Turbulent flow of oil-water emulsions with polymer additives

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Abstract. The article outlines direct and reverse oil-water emulsions. Microphotography study of these emulsions was carried out. The effect of water-soluble and oil soluble polymers on the emulsion structure and their turbulent flow velocity in cylindrical channel was investigated. It has been experimentally proven that if the fluid being transported is not homogeneous, but a two-phase oil-water emulsion, only the polymer that is compatible with dispersion medium and capable of dissolving in this medium can reduce the hydrodynamic resistance of the fluid flow. Thus, the resistance in direct emulsions can be reduced by water-soluble polyacrylamide, while oil-soluble polyhexene can be applied for reverse emulsions.

When a polymer is dissolved in a liquid, there occurs viscosity increase and a simultaneous acceleration of turbulent flow rate of the polymer solution in comparison with the flow rate of low-viscosity solvent. This paradoxical phenomenon is called the Toms effect and it has found a wide practical application in the oil pipeline transportation. When the Toms effect occurs (figure 1), it leads to reduction in the hydrodynamic resistance coefficient ($\lambda$), which is used in Darcy-Weisbach equation

$$\Delta P = \lambda \frac{\rho L}{4\pi^2 R_w^5} Q^2$$

The $\lambda$ value decrease is accompanied either by the increase of the volume flow rate ($Q$) at a constant predetermined pressure drop $\Delta P = \text{const}$, or by the decrease of the pressure drop ($\Delta P$) caused by friction at a constant flow rate $Q = \text{const}$. 

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Figure 1. Dependence of hydrodynamic resistance on the Reynolds number for different polymer-solvent system [1].

1. Poiseuille theoretical curve for laminar flow \( \lambda_{\text{lamin}} = 64/Re \)
2. Blasius empirical curve for turbulent flow \( \lambda_{\text{turb}} = 0.3164/Re^{0.25} \)
3. Polyisoprene dissolved in toluene solution \( (C = 0.05 \text{ kg/m}^3; \ M_r = 0.5 \times 10^6) \)
4. Polyisoprene dissolved in toluene solution \( (C = 0.1 \text{ kg/m}^3; \ M_r = 0.5 \times 10^6) \)
5. Polybutadiene dissolved in toluene solution \( (C = 0.1 \text{ kg/m}^3; \ M_r = 0.6 \times 10^6) \)
6. Polybutadiene dissolved in toluene solution \( (C = 0.1 \text{ kg/m}^3; \ M_r = 1.2 \times 10^6) \)
7. Polyisoprene dissolved in oil \( (C = 0.1 \text{ kg/m}^3; \ M_r = 0.5 \times 10^6) \).

The magnitude effect of reducing the hydrodynamic resistance (DR,\%) which characterizes the energy yield obtained through pumping oil with polymer additives in comparison with pumping fluid without additives, is calculated by the formula

\[
DR,\% = \frac{\lambda_S - \lambda_P}{\lambda_S} \times 100\%
\]

(1)

Where \( \lambda_S \) and \( \lambda_P \) - hydraulic resistance coefficients of solvent and polymer solution, respectively.

Under actual operating conditions delivering oil through trunk pipeline by centrifugal pumps one can simultaneously observe decrease in the pressure drop in the pipe and increase of the volumetric flow rate (figure 2). When the pipeline is filled with oil-treated polymer additive, there is an increase in the Toms effect (figure 3).
In laboratory investigations, we conducted a pilot study of the effect of polymer additives on the flow rate of oil-water emulsion. During the in-situ filtration and delivery of oil-water mixture through gathering pipeline both "direct" emulsions (O/W) and "inverse" emulsions (W/O) can occur. Depending on the physicochemical nature of the dispersion medium, we used both a water-soluble polymer (polyacrylamide - PAA) and an oil-soluble polymer (polyhexene - PH).

The experimental part of the research was carried out using turbulent rheometer, which is structurally simple and similar to the capillary viscometer, but allows the study both in the laminar and turbulent flow regime.

The receiving chamber of the rheometer is filled with working fluids (solvents) and the polymer solutions produced from these solvents. The usual working fluids are water, ethanol, toluene, heptane, gasoline, oil and etc. By using the gas system operating on inert gas, in the chamber of the rheometer it is possible to produce different pressure drop effects ($\Delta P$) and, therefore, different flow rates of fluid through the tube with the radius ($R_w$) and the length ($L$), connected to the chamber. An electronic stopwatch records the elapsed time ($t$) required for a constant volume of fluid ($V$) to flow out of the chamber. Then we can calculate the volumetric flow rate $Q = \frac{V}{t}$, as well as the shear stress at the channel wall ($\tau_w$) and the Reynolds number (Re):

$$\tau_w = \frac{\Delta P \cdot R_w}{2L}$$

$$Re = \frac{2Q}{\pi R_w \cdot \nu}$$

More detailed information about the turbulent rheometer is given in the article [3].

At the initial stage of experiment we determined the effect of these polymers on the individual fluids (water and oil). The graphic illustration of the dependence of the effect (DR,%) on the concentration of PAA dissolved in water or PH dissolved in benzene is shown in Figures 4 and 5. The analysis of the results presented in the figures shows that these polymer samples are approximately
equal in their anti-turbulent efficiency, but each of them can only be used in the dispersion medium of certain physical and chemical nature (water or oil).

Under hydrodynamic conditions typical for trunk pipeline operation (shear stress on the tube wall $\tau_W \approx 1 – 10 \text{ Pa}$) both of these samples are capable of reducing the resistance by more than 50% at the “optimal” concentration of $C_{\text{opt}} \sim 10 \text{ ppm}$ (i.e. concentration at which the maximum magnitude of $\text{DR}_{\text{MAX}}$ effect is achieved).

However, the laboratory tests showed that if the transported liquid medium is not a homogeneous liquid (figure 4 and 5) but a two-phase oil-water emulsion, then its hydrodynamic resistance can be reduced only using the polymer that is compatible with the dispersion medium, i.e. which is soluble in that dispersion medium.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** Dependence of the effect (DR,%) on the concentration (C, ppm) of polyacrylamide in water at different shear stresses: 1 – $\tau_W = 8 \text{ Pa}$; 2 – $\tau_W = 4 \text{ Pa}$.

**Figure 5.** Dependence of the effect (DR,%) on the concentration (C, ppm) of polyhexene in benzene at different shear stresses: 1 – $\tau_W = 11 \text{ Pa}$; 2 – $\tau_W = 4 \text{ Pa}$.

Thus, the water-soluble PAA is capable to reduce the resistance in "direct" emulsions, while oil soluble PH can produce a similar effect in "reverse" emulsions. The experimental results of the effect of these polymers on the "direct" or "reverse" emulsions are shown in figure 6.

The figure shows that in the turbulent flow region at $Re > 2300$ hydrodynamic drag coefficients ($\lambda_S$) of water, oil and oil-water mixture without polymer additives, calculated by Darcy-Weisbach formula, can be naturally superimposed on the Blasius empirical curve. With the same polymer being added to oil-water emulsions, hydrodynamic drag coefficients ($\lambda_P$) decrease and enter $64/Re < \lambda_P < 0.3164/Re^{0.25}$ range, i.e. a zone between the Blasius curve and the hypothetical extension of the Poiseuille curve to a turbulent region (figure 6).
Figure 6. Dependence of hydraulic resistance factor on the Reynolds number for different systems:
1- Blasius empirical curve $\lambda = \frac{0.3164}{Re^{0.25}}$;
2- Poiseuille curve and its hypothetical extension to a turbulent region $\lambda = \frac{64}{Re}$;
3- Water;
4- Oil;
5- Oil-water emulsion;
6- 'Direct' oil-water emulsion containing PAA (C = 10ppm);
7- 'Reverse' oil-water emulsion containing PH (C = 50ppm).

After the experimental measurements with turbo-rheometer for given pressure drops ($\Delta P$) in volumetric flow rates of "direct" emulsions with additives of various concentrations of PAA ($Q_{PAA}$) and flow rates of "reverse" emulsions with additives of various concentrations of PH ($Q_{PH}$), hydrodynamic drag coefficients were calculated by Darcy-Weisbach equation. The further calculations were made by the formula (1) and determined hydrodynamic drag reduction values (DR,%). Their dependence on the concentration of polymer added to the oil-water emulsion is illustrated in figures 7 and 8. These figures show that for reducing hydrodynamic drag of turbulent flows of oil-water emulsions it is necessary to saturate these emulsions with polymer additives in amounts significantly above their "optimal" concentration for individual fluids (figure 4 and 5).
Figure 7. Dependence of effect DR (%) on the concentration of polyacrylamide in the "direct" emulsion.

Figure 8. Dependence of effect DR (%) on the concentration of polyhexene in the "reverse" emulsion.

This substantial increase in the number of input anti-turbulent additives is required due to the fact that a significant portion of polymeric macromolecules with asphaltenes and resins from the water mixture is adsorbed at the interface, i.e. on solvent-adsorption layers of micro-emulsion droplets. This explanation is confirmed by photomicrographs which are taken with a modular biological microscope Olympus SKH41 and presented in figures 9 and 10.

Figure 9. "Reverse" emulsion (50% water and 50% oil) with PAA.

Figure 10. "Reverse" emulsion (50% water and 50% oil) with PH.

Summing up, transport of oil-water mixtures through pipeline requires a significantly greater amount of polymer additives than it does while delivering a single-phase liquid - either oil or water. This conclusion is, particularly, characteristic of emulsions of a "reverse" type.

References
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