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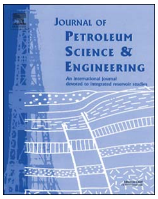

Effective viscosity prediction of crude oil-water mixtures with high water fraction

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ABSTRACT

In the petroleum industry, a flowing crude oil-water system with high water fraction usually does not exist as a stable and homogeneous emulsion, but in the form of a mixture of oil and free water with some water being emulsified into the oil and thus, hydrodynamically, acting as part of the oil. Therefore, the existing viscosity models developed for stable and homogeneous emulsions cannot accurately predict viscosity of this kind of liquid-liquid mixtures. In the present work, the effective viscosity of crude oil-water mixtures with high water fraction was measured by using a stirring method. It was found that the effective viscosity of the mixtures decreased with increasing shear rate, water fraction and temperature. Based on the Taylor viscosity model and combined with our previous study on the emulsification behaviors of crude oil-water systems, a viscosity model was developed for crude oil-water mixtures with high water fraction, which is characterized in covering the effects of shear rate, emulsified water fraction and crude oil compositions. Validation was done by using 40 data points which were obtained from mixtures of two crude oils and not used for model development, and the results showed that the proposed model gave accurate predictions of the mixture viscosity, with an average relative deviation of 7.4%. Approach is proposed to application of this model in the prediction of the frictional loss of oil and water two phase flow in pipes.

1. Introduction

The crude oil-water two-phase or crude oil-gas-water multiphase flow is quite common in the petroleum industry. Due to the natural surfactants such as resins, asphaltenes and wax particles containing in the crude oil, crude oil and water emulsify easily in the process of production. The emulsification of crude oil and water has significant influences on multiphase flow (Grassi et al., 2008; Nädler and Mewes, 1997; Wang et al., 2011; Yusuf et al., 2012). Actually, a flowing crude oil-water system usually does not exist as a stable and homogeneous emulsion, but in the form of an unstable oil-water mixture composed of W/O emulsion and free water, significantly differing from a stable emulsion in dispersity and static stability.

A large number of viscosity models for stable emulsions have been developed in the previous studies. In 1906, Einstein (1906) derived an equation for the viscosity of dilute dispersed systems.

$$\eta_r = (1 + 2.5\phi_d) \tag{1}$$

where η_r is the relative viscosity, defined as the ratio between emulsion viscosity (η_e) and continuous phase viscosity (η_c), i.e., $\eta_r = \eta_e/\eta_c$; ϕ_d is the volume fraction of the dispersed phase.

Later researchers (Schramm, 1992) added more terms into the Einstein's equation to extend its applicability to emulsions, with the general form as follows.

$$\eta_r = 1 + k_1\phi_d + k_2\phi_d^2 + k_3\phi_d^3 + \dots \tag{2}$$

where k_1, k_2, k_3 are parameters associated with particular emulsion systems.

Brinkman (1952) proposed a model for the emulsion with spherical droplets.

$$\eta_r = (1 - \phi_d)^{-2.5} \tag{3}$$

Richardson (1933) firstly developed an exponential relationship between the relative viscosity and the volume fraction of the dispersed phase.

$$\eta_r = e^{k\phi_d} \tag{4}$$

where k is an undetermined parameter, if $\phi_d < 0.74$, k=7, if $\phi_d > 0.74$, k=8. The Richardson equation has been found suitable for many emulsion systems. And it has been modified by many researchers to

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adapt more emulsion systems (Broughton and Squires, 1938; Marsden, 1977; Mooney, 1951).

The above-mentioned viscosity models correlate the relative viscosity with the volume fraction of the dispersed phase only, with the effect of other factors implied in the undetermined parameters. While Taylor (1932) assumed that the dispersed phase was extremely small spherical droplets, and derived an equation for dilute emulsions which contains the dispersed phase viscosity η_d

$$\eta_r = 1 + \left(\frac{\eta_c + 2.5\eta_d}{\eta_c + \eta_d}\right)\phi_d \tag{5}$$

Based on the Taylor model and the continuum theory, Phan-Thien and Pham (1997) developed an equation for emulsion viscosity.

$$\eta_r^{2/5}\left[\frac{2\eta_r + 5K}{2 + 5K}\right]^{3/5} = (1 - \phi_d)^{-1} \tag{6}$$

where K is the ratio of dispersed phase viscosity and the of continuous phase viscosity, i.e., $K = \eta_d/\eta_c$.

After Phan-Thien and Pham, Pal (2000) proposed an improved model by considering the effect of surfactants on the viscosity.

$$\eta_r^{-2/5}\left[\frac{2\eta_r + 5K}{2 + 5K}\right]^{-3/5} = 1 - K_s\phi_d \tag{7}$$

where K_s is a coefficient associated with surfactants, which needs to be determined by fitting experimental data.

Emulsions often exhibit non-Newtonian flow behaviors, such as the shear-rate-dependence of viscosity. Therefore, some works had been done to cover this non-Newtonian property.

Based on the Brinkman's equation (Brinkman, 1952), Pal and Rhodes (1989) developed a model for predicting the shear-rate-dependence of emulsion viscosity.

$$\eta_r = [1 - K_0K_f(\dot{\gamma})\phi_d]^{-2.5} \tag{8}$$

where K_0, $K_f(\dot{\gamma})$ are defined as the non-Newtonian coefficients; K_0 represents the influence of hydration, which associates with the emulsion;$K_f(\dot{\gamma})$ represents the influence of droplets coalescence, which associates with shear rate.

Based on the Richardson's equation (Richardson, 1933), Rønningsen (1995) proposed an empirical equation which correlates the emulsion viscosity with shear rate and temperature.

$$\ln\eta_r = k_1 + k_2T + k_3\phi_d + k_4T\phi_d \tag{9}$$

where T is temperature; k_1, k_2, k_3, k_4 are the parameters associated with shear rate, which can use the following empirical values: k_1=0.0412, k_2=−0.002605, k_3=0.03841, k_4=0.0002497.

After Pal and Rhodes (1989), Dou and Gong (2006) developed an equation for water/heavy crude oil (W/O) emulsion, which includes the effect of the water fraction on the non-Newtonian coefficient.

$$\eta_r = [1 - K_f(\dot{\gamma})K_f(\phi_d)\phi_d]^{-2.5} \tag{10}$$

$$K_f(\phi_d) = \frac{\dfrac{1 - \eta_r^{-0.4}(\dot{\gamma}, \phi_d)}{\phi_d}}{\dfrac{1 - \eta_r^{-0.4}(\dot{\gamma}, \phi_{max})}{\phi_{max}}} \tag{11}$$

where $K_f(\phi_d)$ is the coefficient of water fraction, representing the effect of water fraction on the non-Newtonian rheological behavior; ϕ_{max} is maximum water fraction of the emulsion.

It has been known that the droplet size and size distribution of the dispersed phase has significant effect on emulsion viscosity. Wang (2009) incorporated the effect of droplet size into the Dou's equation and derived the following viscosity model.

$$\eta_r^{2/5}\left(\frac{\eta_r + 2.5K}{1 + 2.5K}\right)^{3/5} = [1 - K_f(\phi)\cdot K_f(N_{Re,p})\cdot\phi_d]^{-1} \tag{12}$$

where $K_f(N_{Re,p})$ is the Reynolds number factor of the droplets associated with shear rate and droplet size.

By taking into the consideration of the effects of interfacial rheology, Pal (2011) developed a new model for the viscosity of concentrated emulsions.

$$\eta_r\left[\frac{2\eta_r + 5\varepsilon_m/(1 - \varepsilon_m)}{2 + 5\varepsilon_m/(1 - \varepsilon_m)}\right]^{3/2} = f(\phi_d) \tag{13}$$

$$f(\phi) = (1 - \phi)^{-5/2} \tag{14}$$

where ε_m is the interfacial mobility parameter.

Based on the factors of shear rate, oil concentration, emulsifier concentration and temperature affecting viscosity, Azodi and Nazar (2013) developed a rheological equation for predicting the viscosity of oil in water emulsion.

$$\eta = k_1\dot{\gamma}^n\exp\left(C_1\phi_d + \frac{C_2}{T} + C_3\omega\right) \tag{15}$$

where k_1, n, C_1, C_2 and C_3 are the constants and depend on the emulsion system; ω is the emulsifier concentration, wt%.

Strictly speaking, the classic viscosity definition for homogeneous fluids cannot be applied to unstable and inhomogeneous oil-water mixtures. That is to say, existing viscosity models developed for stable emulsions are no longer applicable for this mixture. Moreover, according to their principle of measurement of the traditional viscometers, such as coaxial cylinder viscometer and cone-plate viscometer, are not suitable for measuring "viscosity" of this inhomogeneous and unstable mixture.

At the earliest stage, the effective viscosity of the oil-water mixture was estimated by using the weighed mean method to meet the need of the industry (Govier and Aziz, 1972):

$$\eta_m = \eta_o(1 - \phi_w) + \eta_w\phi_w \tag{16}$$

where $\eta_m$is the viscosity of an oil-water mixture; η_o is the oil viscosity; $\eta_w$and ϕ_w are the viscosity and the volume fraction of water, respectively. Obviously, this simple weighted rule does not give accurate prediction of the mixture viscosity.

It is common practice in the industry to obtain the effective viscosity of an oil-water mixture on the basis of pressure drop vs. flow rate relation and flow loop data. Pan (1996) studied the stratified flow and dispersed flow in a flow loop, and developed a correlation for calculating the viscosity of oil-water mixture by considering the influence of flow-induced mixing degree on viscosity.

$$\eta_m = (1 - c_m)[\phi_o\eta_o + \phi_w\eta_w] + c_m\eta_c(1 - \phi_d)^{-2.5} \tag{17}$$

where $c_m$is the mixing coefficient representing the mixing degree of the oil-water two phase flow; ϕ_o and ϕ_w are the volume fraction of oil phase and water phase, respectively. However, Pan's model covers neither the effect of the emulsified water in the oil phase, nor the effect of oil compositions; it is hard to be applicable to broad crude oil-water systems.

An oil-water system may become homogeneous if sufficient stirring is applied to it. Effective viscosity of a stirred fluid system may be determined according to the shaft torque and stirring speed. In the present study, the effective viscosities of crude oil-water mixtures of eight crude oils with high water fractions were measured by using this stirring method, and the effects of shear rate, water fraction and temperature on the effective viscosity of mixtures were studied. Moreover, a model for predicting the effective viscosity of the crude oil-water mixtures with high water fraction was developed and validated by using experimental data of mixtures prepared with other two crude oils. Finally, approach is proposed to application of this model in the prediction of the frictional loss of oil and water two phase flow in pipes.