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Investigation of density inversion induced by gas charges into oil reservoirs using diffusion equations

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ABSTRACT

A reservoir crude oil consists of dissolved gas, liquid and dissolved solid (asphaltenes). It is well known that asphaltene solubility in oil decreases with an increase in solution gas content (gas/oil ratio, GOR). For example, a late gas charge into a reservoir crude oil over geologic time can cause asphaltene instability and phase separation to form a tar mat. This tar mat is often spatially separated by significant distances from the location of the asphaltene instability, thus requiring asphaltene migration in porous media at rates greatly exceeding diffusive velocities. Therefore, a dynamic mechanism is proposed to account for these known observations. Diffusive entry of gas from a gas cap into an oil column gives rise to chemical potential gradients (diffusion driving forces). The cross-term effect in diffusion makes asphaltenes move in the opposite direction to the concentration gradient in a certain region, which is referred to as the gas expulsion effect. On the other hand, the diagonal-term effect in diffusion moves asphaltenes along the concentration gradient. Consequently, both competing effects result in asphaltene concentration fingering at a certain location and thus creates fluid density inversion. In turn, this fluid density inversion in the oil column leads to gravity currents (gravitational instability – diffusion induced convection) that enable the migration of asphaltenes over large distances in porous media over geologic time.

A one dimension (1-D) diffusive model with a moving boundary is developed in this paper coupled with the FHZ EOS(Flory-Huggins-Zuo equation of state) and applied to three component (gas, maltene and asphaltene) systems. The gas/oil contact moves up with time due to the swelling effect of a gas charge into a crude oil reservoir. Density inversion can be produced mainly by the cross-term effect in diffusion (i.e., the impact of the presence of charging gas on the chemical potential of asphaltenes or gas expulsion) in a relatively wide range of conditions. Parameter sensitivity analyses demonstrate that significant fluid density inversion is generated at the conditions close to the asphaltene phase instability boundary, which is not surprising because the cross-term effect in diffusion becomes significant at those conditions. In addition, the diffusion model can be used to identify asphaltene phase instability directly. Application of this diffusive model to oilfield cases is in progress.

1. Introduction

Reservoir crude oils consist of dissolved gases, liquids and dissolved solids, the asphaltenes. Gas-liquid equilibria have long been treated with the cubic EOS (equation of state) [1] with its origins in the van der Waals EOS. Previously the lack of understanding of the physical state and size of asphaltene particles in crude oil precluded determination of gravitational and other terms in an EOS for asphaltene gradients, where gravity is key. The molecular and colloidal species of asphaltenes have been resolved and codified in the Yen-Mullins model (cf. Fig. 1) [2–4]. It is now understood that mean asphaltene molecular weight is rather modest at ~750 g/mole as given by molecular diffusion [4–7] and mass spectrometry [8–11]. Moreover, the so-called 'island' molecular architecture dominates, with its single PAH (polycyclic aromatic hydrocarbon) per molecule (cf. Fig. 1) [4–11]. With asphaltene molecular architecture understood, the resolution of asphaltene nanocolloidal species followed. Asphaltene nanoaggregates are composed of

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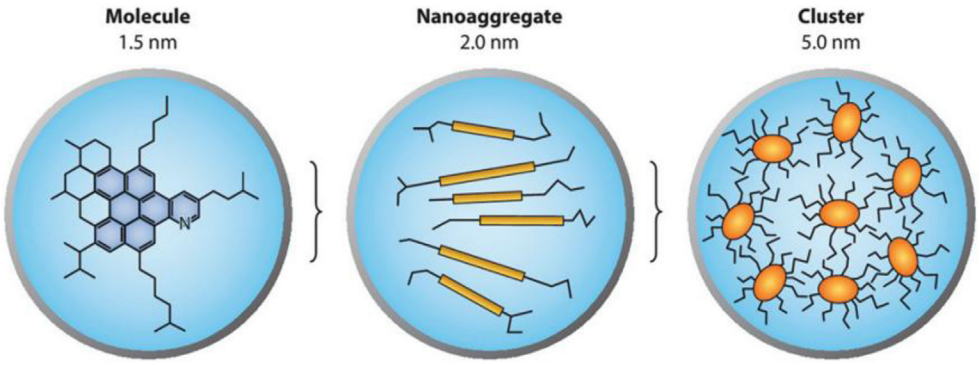

Fig. 1. Yen-Mullins model of asphaltenes depicting the dominant molecular and nanocolloidal species of asphaltenes [2–4]. At low asphaltene concentrations such as in light crude oils, asphaltenes are dispersed as molecules (left), and moderate concentrations as in black oils, asphaltenes are dispersed as nanoaggregates (center) and in high concentrations as in heavy oils, asphaltenes are dispersed as clusters (right).

about 6 molecules. Clusters of nanoaggregates consist of about 8 nanoaggregates [2–4]. Recent results in NMR [12], DC-conductivity and centrifugation [13], mass spectroscopy [8,14], interfacial tension [15–17], theoretical chemistry [18,19], and coarse-grain dynamic simulations [20] confirm all key aspects of the Yen-Mullins model. In light oils with low asphaltene concentration, asphaltenes tend to be dispersed as molecules in a true molecular solution. In black crude oils with moderate concentrations of asphaltenes, asphaltenes tend to be dispersed as nanoaggregates and in heavy oils with high asphaltene concentrations, asphaltenes tend to be dispersed as clusters [2–4].

With asphaltene size resolved in crude oils (and laboratory solvents), gravitation and other terms can be determined. This led to the development of the FHZ (Flory-Huggins-Zuo) EOS for determination of asphaltene gradients in reservoir crude oils [21–25]. The Flory-Huggins-Zuo EOS is given below.

$$\frac{OD(h_2)}{OD(h_1)} = \frac{\phi_a(h_2)}{\phi_a(h_1)} = \exp\left\{\frac{v_a g(\rho-\rho_a)(h_2-h_1)}{RT} + \frac{v_a}{RT}\left[(\delta_a-\delta)^2_{h_1} - (\delta_a-\delta)^2_{h_2}\right] + \left[\left(\frac{v_a}{v}\right)_{h_2} - \left(\frac{v_a}{v}\right)_{h_1}\right]\right\} \quad (1)$$

where OD, R, ϕ, v, δ, T, g, ρ, and h are the optical density, universal gas constant, volume fraction, molar volume, solubility parameter, temperature, gravitational acceleration, density and depth, respectively. Subscript a denotes the properties of asphaltenes; subscripts h_1 *and* h_2 stand for the properties at depths h_1 *and* h_2, respectively. It should be pointed out that the solubility parameter, molar volume, and density of bulk fluids, temperature, pressure and compositions are dependent on depth.

For low-GOR fluids, the solubility and entropy terms can approximately be canceled out due to the opposite influence on the asphaltene concentration gradient. Thus Eq. (1) can be rewritten as

$$\frac{OD(h_2)}{OD(h_1)} = \frac{\phi_a(h_2)}{\phi_a(h_1)} = \exp\left\{\frac{v_a g(\rho-\rho_a)(h_2-h_1)}{RT}\right\} \quad (2)$$

The FHZ EOS has been successfully used to analyze asphaltene (or heavy end) gradients in many field studies [26]. For example, the reservoir property of fluid flow connectivity was analyzed using measured fluid gradients combined with the FHZ EOS [27]. The simplified FHZ EOS for low GOR oils has been used for black oils with nanoaggregates [28–30] and heavy oils with asphaltene clusters [31]. Other formalisms have also been used to analyze asphaltene gradients in black oils and employ asphaltene particle sizes fairly similar, not identical, to asphaltene nanoaggregates as in Fig. 1 [32].

This new thermodynamic analysis of asphaltene gradients in oil reservoirs is enabling a first principle approach to understanding the origins of many complexities in oil reservoirs [21,31,33]. One fairly common complexity encountered in many oil reservoirs is a tar mat at the base of the oil column (and above water residing below the oil) [21,31,33]. Tar mats possess a very high asphaltene content often approaching 60%, and form an immobile layer in the reservoir porous media. These tar mats form by asphaltene phase separation once the asphaltene content exceeds the solvency capacity of the oil [33]. The 60% limit of asphaltene content can be thought of as the random packing limit (~63%) of monodisperse spheres, the asphaltene nanoaggregates [33]. If the tar mat is laterally extensive, it can preclude any aquifer pressure support in the oil column as oil is produced. Fig. 2 depicts a schematic of a massive anticlinal oil reservoir underlain by a tar mat, and with the aquifer below the tar [33].

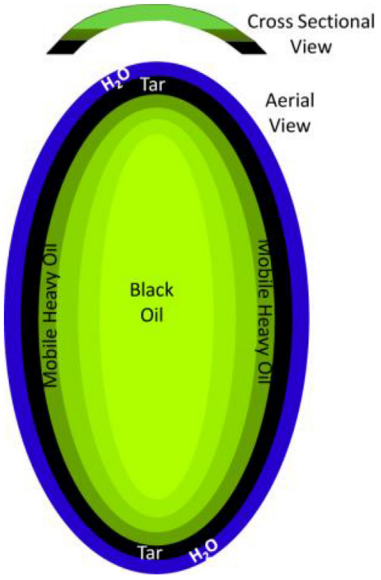

Fig. 2. Depiction of an upper-Jurassic lower-Cretaceous, anticlinal structure that contains a black oil reservoir of low GOR oil. There is a mobile heavy oil (insitu viscosity < 5000 cp) section at the base of each oil column, underlain by a tar mat at the oil–water contact. The oil rim and tar mat of this massive field extends for ~100 km. The tar mat is approximately 10 m thick [33].