag{2}$$

where, σ is deposition constant; R referes to the ratio of particle size to pore throat size, R_c refers to the critical ratio of particle size to pore throat size. According to Eq. (2) ore throat plugging occurs at conditions where critical pore throat diameter is greater than the average pore throat diameter.

Boek et al [4] discussed that DBF models are very simplistic. Thus, using stochastic rotation dynamics models in capillary flow, Boek et al. [4] estimated coefficients needed for DBF deposition model at the Darcy-scale. They have suggested that experimental deposition data can be modeled using only surface deposition rate, (α) parameter obtained from straight capillary model. However, their model still neglects the effect of pore blockage on permeability reduction.

Asphaltene deposition can lead to porosity and permeability reduction; however, in the majority of existing models, permeability reduction is only attributed to pore volume shrinkage (porosity reduction). Local dynamic porosity is computed as the difference between the original porosity, ϕ_i, and the fraction of asphaltene deposits, ε:

$$\phi = \phi_i - \varepsilon \tag{3}$$

Further, permeability change as a function of porosity is estimated as a function of porosity reduction [32,21]:

$$\frac{k}{k_i} = \left(\frac{\phi}{\phi_i}\right)^3 \tag{4}$$

However, in Eq. (4) connectivity loss (pore connectivity) has not been considered and permeability reduction is only attributed to pore volume reduction. It is well known that effective porosity can decrease owing to pore volume shrinkage and thus permeability can be reduced. However, permeability can be also altered because of hydraulic conductivity/connectivity loss (coordination number reduction) owing to pore plugging mechanism (Fig. 1). In the extreme cases where significant pore blockage occurs, total pore volume may not even greatly change. As it will be discussed later in detail, when the rock sample has a large fraction of pores with the diameter comparable to the size of particles, pore throats can be easily plugged and blocked; this will lead to severe permeability reduction even when the large fraction of pore space yet remains intact. Thus, it is crucial to study asphaltene deposition in porous media via permeability models which consider both porosity reduction and pore connectivity loss, especially for reservoirs with small size pores that are comparable to the particle size.

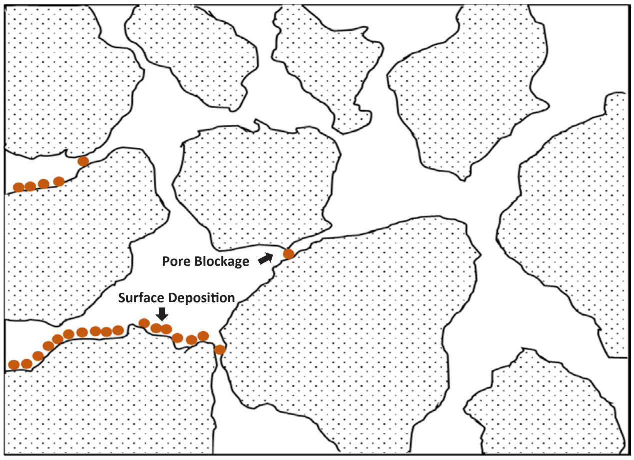

Fig. 1. Schematic of permeability reduction due to surface deposition and pore plugging.

Table 1
Initial parameters of samples.

Sample #	Asphaltene wt%	Initial Porosity, %	Initial Permeability, md	Initial Coordination Number, z
Limestone #1	6.56	48.54	1062.5	8.5
Limestone #2	16.3	22.5	106.6	6.4
Sandstone #1	6.56	49.16	1089.6	8.5
Sandstone #2	16.3	13.5	22.8	4.9
Sandstone #3	12.94	16.0	66.3	5.4
Carbonate #1	0.06	17.17	4.67	5.6
Carbonate #2	0.87	21.2	6.32	6.2
Carbonate #3	1.5	19.24	5.48	5.9

In this study, we develop a permeability model based on Critical Path Analysis (CPA) that is a function of average coordination number (average number of available/connected neighbor pores). Furthermore, experimental data in the literature related to limestone, sandstone and carbonate (dolomite) samples are utilized to understand combined effects of surface deposition and interconnectivity loss due to pore blockage on permeability reduction.

2. Permeability model

The interplay between porosity/storage and permeability/hydraulic conductivity has been studied for decades. As a result, many theoretical models have been developed to estimate hydraulic conductivity of porous media [12,6], Bernabé et al. [2]. One of the fundamental permeability models is Kozeny-Carmen (KC) equation that considers porous medium as a bundle of cylindrical tubes:

$$k = \frac{1}{c}\frac{\phi}{\tau}\frac{1}{S_{gv}}\left(\frac{\phi}{1-\phi}\right)^2, \tag{5}$$

However, Civan [5] suggested that KC equation cannot properly address the gate/valve effect of porous media (pore/hydraulic connectivity) to predict permeability when pore throats are blocked and isolated. Therefore, he modified KC model by including interconnectivity parameter, Γ:

$$k = \Gamma\phi\left(\frac{\phi}{1-\phi}\right)^{2\beta}, \tag{6}$$

Γ is a measure of the pore space connectivity, and it represents the valve effect of the pore throats controlling the pore connectivity to other pore spaces [6]. the interconnectivity parameter is strong function of average coordination number, z (the number of the pore throats)