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BRIEF COMMUNICATION
EMULSION FLOW IN PIPELINES

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1. INTRODUCTION

Stable oil-in-water (o/w) emulsions are encountered in various operations in the petroleum industry such as oil well drilling (Gray *et al.* 1980), oil well fracturing (Williams *et al.* 1979) and oil production (Lissant 1976; Jenkins 1977). In some situations, o/w emulsions are deliberately produced to take advantage of their relatively low viscosity (Zakin *et al.* 1979; Simon & Poynter 1968; McAuliffe *et al.* 1968; Beyer & Osborn 1968; Marsden & Raghavan 1973). Recently, interest has been shown in using o/w emulsions as blocking agents to improve the recovery of oil (Decker & Flock 1988).

In all the above applications, pumping of emulsion in the pipeline is required. Therefore, a knowledge of the pipeline flow characteristics of emulsions is important. The objective of the present work was to experimentally investigate the laminar and turbulent flow behaviors of stable o/w emulsions in horizontal pipelines.

2. EXPERIMENTAL WORK

2.1. *Apparatus*

A flow-rig was designed and constructed to allow investigation of the pipeline flow behavior of emulsions. Figure 1 shows a schematic diagram of the flow-rig. Five pipeline test sections (stainless steel, seamless) each having a different diameter were installed horizontally. Table 1 lists the various dimensions of these test sections. A metering test section containing an orifice, a venturi, a magnetic flowmeter and an inline conductance cell was also installed.

The emulsions were prepared in a large tank (capacity $\simeq 1\ \text{m}^3$) equipped with two high shear mixers. The emulsion from the tank was circulated to the pipeline test sections, one at a time, by a centrifugal pump. From the pipeline test section, emulsion entered the metering test section—where its flow rate was measured. The pressure drops in the various pipeline test sections were measured by means of pressure transducers.

A Fann coaxial cylinder viscometer was used to measure the rheological properties of emulsions. The particle size information of emulsion was obtained by taking photomicrographs with a Zeiss microscope.

2.2. *Emulsion preparation*

The emulsions were prepared by the *agent-in-water* method. The emulsifier was dissolved in water at a concentration of 1% by wt. A known volume of oil was added to the emulsifier solution. The mixture was then sheared by the pump and the mixers (installed in the tank) for a fixed period of time. To prepare a higher concentration o/w emulsion, more oil was added to an already existing lower concentration emulsion. In this way, the highest dispersed phase concentration achieved was

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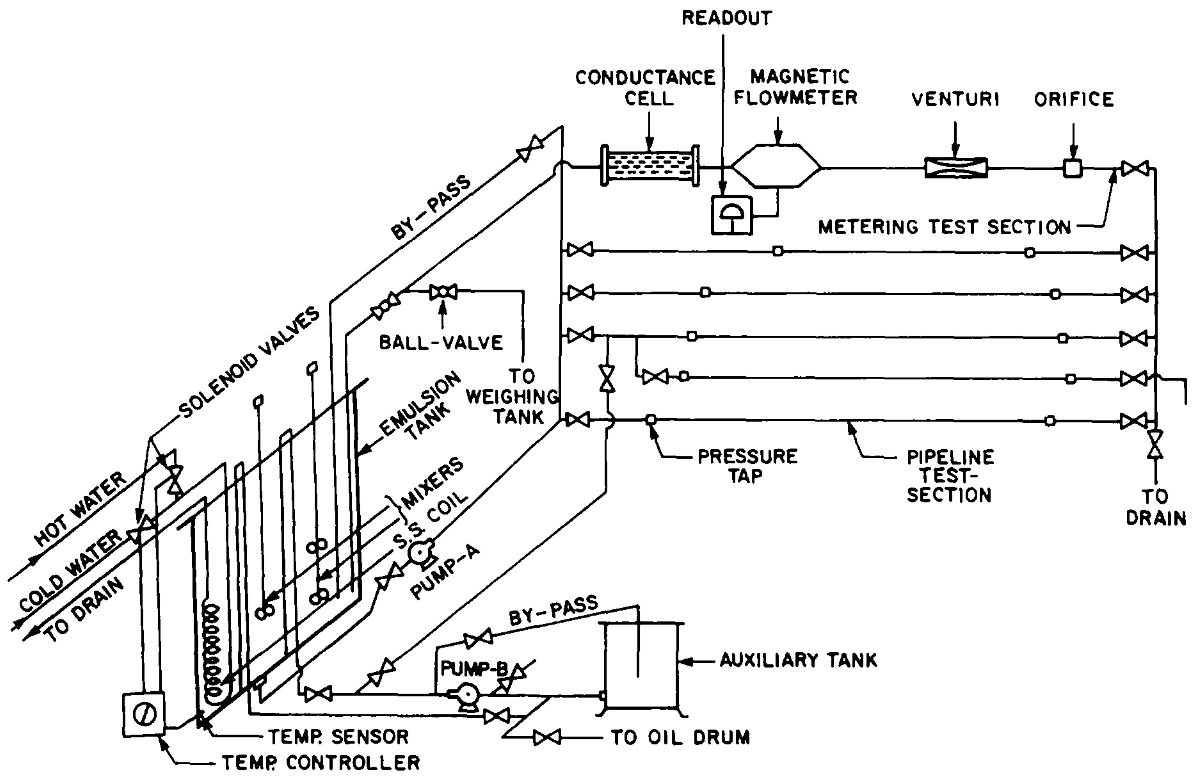

Figure 1. Schematic diagram of the flow-rig.

72.21% by vol. Throughout the experimental work, the temperature was maintained at 25°C with the help of a temperature controller.

2.3. *Materials used*

The oil used in the experiments was Bayol-35. It is a refined white mineral oil. It has a density of 780 kg/m^3 and a viscosity of 2.4 mPa s at 25°C.

Triton X-100 (isooctylphenoxypolyethoxy ethanol) was used as an emulsifier. It is a non-ionic water soluble emulsifier. The water used in the experiments was tap water.

3. RESULTS AND DISCUSSIONS

Homogeneous flow theory (Wallis 1969) can be applied to emulsion flow under certain conditions. When the flow is laminar, the necessary conditions are: (i) negligible settling of the dispersed particles; and (ii) a large pipe-to-particle diameter ratio. When the flow is turbulent, the necessary condition is that the turbulence of the continuous phase should not be affected by the presence of the dispersed particles. This latter condition is met when the dispersed particles are

Table 1. Various dimensions of pipeline test sections

Pipe No.	i.d. (m)	Entrance length (m)	Actual length of test section (m)	Exit length (m)
1	8.89	0.89	3.35	0.482
2	7.15	1.07	3.05	0.457
3	12.60	1.19	2.74	0.533
4	15.80	1.65	2.59	0.561
5	26.54	3.05	1.22	0.670

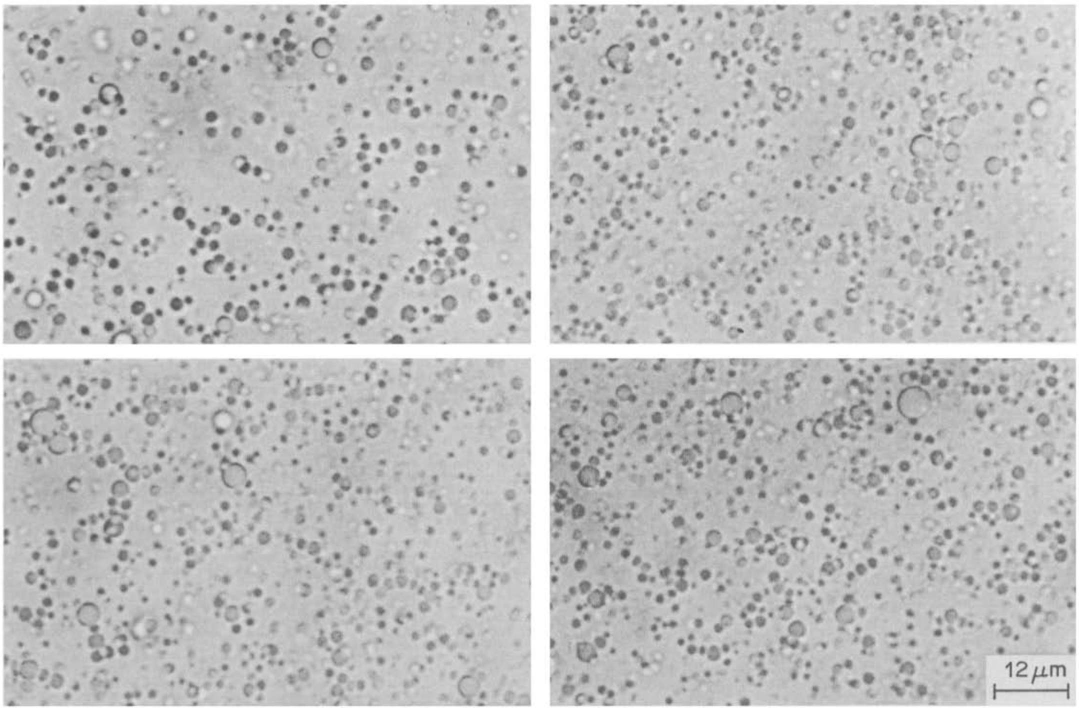

Figure 2a. Typical photomicrographs of a 16.53% o/w emulsion.

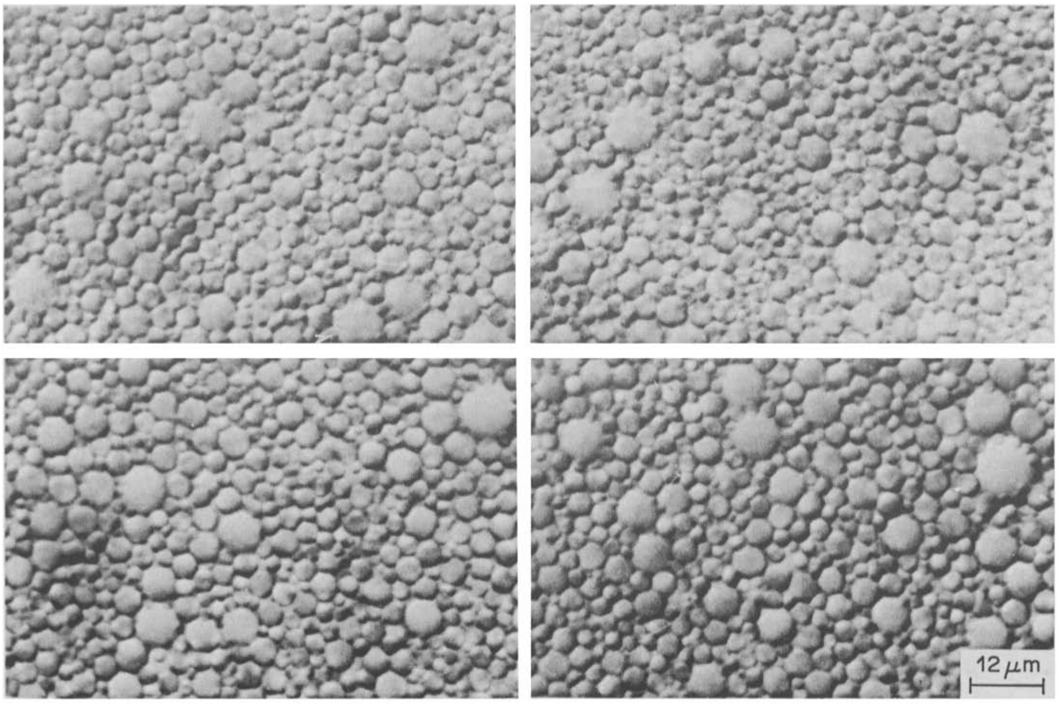

Figure 2b. Typical photomicrographs of a 72.21% o/w emulsion.

significantly smaller than the scale of turbulence. Baron *et al.* (1953) developed the following criterion for emulsions to be treated as single-phase fluids in the turbulent regime:

$$\frac{\text{Inertial forces acting on dispersed particles}}{\text{Drag forces acting on the dispersed particles}} = \frac{\dfrac{d^2\rho_d \bar{V}^2}{D}}{\eta_c \bar{V}} = (N_{Re})_c \left(\frac{d}{D}\right)^2 \left(\frac{\rho_d}{\rho_c}\right) < 1. \qquad [1]$$

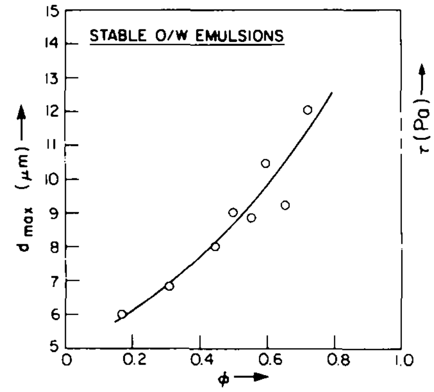

Figure 3. Maximum droplet size as a function of dispersed phase concentration.

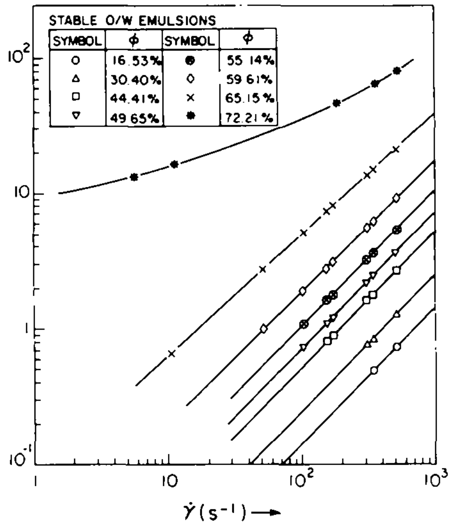

Figure 4. Rheograms of various emulsions

Here d is the particle diameter, D is the pipe diameter, ρ_c is the continuous phase density, ρ_d is the dispersed phase density, η_c is the continuous phase viscosity, $\bar{V}$ is the average velocity of an emulsion and $(N_{Re})_c$ is the continuous phase Reynolds number $(\rho_c D\bar{V}/\eta_c)$.

Figures 2a and 2b show photomicrographs of emulsion at low and high concentrations of the dispersed phase, respectively. As the concentration increases, the particle size increases. The plot of the maximum particle size (observed at any given concentration) as a function of dispersed phase concentration (ϕ) is given in figure 3. It can be seen that the largest particle size encountered in the present study is about 12 μm. This size is sufficiently small so that condition [1] is satisfied. Also, the terminal rise velocity of the dispersed particles is only 1.74 mm/s and the ratio of the pipe-to-particle diameter is > 600. Thus, we can regard the emulsions as homogeneous fluids.

The rheograms of the various o/w emulsions are given in figure 4. Up to a dispersed phase concentration of 55.14% by vol, emulsions are Newtonian i.e. the rheograms are linear having slopes of unity. The rheograms of the 59.61 and 65.15% o/w emulsions are linear but have slopes less than unity, indicating that these emulsions are non-Newtonian power-law fluids. The rheogram of a 72.21% o/w emulsion is non-linear and therefore, this emulsion does not follow the power-law. The rheological data of this emulsion follows the Sisko (1958) model:

$$\tau = a\dot{\gamma} + b\dot{\gamma}^N, \qquad [2]$$

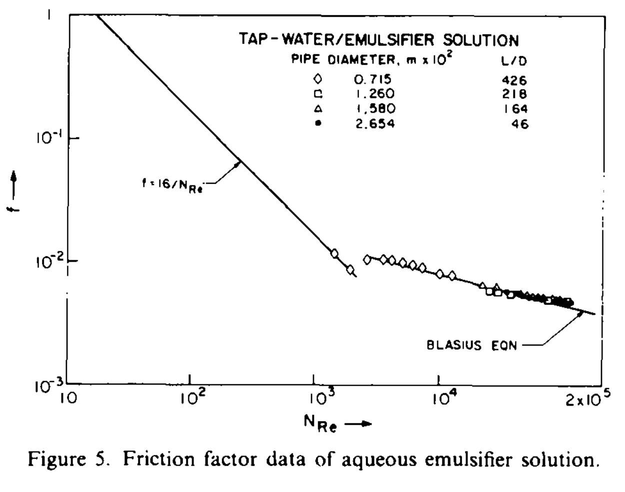

Figure 5. Friction factor data of aqueous emulsifier solution.

Table 2 Rheological data of emulsions

ϕ (% vol)	$K \times 10^3$	n
16.53	1.42	1.00
30.40	2.46	1.00
44.41	5.22	1.00
49.65	7.16	1.00
55.14	10.6	1.00
59.61	22.0	0.96
65.15	82.8	0.89

K and n are power-law constants (K is in Pa s^n). For 72.21% o/w emulsion, the Sisko constants are: $a = 6.72 \times 10^{-2}$ Pa s, $b = 8.17$ Pa s^N and $N = 0.27$.

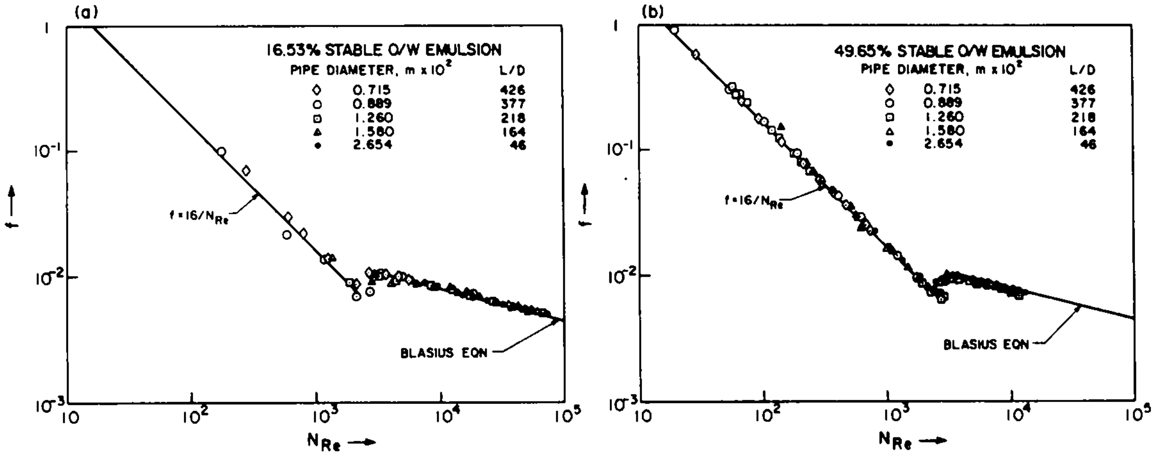

Figure 6. Friction factor data of (a) 16.53 and (b) 49.65% o/w emulsions.

where τ is the shear stress, $\dot{\gamma}$ is the shear rate and a, b and N are constants. Table 2 summarizes the rheological data of the emulsions.

The friction factor vs Reynolds number data for aqueous emulsifier solution are shown in figure 5. The data are in good agreement with the friction factor equations which are valid for the single-phase Newtonian fluids. This indicates that the rig was operating satisfactorily and all the test sections were hydraulically smooth.

Figures 6–8 show the friction factor vs Reynolds number data for different concentration emulsions. For the Newtonian emulsions, the conventional Reynolds number is used and for the non-Newtonian emulsions, the generalized Reynolds number (Metzner & Reed 1955) is used.

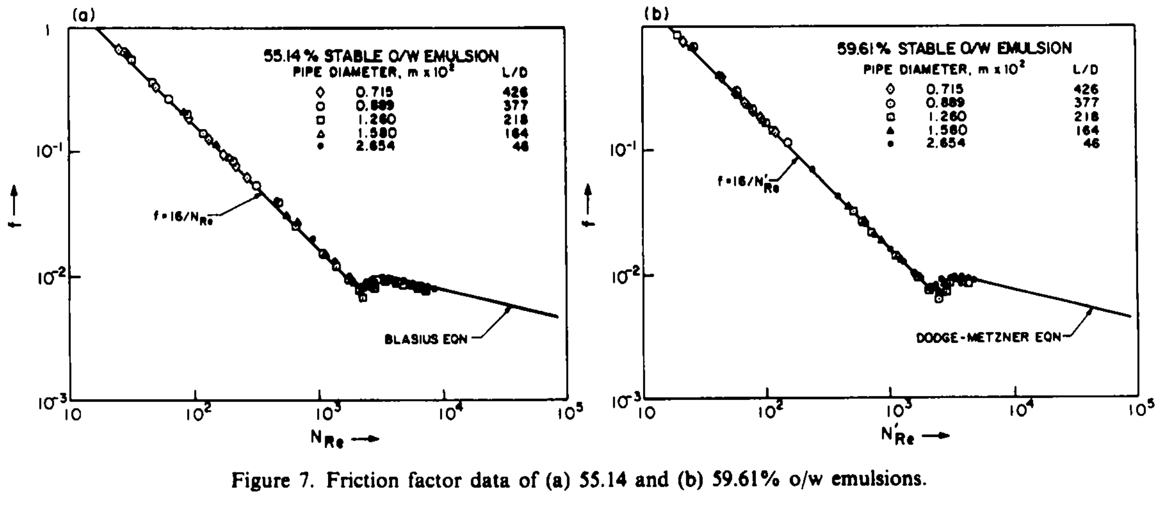

Figure 7. Friction factor data of (a) 55.14 and (b) 59.61% o/w emulsions.

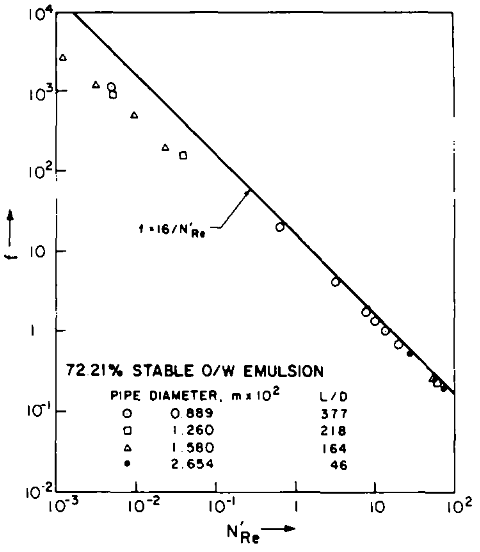

Figure 8. Friction factor data of 72.21% o/w emulsion.

In the laminar regime, the experimental data of the Newtonian and non-Newtonian emulsions agree very well with the friction factor equations which are valid for the single-phase Newtonian and non-Newtonian fluids, respectively. The small deviation of the 72.21% o/w emulsion data at low Reynolds number could be due to errors in the measurement of the extremely low flow rates.

The turbulent flow data are obtained only for the emulsions with $\phi \leqslant 59.61\%$ (at higher ϕ, emulsions are too viscous to achieve turbulent flow). The turbulent data of the Newtonian emulsions agree quite well with the single-phase Blasius equation. In the case of the non-Newtonian emulsion ($\phi = 59.61\%$), the data seems to follow the Dodge–Metzner equation (Dodge & Metzner 1959). Also, the onset of turbulence occurs at a Reynolds number of about 2100.

Thus, it can be concluded that the stable o/w emulsions investigated in this study follow the usual equations of single-phase flow with averaged properties.

It may be of interest to point out that Zakin *et al.* (1979), in their study on highly concentrated ($\phi > 50\%$) stable o/w emulsions, found that the emulsions exhibit drag reduction in turbulent flow, i.e. the experimental friction factors fall somewhat below the single-phase equation. As, in the present work, turbulent flow data could not be obtained for highly concentrated emulsions, it is difficult to compare the two studies. However, it is quite possible that at very high concentrations dispersed particles may form flocs large enough in size that they can affect the turbulence.

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