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CHEMICAL ENGINEERING

Flow of Oil Emulsion Through Porous Media

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Abstract. The flow through porous media of oil emulsion is reported in this paper. Base oil, water and Triton X-100 were used to produce O/W and W/O type emulsions. Shear stress, shear rate, and yield stress were measured for the emulsions at different temperatures and oil concentrations.

Results show that at low oil concentration (10% to 40%), the emulsion was oil in water type and a Newtonian behavior was observed with viscosity ranging from 1.5 to 7.7 cP. Medium oil concentration (50% to 60%) data were interpreted in terms of the power law model relationship for non-Newtonian fluid. While at high oil concentrations (70% to 90%) data were interpreted in terms of the Hershel-Bulkley model relationship for a non-Newtonian fluid with yield stress. At high oil concentration of 50 90% oil, the emulsion was water in oil type.

Data for porous packed bed of glass beads are presented using friction factor and a general Reynolds number for the flow through porous media, which includes a fluid yield stress.

Nomenclature

C'' = Constant in equation 5.
D_p = Particle diameter, m.
f^* = Friction factor for porous medium
H = Consistency index, Pa S^n
L = Bed length, m.
n = Flow behavior index
ΔP = Pressure drop, Pa.
R = Radius of tube, m.
R'_e = Reynolds number for Newtonian fluid flow through porous media.
R^*_e = Reynolds number for Hershel-Bulkley fluid flow through porous media.
$\overline{V}$ = Average intersitial velocity component parallel to bed axis, m/sec.

V_0 = Superflicial velocity, m/s

ε = Porosity

μ = Viscosity, Pα. S

τ = Shear stress, PA

τ_0 = Yield stress, Pa

$\dot{\gamma}$ = Shear rate, 1/S

$\overline{\phi}$ = Coefficient defined in equation 9

ρ = Density of emulsion, Kgm/m^3.

$\varnothing$ = Oil concentration

Background

Most of the world's crude oil include emulsions [11,13,15,16]. These emulsions are generally water-in-oil emulsions (W/O), which are more viscous than either of their constituents. It is common practice to separate the emulsion into its components, thereby obtaining reduced viscosity. This is accomplished in the oil field by using chemical and heat treatments. In contrast to W/O emulsions, oil-in-water emulsions (O/W) have lower viscosities than their oil constituent (at low concentrations). This was considered by some investigators during the development of systems for producing and transporting crude oil as O/W emulsions [3].

To describe properly the flow behavior of emulsions in both pipeline and reservoirs, the properties of emulsions and the physical laws controlling their flow through tubes and porous media must be known.

Transporting of crude oil as O/W emulsion has a major advantage due to its low viscosities compared with other techniques such as diluting or increasing the temperature.

Rheology of emulsions

The rheological properties of emulsion are effected by factors controlled by the nature of the constituents of the emulsion such as; viscosity of external phase, volume concentration of the dispersed phase, viscosity of the internal phase, nature of the emulsifying agent and the interficial film formed at the interface, particle size distribution and electroviscous effect.

Mechanism of flow through porous media

Emulsion which may be either of O/W or of the W/O type, have drop sizes of few micrometers, and they must be transported in the reservoir rock having permeabilities ranging from a tenth to several Darcys. Experimental findings of several researchers [17] reveal the following features: (a) the permeability of the porous media decreases monotonically with time, (b) the particles do not appear in the effluent directly after a through put of one pore volume of emulsion injected, (c) the rate and the amount of permeability decrease and the droplet breakthrough time increase with increasing drop size, (d) in some cases the rate and the amount of permeability reduction increase slightly with decreasing flow rate, eventually a steady state is reached and, (f) when emulsion injection is followed by many pore volumes of water flow, droplets elute for about the first pore volume but the original permeability decrease caused by the emulsion remains.

In tertiary oil recovery process, similar to primary and secondary recovery processes, one encounters problems associated with the formation of emulsions. Evidently such emulsions may either impede or accelerate the recovery depending on their physico-chemical characteristics under given conditions. For example, if the formation of emulsion is considered adverse in operating the recovery scheme then selective methods of demulsification should be invoked.

A review of the literature shows very little mention of flow of emulsions through porous media. Some interesting observations favouring the presence of macroemulsion in the oil recovery process have been reported by McAuliffe [14]. The ease with which emulsions flow at high pressure gradients was proposed by McAuliffe to be an advantage in the field applications because in a radial flow system the highest pressure decrease per unit distance occurs near the well-bore.

The unfavorable aspect of having an emulsion arises outside the reservoir conditions. Although it is well known that macro-emulsions are thermodynamically unstable, the presence of multiple surfactants in the flood can effectively prolong the emulsion stability to time periods of the order of weeks or months.

Lissant [12] in a recent review indicated that the occurrence of emulsion is a natural and all perverse phenomenon in petroleum production and emulsions are to be avoided if possible. He further reported that a considerable amount of literature on the development of techniques for resolving emulsions can be found and that this technology should be taken into consideration when emulsification is deliberately employed to achieve additional oil recovery.

There are many theories in the literature available to describe emulsion transport behavior. The retardation, originally, delineated by McAuliffe, does consider transient permeability reduction. In this model, the emulsion drops are retarded during their passage along the tortuous paths of the medium, when a droplet encounters a pore of throat size smaller than its own diameter, it deforms and squeezes through. In the constricted pore it experiences capillary resistance force, therefore, moves at slower speed than the continuous phase, thereby causing an overall permeability reduction. A steady state is reached when the emulsion breakes through the porous media. In the case of high concentration emulsions no permeability reduction is predicted and the emulsion particles must elute exactly at one pore volume of fluid injection. At high concentrations steady state is quickly approached, which have small drop size to pore-size ratios.

The purpose of this research is to study the flow of O/W and W/O macroemulsion through porous media. The rheological characteristics of emulsions are analyzed by using rotational viscometer. A new method developed by Al-Fariss and Pinder [1] is used to describe the flow of emulsions through porous media that uses both capillary and core flow data. Results are presented in the form of modified friction factor and modified Reynolds number correlation.

Model Development

Al-Fariss and Pinder [1] have developed a general model describing the flow of shear thinning liquid with yield stress through porous media in the form of modified friction factor-Reynolds number correlation. Their work and ours used the Herschel-Bulkley model to describe the rheological behaviour of the fluid used:

$$\tau = H\dot{\gamma}^{n} + \tau_o \tag{1}$$

This model was used because the rheological data for the emulsions tested show Newtonian, Power-Law, and shear-thinning with yield stress behavior.

By making force balance in a tube and integrating the average velocity was obtained as:

$$\bar{V} = \frac{nR^{\left(1+\frac{1}{n}\right)}}{1+3n}\left(\frac{\Delta P}{2LH} \quad \frac{\tau_o}{RH}\right)^{\frac{1}{n}} \tag{2}$$

For special case when $\tau_0 = 0$, $n = 1$, *i.e.* $H = \mu$, equation (2) reduces to Hagen-Poiseuille equation for the flow of Newtonian fluids;

$$\bar{V} = \frac{R^2 \ \Delta P}{8 \ \mu L} \tag{3}$$

By using capillary approach to describe the flow through porous media, the hydraulic radius, superficial velocity, and tortuosity effect are introduced in equation 2 to get the following equation;

$$V_o = \frac{\varepsilon n}{3n+1}\left[\frac{D_p\varepsilon}{3(1-\varepsilon)}\right]^{1+\frac{1}{n}}\left[\frac{\Delta P}{2HL} - \frac{3(1-\varepsilon)}{\varepsilon D_p H}\tau_o\right]^{\frac{1}{n}} \tag{4}$$

Blake [4] was first to present the equation for the flow through porous media in the form of a friction factor-Reynolds number correlation. The relation for viscous flow was given as:

$$f^{*} = C'' / R_e' \tag{5}$$

where, C'' is a constant and

$$f^{*} = \frac{\Delta P \ D_p \ \varepsilon^3}{\rho V_o^2 L(1-\varepsilon)} \tag{6}$$

and

$$R_e' = \frac{V_o D_p \rho}{(1-\varepsilon)\mu} \tag{7}$$

By analogy with equation 5 and by substituting equations 4 and 5 into equation 6 we get the definition of Reynolds number for the flow of emulsions through porous media

$$R_e^{*} = \frac{12\rho V_o^2}{2HD_p\varepsilon^3 V_o^n / \overline{\phi} + \tau_o \varepsilon^2} \tag{8}$$

where

$$\overline{\phi} = 6\left(\frac{\varepsilon n}{3n+1}\right)^n \left(\frac{D_p \varepsilon}{3(1-\varepsilon)}\right)^{n-1} (1-\varepsilon) \tag{9}$$

$$f^{*} = \frac{C''}{R_e^{*}} \tag{10}$$

The modified Reynolds number defined by equation 8 appears to be more general form, since it includes yield stress and the flow parameters H and n of Hershel-Bulkley model. Equation 8 reduces to equation 7 for the flow of Newtonian fluids through porous media when ($\tau_0 = 0$, n = 1, and H = μ) [1].

Experimental Work

The emulsions tested in this work were oil in water (O/W) type, *i.e.*, the oil droplets formed the disperse phase and the aqueous emulsifier solution formed the continuous phase. The oil used was a refined base-oil 700 from Riyadh Refinery. The base-oil was used because it is free of any additive or any other parameters which may affect the results. The commercially available surfactant Triton X-100 was used to stabilize the emulsions. Triton X-100 is a nonionic water soluble molecule (isoctylpheoxy polyethoxy ethylen) with 9 to 10 ethylene oxide units. The surfactant has a density of 1.065 gm/cc and a viscosity of 240 cp at 25°C. Its surface tension at 0.5% (by volume concentration) is about 31 dyne/cm.

Experimental technique

The viscosity of emulsion was measured for different concentration of oil-in-water (10% to 90% oil concentration in water, and at different temperatures 5°C to 35°C by 5°C increment). The samples were prepared by mixing triton X-100 with water first for 5 minutes then oil was added to give the desired concentration of oil and Triton X-100 (0.5% by volume of the emulsion). Then solution was mixed at high rate for 15 minutes to ensure uniform droplet size. For preparation of low oil concentration (10% to 40% oil) samples; first the oil emulsion was prepared then it was diluted by 0.5% Triton X-100 in water to the desired concentration and this is to provide a larger stability [8]. For low concentration samples (from 10% to 30% oil), it tends to cream within nearly two hours and mixing rate has no major effect on the period of stability. This creaming instability is due to the use of a nonionic emulsifier (Triton X-100) for emulsification because it produces a skin of the internal phase (oil) droplets and prevents coalescence but it will not keep them part and prevent creaming as an ionic emulsifier will do. In low oil concentrations, there is random distribution of the droplets.

While for medium oil concentrations (40% to 60%) the mixing rate has an effect on the stability of the emulsion, at high mixing rates the size distribution will be more uniform and will give a monodisperse droplets which form a uniform packing. A mixture of ionic and nonionic emulsifier should be used for this range of oil concentration (40% to 60%) to keep the droplets apart by means of the ionic emulsifier and to decrease the creaming rate while the nonionic emulsifier should be used to prevent coalescence. For high oil concentrations (70% to 90%) the emulsions are in super creamed condition and nearly reach the maximum uniform packing tesselation (F.C.C. PF = 74%), therefore the solution reached a stable condition by standing more than 72 hours. For this range of oil concentration a relatively high rate of mixing should be provided. A nonionic emulsifier is the best for high oil concentrations because it prevents creaming.

Rheological properties measurements

The viscometer used to measure the shear stress, shear rate and yield stress of the emulsion tested was a rotating bob type coaxial cylinder viscometer (HAAKE Rotovisco Model RV-12). The outer stationary cylinder (cup) is surrounded by a temperature controlled water-jacket. Inside the cup, there is an inner cylinder (bob) of smaller diameter which rotates to shear the emulsion in the gap between the cup and bob. There are many possible combinations of the size and type of bobs and cups for this instrument depending on the material to be tested. The set of NV cup and bob was chosen for the relatively low viscous emulsions (10% to 50% by volume of oil). The set of MV profiled cup and MVIIP bob was chosen for intermediate emulsion viscosities (60% to 80% oil). And for 90% oil cone and plate combination was chosen due to high viscosity of this emulsion concentration.

The viscosity of the emulsion samples was measured at 7 different temperatures in the range from 5°C to 35°C with 5°C increment. The sample was changed after each temperature test to avoid separation of emulsion.

Flow test equipment

The packed bed consists of glass beads packed in a plexiglass column surrounded by a plexiglass water jacket in which constant temperature water is circulated. To maintain a large column diameter to particle diameter ratio and reduce wall effects, beads of 1.5 mm particle size was used to pack the plexiglass column (100 mm internal diameter, with pressure taps interval of 1200 mm), this gives a ratio of column to particle diameter value of 66.7. The sample was kept in a tank with a mixer to avoid separation of emulsion, and surrounded by a jacket in which a constant temperature water is circulated. When the desired temperature is reached, the sample is introduced to a shell and tube heat exchanger (made of mild steel) to reach the accurate needed temperature. Then a pressure is applied to the heat exchanger from a pressurized nitrogen cylinder, therefore, the emulsion will flow from the heat exchanger through a control valve to the packed bed. The temperatures at the heat exchanger outlet and the inlet of the packed bed stream were measured by a thermocouple thermometer. The outlet stream from the packed bed flow through a rotameter to indicate a steady state flow, and the mass flow rate is measured by timing the accumulation of known weight. A schematic diagram of the flow tests equipment is shown in Fig. 1.

Results and Discussion

A Newtonian behavior was observed for emulsions of 10, 20, 30 and 40% oil content as shown in Fig. 2. Their viscosities are relatively low which range between 1 to 9 cp. At low oil concentration the droplets do not interfere with each other appreciably, but as more internal phase is introduced the droplets begin to collide more frequently. This causes an increase in the viscosity of the whole mixture. At this range of oil concentration (10% – 40% oil) the rheological characteristics of the emulsions are governed mainly by the rheological characteristics of external phase.

When the oil concentration was increased above 40% to about 60% oil, the emulsion behaved as a non-Newtonian fluids (pseudoplastic behavior) which was fitted by power law model, as shown in Fig. 3).

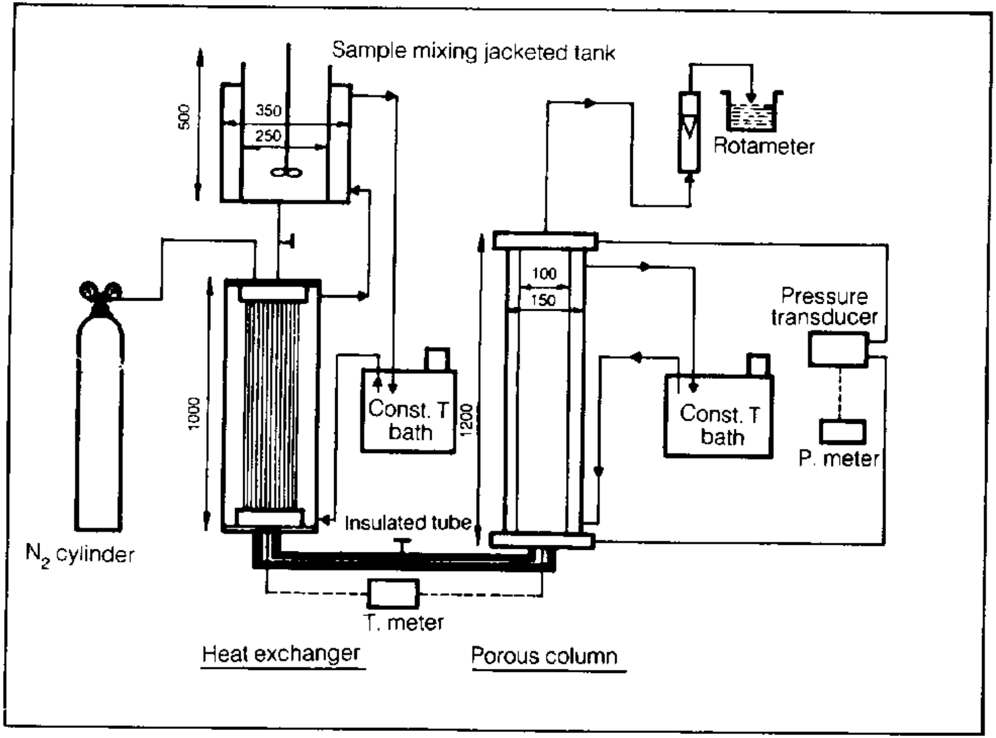

Fig. 1. Schematic diagram for the flow test.

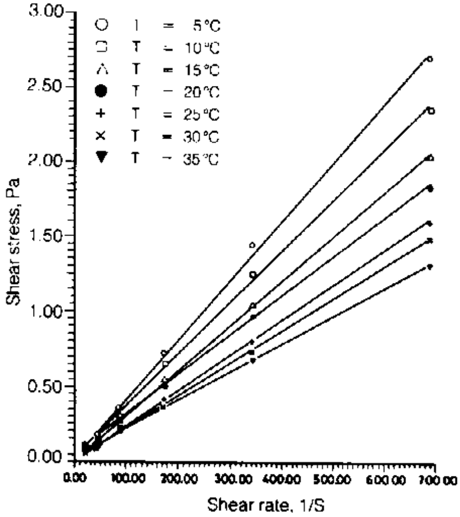

Fig. 2. Shear stress versus shear rate for 20% emulsion (Newtonian Fluide).

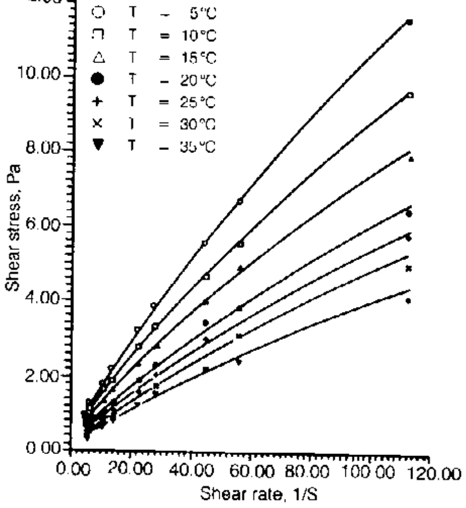

Fig. 3. Shear stress versus shear rate for 60% emulsion (power Law Fluid).

It was noticed that at low shear rates, viscosity was considerably higher than that of lower oil content emulsions. Since at medium internal phase concentration (50% and 60% oil), the packing of regular cubic array might have been reached (PF = 0.52), the droplets interfere with each other rather drastically, and hence flow properties become non-Newtonian and the apparent viscosity of the emulsion can reach high values.

Finally, when the oil concentration was increased above 60% oil, the non-Newtonian behavior becomes significant. Yield stresses were observed and their values were in the range of 1.0 to 16.0 Pa. as oil concentration increases. Values of the viscosity increased rapidly as the oil concentration was increased. Data at these concentrations of oil (70%, 80% and 90%) were fitted to Hershel – Bulkley model (Equation 1) as shown in Fig. 4. At high concentration of oil, the droplets reach the most crowded packing (faced centered cube PF = 0.74) then as further increase in the internal phase, the droplets begin to flatten and the non-Newtonian behavior becomes remarkable with rapid increases in viscosity. At this situation a yield stress was observed as a minimum stress needed to deform the fluid.

It was noticed from the rheological measurement that at oil concentration less than 40%, the behavior of the emulsion is Newtonian *i.e.*

$$\tau = \mu\dot{\gamma} \tag{11}$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate and μ is the viscosity of emulsion. This behavior was expected since the external phase was water which is a Newtonian fluid. While at higher oil concentration (50% – 60% oil), the results showed that the relation between τ and $\dot{\gamma}$ is non-linear which indicates a pseudoplastic behavior following the Power-Law, *i.e.*

$$\tau = \mu\dot{\gamma}^{n} \tag{12}$$

where H and n are constant.

At high oil concentrations (70% – 90% oil) where droplets become more crowded, the emulsions started to exhibit yield stress and behaved as a shear-thinning behavior following Hershel-Bulkley model, *i.e.*

$$\tau = \mu\dot{\gamma}^{n} + \tau_{o} \tag{13}$$

Values of the coefficients *H,n,* and τ_0 are shown in Table 1 [2].

Table 1. Rheological characteristics of emulsions

Emulsion concen-	Tempera-ture °C	$Pa\,S^n \times 10^3$ H	n	Yield value τ_0, Pa.
20% Oil	5	3.984	1.0	0.00
	10	3.461	1.0	0.00
	15	3.009	1.0	0.00
	20	2.675	1.0	0.00
	25	2.381	1.0	0.00
	30	2.203	1.0	0.00
	35	1.926	1.0	0.00
60% Oil	5	266.59	0.803	0.00
	10	244.72	0.741	0.00
	15	216.90	0.769	0.00
	20	166.69	0.784	0.00
	25	140.33	0.796	0.00
	30	113.75	0.817	0.00
	35	102.56	0.799	0.00
90% Oil	5	49215	0.416	14.60
	10	46293	0.411	11.52
	15	37019	0.414	10.24
	20	31859	0.419	8.96
	25	21038	0.455	16.64
	30	23989	0.427	15.36
	35	21976	0.430	14.08

For the flow through porous media the analysis of the experimental results was based on the friction factor – Reynolds number correlation in the laminar region where [5] Re < 10 (*i.e.* the flow data were presented as Equation 10).

A number of values of C'' have been used by many investigators. Carman [6] and Kemblowski and Michniewicz [9] reported value of 180, Ergun [7] and Larkins [11] found it to be 118. Values of 180 and 150 appear to be more common for fitting similar experimental data for different kind of fluids and packings. The value of C'' depends on many factors, such as shape, type and size packing, and the technique used for packing [1].

The results are shown in Figs. 5, 6 and 7 for 40%, 60% and 80% emulsions respectively. The 40%, 60% and 80% emulsions have been chosen because each concentration represents one of the three models used to fit the experimental data (*i.e.* Newtonian, Power-Law, and Hershel-Bulkley model). The solid line on each graph

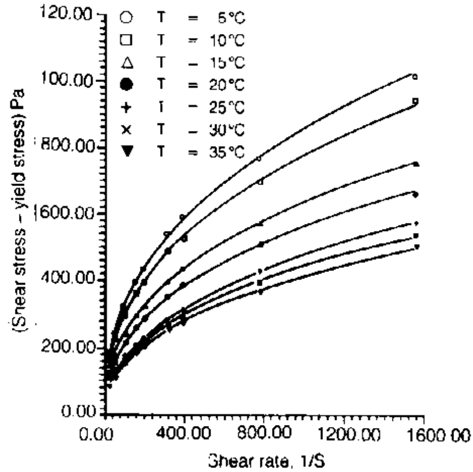

Fig. 4. Shear stress versus shear rate for 90% emulsion (Hershel – Bulkley Fluid).

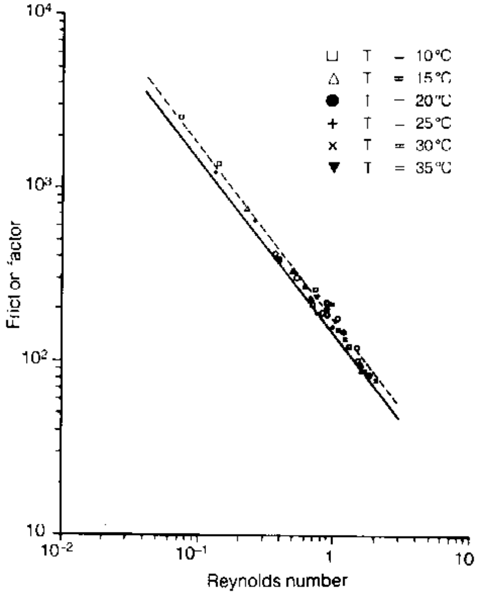

Fig. 5. Friction factor versus Reynolds number for 40% emulsion.

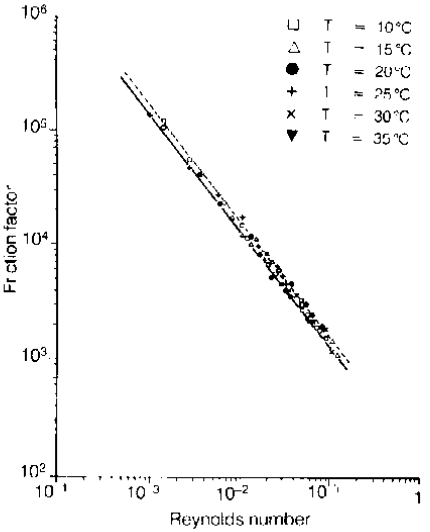

Fig. 6. Friction factor versus Reynolds number for 60% emulsion.

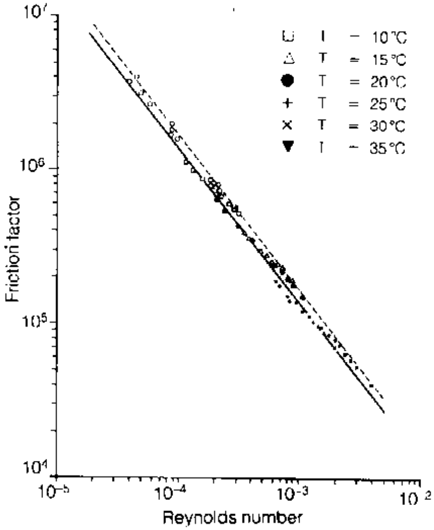

Fig. 7. Friction factor versus Reynolds number for 80% emulsion.

represents Equation 10 with $C'' = 150$, while dashed line represents the same equation with $C'' = 180$.

These figures show how good the model proposed fits the experimental data for each concentration. The average error was calculated for each emulsion concentration for the two values of C''. For 40% oil the average error for 34 data points was 1.61% and 3.0% for $C'' = 180$ and $C'' = 150$ respectively. For 60% oil the average error for 58 data points was 1.06% and 1.37% for $C'' = 180$ and $C'' = 150$ respectively. Finally for 80% oil with 68 data points the average error was 0.86% and 0.81% for $C'' = 180$ and $C'' = 150$ respectively.

Conclusions

1) The emulsion stability is mainly governed by the properties of the emulsifier and the applying shear rate. Where for low internal phase ratio emulsion (10% to 40%) an ionic emulsifier should present and a moderate shear rate should be applied. On the other hand for medium internal phase emulsion a mixture of ionic and nonionic emulsifiers should be applied with high shear rate. For high internal phase ratio (70% to 90% oil) a nonionic emulsifier should be sufficient to produce stable emulsion.

2) By analyzing the rheological data for the emulsion. Newtonian behavior was observed for a low oil concentration of 10 – 40% oil and the emulsions was oil in water type. For medium internal phase concentrations (50 – 60% oil), a pseudoplastic behavior was observed and data were fitted to the power law model with an acceptable error. Shear thinning with initial yield stress behavior was observed for high internal phase ratio (70% to 90%) and data represented by the Hershel – Bulkley model. For medium and high oil concentration (50 – 90% oil), the emulsion was water – in – oil type.

3) Experimental data for the flow of the emulsion through porous medium were fitted to the model developed by Al-Fariss and Pinder correlation [1] which was presented as friction factor-Reynolds number relationship for viscous flow through porous media. This correlation (equation 10) fitted the data with an acceptable average error. The values of C'' used in this study was 150 and 180.

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سريان المستحلبات الزيتية خلال وسط مسامي

طارق فارس الفارس، أنيس حمزة فقيها و ماهر عبدالله العودان

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(استُلم في ٢/١١/١٩٩١م؛ قُبل للنشر في ١/٦/١٩٩٢م)

ملخص البحث. تمت دراسة سريان مستحلبات الزيت والماء خلال وسط مسامي وذلك بتحضير نوعين من المستحلبات أحدهما زيت في ماء والآخر ماء في زيت، وذلك بخلط الزيت الأساسي مع الماء ومادة (Triton X-100) وقياس كل من الإجهاد القصي، معدّل القص والإجهاد الناتج للمستحلبات عند العديد من درجات الحرارة وتراكيز الزيت المستخدم. وقد أظهرت نتائج الدراسة أن المستحلبات ذات التركيز المنخفض من الزيت (١٠ - ٤٠٪ تكون مستحلبات زيت في ماء) تتصرف كالمحاليل النيوتونية وتتراوح لزوجتها من ١,٥ إلى ٧,٧ سنتبواز. أما المستحلبات ذات التركيز المتوسط من الزيت (٥٠ - ٦٠٪) فقد وجدت أنها تمثل بقانون أسي للمحاليل اللانيوتونية بينما للمستحلبات ذات التركيز العالي من الزيت (٧٠ - ٩٠٪ تكوّن مستحلبات ماء في زيت) فَتُمَثَّل بنموذج هرشل - بكلي للموائع اللانيوتونية. وقد مُثِّلت النتائج للمستحلبات خلال مهد مسامية ثابتة من حبيبات زجاجية للدلالة على وجود علاقة بين معامل الاحتكاك ورقم رينولد العام لسريان الموائع خلال الوسط المسامي بوجود القص الناتج.