Model for Rheological Behavior of Crude Oil and Alkali-Surfactant-Polymer Emulsion

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Abstract: Characterization of rheological behavior of alkali-surfactant-polymer (ASP) solution and oil emulsion is difficult, due to the complex chemical components and various physiochemical reactions with oil during chemical flooding. Through rheological experiments of ASP and crude oil emulsion, this paper presents the studies on influencing factors of rheological behavior, including interfacial tension, polymer and water cut, and discusses the stability mechanism of ASP and crude oil emulsion. The relationships among viscosity, interfacial tension, water cut and sheer rate were built through fitting the experimental data. The model and calculation can be used to more accurately simulate the ASP flooding in oil reservoirs.

Keywords: Emulsion, chemical flooding, rheological behavior, viscosity model.

INTRODUCTION

Alkali-surfactant-polymer (ASP) solution flooding has been used in oil reservoir developments since late 1980s, and oil recovery can be greatly enhanced because of the synergistic effect of three chemical flooding [1,2]. One important mechanism of ASP flooding is that the in-situ-formed soaps resulted by alkali reacting with naturally occurring organic acid in crude oil, interact synergistically with added surfactant, which produces ultralow interfacial tension (IFT), increases the capillary number [3] and enhances microscopic displacing efficiency. Besides, the polymer could increase viscosity of solution to improve the mobility ratio, and also increase microscopic sweeping efficiency [2]. The ultralow IFT results in oil and water flowing through porous media in the form of emulsion [4]. Emulsions are playing a more and more important role in oil recovery as they are found to occur in most enhanced oil recovery processes and are involved in certain modes of crude oil transportation [5]. Furthermore, they can also be used in secondary recovery as blocking agents to improve water flooding performance in layered reservoirs or under bottom-water conditions [6].

Rheological behavior is impacted by multicomponents of aqueous phase, concentration of disperse phase and size of emulsion droplet [7]. Rheological behavior of ASP-oil emulsion is more complex due to chemical components and productions from chemical action of ASP-oil. Alvarado and Marsden [8] studied the flow of oil-in-water macroemulsions through both porous media and capillary, in which rheological behavior of macro emulsions with oil concentrations ranging from 10% to 70% was obtained using capillary tube data; it was found that emulsions with oil concentrations less than 50% behaved like Newtonian fluids, while those with concentration greater than 50% behaved like pseudo plastic fluids. Coombe, Oballa and Buchanan [9] used a generalized compositional simulator to analyze the impact of non-Newtonian flow characteristics of polymers and emulsions at three length/time scales. In their study, the shear rate dependence of in situ emulsion generation suggested different modeling approaches at the core and field scales, with core scale rate processes replaced by pseudo-equilibrium K values at the field scale. Clark [10] studied the relationship between emulsion's rheological behavior and droplet size, and found that the viscosity of emulsion decreased with increasing droplet size. Khambharatana [5] investigated emulsion theologies and droplet captures for both caustic and surfactant emulsions flowing through Berea sandstone and Ottawa sand packs. His results showed that the change in emulsion rheology in a porous medium had an overall trend similar to that in a viscometer for the shear rates of interest; rheological behavior was found to be very different for the emulsion with different chemicals.

Although a number of studies have shown that the emulsion has the classic non-Newtonian flow characteristics, few studies have been carried out in the area of rheological behavior of emulsion during the ASP displacement process. Moreover, there is still a lack of a viscosity model, which could describe the emulsion rheology under influence of chemicals and be directly used in a flow simulator. Therefore, it is important to study the emulsion's flow behavior under the influence of polymer, surfactant and alkali simultaneously, which is the main subject of the present paper.

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agents, sheer rate, etc. The model includes the following steps:

1. Measure the viscosity of ASP solution at a certain sheer rate;
2. Determine the phase inversion point according to the viscosity and interfacial tension of ASP system and crude oil;
3. Estimate the ASP-oil emulsion type based on the phase inversion point, determine the emulsification, and divide the compound system into incomplete emulsion phase, and emulsion phase;
4. If emulsion is W/O type, there exists W/O emulsion and water phase (incomplete emulsion) in reservoir. Thus, water phase viscosity model matches the viscoelastic polymer emulsion model. Otherwise, emulsion is O/W type, there exist O/W emulsion and emulsified oil phase;
5. In an oil reservoir, we can build 3 equations of motion based on the viscosity model to simulate every phase's flow condition for calculating the flow of ASP flooding in porous media. The viscosity model of oil phase could use the conventional Newton rheology model, the viscosity model of water phase (ASP solution) could use the viscoelastic polymer emulsion model, and the viscosity of ASP/oil emulsion calculation could use the modified model (Gauss function Eq.3 and Power-Law model in Eq.4). The latter model is fitted by water cut and sheer rate to describe W/O and O/W emulsion viscosity (Fig. **5**). For the ASP or polymer flooding in reservoir, we could also use the viscoelsatic model (Eq. 5) of polymer solution in porous media to approximate the ASP flooding [15].

$$\mu_{polymer} = \left(1 + \frac{\frac{12n}{3n+1}\alpha\dot{\gamma}\theta_f\left(1-\frac{1}{\lambda_1^6}\right) - \frac{(B^4-1)^{1/2}}{(1+\beta)\alpha'}\left(1-\frac{1}{\lambda_3^3}\right)}{\frac{1}{\alpha}\left(1-\frac{1}{\lambda_1^3}\right)+6\xi+\frac{1}{\alpha'}\cdot\left(1-\frac{1}{\lambda_3^3}\right)} \right) H\dot{\gamma}^{n-1} \quad (5)$$

We used the new model to calculate the viscosity of emulsion. The Fig. (**6a**, **b**) show the verification of oil and water emulsion (the experimental data is from the reference 14). The Fig. (**6c**, **d**) show the verification of ASP solution and oil emulsion (ASP solution 0.5% HPAM +0.3% ORS-41+0.3% NaOH, the oil viscosity are 20mPa.s in Fig. (**6c**) and 15mPa.s in Fig. (**6d**). It is shown that this model can predict the relationship between water cut and viscosity accurately.

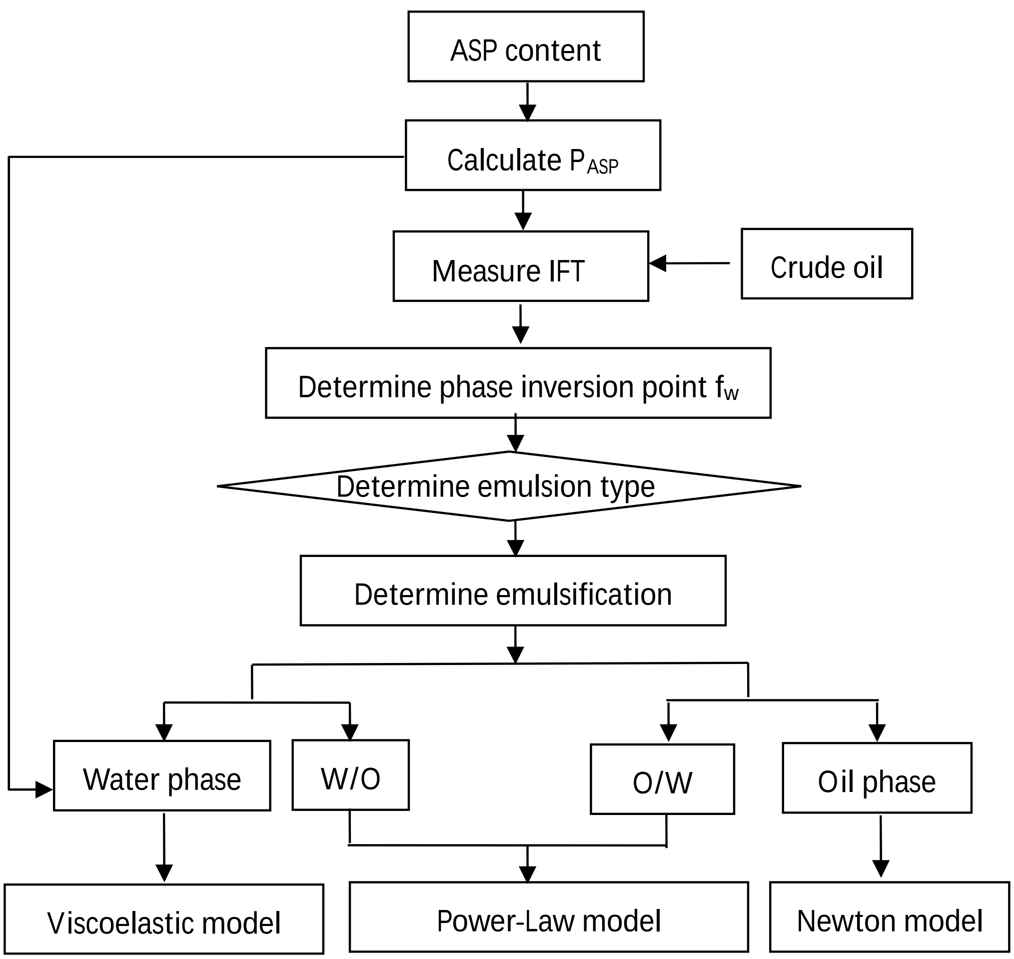
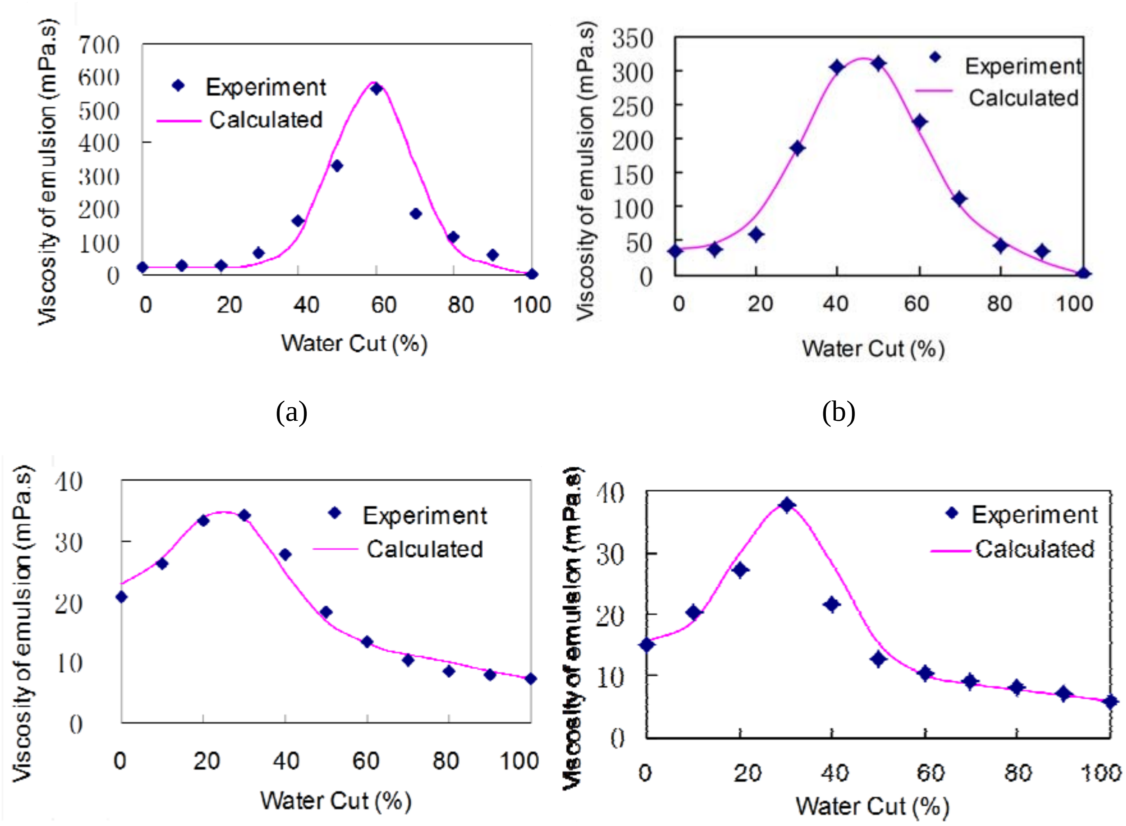


Fig. (5). Calculation steps in emulsion viscosity of ASP system model.



(a) (b)

(c) (d)

Fig. (6). Comparison of emulsion prediction model and experiment data.

CONCLUSION

We draw the following conclusions from our study.

(1) Surfactant concentration is a main factor of emulsion stability and rheology. With lower high concentration of surfactant and low interfacial tension, the ASP solution and oil emulsion are stable and the viscosity of emulsion is high. The impact of interfacial tension on performance is much larger in W/O emulsion than O/W emulsion. There is a good logarithm relationship between the viscosity and interfacial tension of emulsion.

(2) For the O/W emulsion formed by ASP solution and oil, polymer is dissolved in water phase and decreases the collision probability of emulsion drops, and it could increase the stability of O/W emulsion. For W/O emulsion, the influence of polymer is limited. Polymer solution and oil alone cannot form into a more stable emulsion. The rheology of O/W emulsion is similar to polymer solution.

(3) As the water cut increases, the W/O emulsion gradually inverts to O/W emulsion, and its viscosity increases initially and then gradually decreases after reaching the phase inversion point. The relationship between viscosity and water cut of emulsion could be nicely fitted with a modified Gauss function.

(4) For simulation of ASP flooding in oil reservoir, it is possible to build different flow models of water phase (ASP solution), oil phase and emulsion phase. Viscosity model of oil phase can use the Newton model, water phase can use a viscoelastic model in porous media, and emulsion can use a Power-Law model.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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