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Flow of Heavy Oil Emulsions through Porous Media

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Rheological and core flow test data were used to develop a relationship between friction factor and Reynolds number for describing the flow of water/oil emulsions through sandstone cores. The developed correlations are used for determining the pressure drop across the porous medium, particularly in enhanced oil recovery process by surfactant flooding.

The crude oil and sandstone cores used were obtained from Saudi oil reservoirs. Experiments were conducted to measure the rheological properties of emulsions and carry out flow tests.

The results showed that the rheological behavior was found to be that of a pseudoplastic that obeys the power-law mode. It was confirmed experimentally that the friction factor and Reynolds number obtained from core tests are inversely proportional regardless of emulsion composition or viscosity.

1. Introduction

Blake¹⁾ was the first to introduce two dimensionless groups to describe the flow of Newtonian fluids through granular beds. They were given by

$$f = \frac{\Delta P D_p \phi^3}{\rho V_o^2 L (1 - \phi)} \quad (1)$$

$$R_{en} = \frac{D_p V_o \rho}{\mu (1 - \phi)} \quad (2)$$

Equations (1) and (2) were used in the majority of papers published on Newtonian flow through granular beds.

Previous studies of the flow of non-Newtonian fluids through porous media were conducted by Sadowski²⁾, Sadowski and Bird³⁾, Camy *et al.*⁴⁾, Richardson⁵⁾, Marsden and Raghavan⁶⁾, and Alvarado and Marsden⁷⁾. They have studied rheological behavior of different crude oil emulsions and have concluded that, while many of them behave as Newtonian fluids, some show definite non-Newtonian properties. Of the latter, most are pseudoplastic, but some are dilatant, many are thixotropic and a few are rheopectic. The main reasons for this wide variation in emulsion behavior is due to the great disparity in their composition and the conditions under which

they exist. The investigators have suggested several correlations relating the emulsion viscosity to dispersed phase concentration or shear rate using the power-law models⁸⁾.

$$\tau = H \gamma^n \quad (3)$$

Christopher and Middleman⁹⁾ have modified Eq. (2) for power-law fluids as:

$$R_{epi} = \frac{D_p V_o^{2-n} \rho}{\mu_{eff} (1 - \phi)} \quad (4)$$

where the viscosity level parameter (μ_{eff}) is given by

$$\mu_{eff} = \frac{H}{12} \left(9 + \frac{3}{n} \right)^n (150 K \phi)^{(1-n)/2} \quad (5)$$

Equations (1) and (3) through (5) were used to calculate the friction factor and Reynolds number from experimental results. The relation between the friction factor and Reynolds number can be written as follows:

$$f = \frac{A}{R_{epi}} \quad (6)$$

where the constant "A" is experimentally determined.

Once the friction factor is determined from Eq. (6), the pressure gradient across the porous medium can be determined from Eq. (1).

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2. Experimental Work

Rheological properties of heavy oil emulsions were measured using a Brookfield viscometer at a constant temperature of 25°C. The shear rates were ranged from 0.371 to 73.1 s⁻¹. The components of the emulsions were heavy crude oil (API=27°), brine (salinity=15% by weight NaCl), hydrochloric acid (concentration=2% by weight), and Triton X-100 as an emulsifier (concentration=0.5% by weight). The emulsifier was used to produce stable emulsions. It reduces the interfacial energy, thereby enabling easier formation of the greatly extended interface. It also prevents the coalescence of the droplets once they are formed. The hydrochloric acid was added to the crude oil to dissolve the inorganic materials present.

Figure 1 shows the flow test apparatus used to measure the pressure drop and flow rate during the flow of emulsions through sandstone cores. The ranges of pressure drop and flow rate were 30 to 145 psi and 0.15 to 1.6 µm³/s, respectively. The range of shear rate encountered in core test was

from 126.93 to 1,353.9 s⁻¹. Although the range of shear rate encountered in core test (127-1,354 s⁻¹) is higher than that of viscosity data (0.371-73.1 s⁻¹), the type of the emulsion (*i.e.* pseudoplastic fluid) will not significantly change at higher shear rates. This is a property of pseudoplastic fluid⁸. However, the values of H and n may be changed at higher shear rates, by adding new viscosity data. Since the correlation coefficients of the fitted power-law were statistically checked at confidence level of 99%, the acceptance of the values of H and n at higher shear rates will decrease the confidence level to 95%. It is believed that, this limit is experimentally accepted. The properties of the cores used are given in Table 1. Table 2 shows the mineralogical analysis and relative abundance of clay minerals in the cores. The density of the emulsions was measured using a pycnometer.

3. Results and Discussion

The results of emulsion density measurements are given in Table 3. The rheological properties of the emulsions are plotted in Fig. 2. This figure

Fig. 1 Experimental Apparatus

Table 1 Properties of Sandstone Cores

Core No.	Diameter [cm]	Length [cm]	Bulk volume [cm ³]	Pore volume [cm ³]	Porosity [%]	Initial permeability [md]	Permeability after flow of o/w=7/3 emulsion
A ₇	3.60	8.65	88.05	20.12	22.85	620	593
B ₂	3.65	6.15	64.35	13.90	21.60	593	421
B ₃	3.60	9.50	96.70	24.01	24.83	698	651
C ₁	3.60	7.50	76.34	18.27	23.93	638	514
C ₂	3.65	9.30	97.31	23.99	24.66	656	637
D ₂	3.65	8.30	86.85	20.71	23.85	650	569
E ₃	3.60	8.30	84.48	20.29	24.01	646	569
G ₁	3.65	8.30	86.85	19.09	21.98	609	569
X ₁	3.60	8.90	90.59	22.62	22.76	635	610
X ₂	3.60	8.90	90.59	21.49	23.73	622	610

Table 2 Mineralogical Analysis and Relative Abundance of Clay Minerals in the Cores

Mineralogical analysis		Clay minerals	
Element	wt%	Element	Relative abundance
Quartz	85	Kaolinite	40
Feldspar	3	Chlorite	27
Clay	8	Illite	17
Pyrite	4	Montmorillonite	6

Fig. 2 Rheological Properties of Saudi Heavy Oil Emulsions

Table 3 Values of H , n , and A of Heavy Oil Emulsions Using 15% NaCl Concentration

Oil/water	H [mPa·s]	n	A	ρ [kg/m³]
9/1	87.66	0.950	143.65	885.4
7/3	110.69	0.983	154.5	887.5
5/5	67.89	0.704	140.0	890.7
3/7	27.08	0.695	118.8	895.5
1/9	3.02	0.871	165.88	897.2

indicates that the viscosity decreases with either increase in shear rate or decrease in oil concentration, except that viscosities for the oil/water ratio of 7/3 are higher than those for the ratio of 9/1. This means that the emulsions studied exhibit pseudoplastic behavior under the test conditions. These measurements were correlated with the power-law model, and the resulting values of H and n are given in Table 3.

The flow test results (pressure drop and flow rate), values of H , n , and density are given in Table 3, and the properties of the ten sandstone cores given in Table 1 were used to calculate the friction factor and Reynolds number from Eqs. (1) and (4). The friction factor and Reynolds number data of each oil/water ratio were correlated with Eq. (6) and the values of the constant " A " are given in Table 3.

Fig. 3 Friction Factor vs. Reynolds Number for Heavy Oil Emulsion

In order to obtain an average correlation for all emulsions studied, the friction factor and Reynolds number of the various emulsions are plotted in Fig. 3. This figure shows that the friction factor decreases with increasing Reynolds number or with decreasing oil concentration. These data were correlated with Eq. (6) and the correlation obtained is

$$f = \frac{155.34}{R_{ep1}} \quad (7)$$

Equation (7) can be used to predict the pressure drop resulting from the flow of heavy oil emulsions through sandstone cores. An equation similar to Eq. (7) for Newtonian fluids can be obtained by combining Eqs. (1) and (2) and Darcy's law.

$$f = \frac{150}{R_{ep1}} \quad (8)$$

Comparing Eq. (8) with Eq. (7), it can be concluded that the value of the constant " A " in Eq. (7) slightly differs from that of Eq. (8). The difference between the two values of the constant is small and may be related to the acceptance of viscosity data in calculations of friction factor and Reynolds number or the properties of emulsion, or both.

4. Conclusions

Based on the experimental results and the calculated values of friction factor and Reynolds number, the following conclusions were obtained.

1) The heavy oil emulsions studied using 15%

NaCl concentration, 2% HCl, and 0.5% Triton X-100 exhibited pseudoplastic behavior at 25°C.

2) An average correlation was developed to describe the flow of heavy oil emulsions through sandstone cores.

3) It was confirmed experimentally that friction factor and Reynolds number obtained from core tests are inversely proportional regardless of emulsion composition or viscosity.

Nomenclatures

A	: constant in Eq. (6)	
D_p	: effective particle diameter	[m]
f	: friction factor	
H	: consistency index	[Pa·s ⁿ]
K	: permeability resulting from the flow of emulsion through porous media	[m ²]
K_i	: initial permeability of the core	[m ²]
L	: core length	[m]
n	: flow behavior index	
P	: pressure	[Pa]
R_{epi}	: Reynolds number for power-law fluids	
R_{en}	: Reynolds number for Newtonian fluids	
V_o	: superficial velocity	[m/s]
<Greeks>		
ρ	: density	[kg/m ³]

μ	: Newtonian viscosity	[Pa·s]
μ_{eff}	: viscosity level parameter for power-law fluids	[Pa·s ⁿ ·m ¹⁻ⁿ]
ϕ	: porosity	
τ	: shear stress	[Pa]
γ	: shear rate	[s ⁻¹]

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要 旨

多孔質媒体内における重質油エマルションの流動

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流体のレオロジーと砂岩コアを用いた流動試験のデータから、砂岩中を水/油エマルションが流動するときの摩擦係数とレイノルズ数の関係を導いた。得られた相関から、多孔質媒体中を流体が流れるとき、特に界面活性剤を用いた EOR における圧力降下を求めることができる。

実験に用いた原油と砂岩コアはサウジの油層から得られたものである。実験に用いられたエマルションは、べき乗則に従う擬塑性流体であった。流動試験の結果、摩擦係数とレイノルズ数はエマルションの組成および粘度によらず、反比例することが確認された。

Keywords

Emulsion, Porous media, Friction factor, Reynolds number, Pseudoplastic fluid, Viscosity