Non-Newtonian Drag Reducing Flow Characteristics in Porous Media

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Abstract- In this paper, the properties affecting the flow behavior of a non-Newtonian drag reduction fluid through porous media were studied. The experimental work was carried out for the flow of pure water and dilute polyethylene oxide solution with concentrations C = 50, 100, 150, 200, and 250 ppm in a circular pipe with a 2.54 cm inside diameter filled with porous media (uniform size of plastic spheres with 5.5 mm in diameter). The experiments are utilized to show the effect of the variation of polyethylene oxide concentration on the pressure drop and friction factor by changing the flow rate and polyethylene oxide concentrations. To validate the experimental results, a comparison of pressure drop and friction factor for pure water is done with the Ergun model, which gives good agreement. The experiments show that the friction factor and the pressure drop are reduced by the increase in POE concentration. The drag reduction ratio increases with the increase in POE concentration and its effectiveness is higher at low velocities (between 0.012 and 0.068 m/s) than at higher velocities (from 0.068 to 0.157 m/s). A modified relationship was deduced as an extension of Ergun to describe the effect of POE concentrations as a drag reducing additive in the non-Newtonian fluid flow through a porous medium.

***Keywords:* Non-Newtonian flow, Porous media, drag reduction, friction factor, polyethylene oxide.**

I. INTRODUCTION

Non-Newtonian flow through porous media is critical and has numerous practical uses in processes such as enhanced oil recovery in underground reservoirs, polymer solution filters, groundwater hydrogeological, ceramic processing, and solid matrix heat exchangers. Many industrial operations, such as those in the oil and chemical industries, use non-Newtonian fluid flows with drag-reducing features through a porous medium [1-5].

Drag is the pressure head losses inside a pipe that cause the flow rate to decrease. To overcome the decreasing flow rate, more pumping stations are installed along the pipeline to supply energy and uphold the desired flow rate [6]. Consequently, the installation of pumping stations is costly and not economically feasible. Another method to overcome this problem is by reducing the drag inside the pipe. This method is called drag reduction (DR) [7].

Abdulbari et al. [8] defined DR as the science of flow improvement by reducing the frictional pressure drop across a pipe or channel. Truong [9] stated the primary purpose of DR is to prolong the laminar flows inside the channel by delaying the onset of turbulent flows. This reduction can be achieved by adding only minute amount of selected materials known as drag reducing agents (DRA) to the system.

DRA are chemical agents added to the flowing fluid that produce a smaller drop in pressure than flow without those agents. Because these agents are generally hydrocarbons, they have little influence on the physical qualities of the purification processes. The combination of drag-reducing agents and solution produces a non-Newtonian, shear-degradable, viscoelastic, and time-independent fluid solution [10]. The main properties of the polymer that should be found to be an effective drag reducer are very high molecular weight ($M_w > 1 \times 10^6\ g/mol$) shear resistance, linear flexible structure, and quick liquid solubility [11]. From the point of view of drag reduction, the flow of drag reducing polymer solutions in porous media is very interesting. A large amount of experimental work has been carried out in recent decades on the non-Newtonian flow through porous media [12].

Hanna et al. [13] investigated the flow of drag-reducing fluids across a sphere-packed bed experimentally. Drag reduction begins between Reynolds numbers of 150 and 250. By increasing polymer molecular weight and reducing particle diameter, the effectiveness of drag reduction increases. When the particle-to-column diameter ratio is not negligible, the Ergun equation has been adjusted to incorporate a wall correction factor. For this work, an optimum polymer concentration that produces a maximum drag reduction was found.

Alam et al. [14] reported a study of the flow of drag-reducing fluids across packed beds experimentally. The flow was tested using five concentrations of natural polymer material, namely Guar Gum, of 0.0125%, 0.025%, 0.0375%, 0.05%, and 0.0625% (w/v). They discovered that the magnitude of the drag reduction improves with polymer concentration until it attains its maximum at optimum concentration, then progressively decreases as polymer concentration increases further. Their logarithmic plot of friction factor and Reynolds number demonstrated a linear decrease for low Reynolds numbers. The drag reduction for polymeric solutions and with distilled water was investigated using Ergun's empirical equation, the Carmen's Model, and the Sawistowski Model, all of which demonstrate the same type of friction factor variation behavior.

SK Patel and SK Majumder [15] investigated the non-Newtonian flow behavior due to frictional pressure on a packed column with flow speeds ranging from 0.004-0.04 m/s. A Perspex column with an interior diameter of 0.050 m and a length of 0.49 m was packed randomly with ceramic rashing rings. They utilized CMC (Carboxy Methyl Cellulose) solutions of various concentrations (0.3, 0.5, 0.7, and 1.0 wt. %) as a non-Newtonian fluid that was delivered into the packed bed by centrifugal pump. The flow behavior index of a non-Newtonian liquid is integrated into the Ergun equation modification. The rate of frictional pressure loss reduces as the flow behavior index rises, and when the flow behavior index is one, it follows the same pattern as Newtonian flow behavior.

James and McLaren [16] investigated different molecular weights of polyethylene oxide diluted in water and passing across beds of uniformly sized glass spheres. A rapid shift in behavior - an increase in elongation viscosity - at a Reynolds number that was a factor of polymeric molecular weight, polymer concentration, and particle size was discovered. They also looked into They also investigated how polymeric solutions behaved at low Reynolds numbers like Newtonian fluid. Overhead the transition Reynolds number, the polymer information is extremely non-Newtonian, with friction factors up to ten times greater than the Newtonian value.

Rabie et al. [17] conducted drag reduction experiments through capillary tubes for polyacrylamide-water solutions. For capillary tube diameters of 0.45, 0.55, and 0.75 mm, solution concentrations of 0, 10, 50, 100, and 250 ppm were discussed for the Reynolds number range of 1000 to 10,000. They indicated that the friction factor of polymer solution decreases with the increase of Reynolds number, tube diameter, and solution concentration. Also, they investigated that the drag reduction ratio increased with solution concentrations and the decrease of tube diameter.

Tang et al. [18] proposed a theoretical model based on the force balance between pressure, viscous force, and inertia force to predict accurately the pressure gradient and the friction factor of Newtonian and power-law non-Newtonian fluids through porous packed beds. They took inertia effect into consideration, and the flow regime can be extended from Darcy flow to non-Darcy flow. Their model predicted most available experimental data well at a wide range of Reynolds numbers. The results are also compared to the Ergun equation and other drag correlations and good agreement was found.

In this study, the analysis of the flow of non-Newtonian drag-reducing fluid in a circular tube full of porous medium (packed spherical beds) is presented. It focuses on using POE as a drag reducing agent. Also, a higher range of concentration, up to 250 ppm, is prepared to show the effective range of velocity and Reynolds number for using POE as a drag reduction agent.

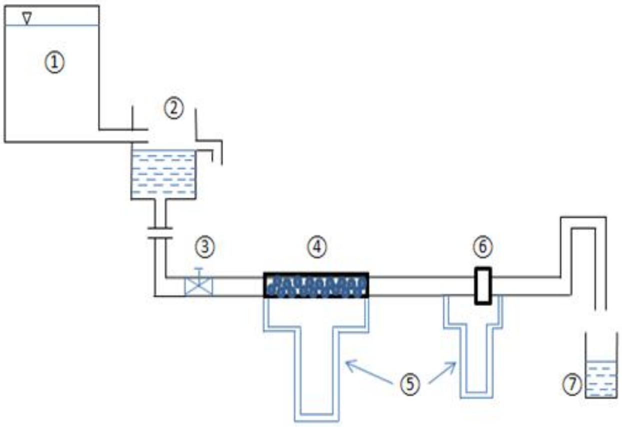
II. EXPERIMENTAL SETUP

A. *Experimental set up*

The schematic and photograph of the experimental setup are shown in Fig. 1, 2. An open loop pipe line system consists of a 500 liter capacity plastic (PVC) tank that acts as an overhead tank (1). This tank supplies a small constant head overflow tank (2) that is located 6.0 m above the test section (4).

The fluid flows from the overflow tank under gravity action through a polypropylene pipe with a 2.54 cm inner diameter. A 2.54 cm inside diameter and 500 mm long copper tube is used as a test section. A 1 inch ball valve (3) is used to control the flow rate value. The tube is filled uniformly with plastic spheres of uniform size to form a packed bed to serve as the solid pore space through which fluid flows. Spheres of 5.5 mm in diameter are kept in the test section in place by wire mesh screens placed at the two ends of the tube, which gives a porosity of 0.5.

The porous section is kept horizontal in the gravitational open flow system. An orifice meter (6) is installed after the test section to measure the high flow rates and from which the mean velocity and Reynolds number of flow are calculated. For the small flow rates, the outlet flow is collected into a 2 liter flask (7) and by measuring the time of filling this flask, the flow rate is calculated. A U-tube mercury and carbon tetrachloride manometer (5) is connected to two pressure tabs located at the inlet and exit of the test section to measure the pressure drop along the test section.



(1) Overhead tank.
(2) Constant head tank.
(3) Ball Valve.
(4) Test section.
(5) U-tube manometer.
(6) Orifice meter.
(7) Collecting flask.

Figure 1. Schematic diagram of experimental apparatus.

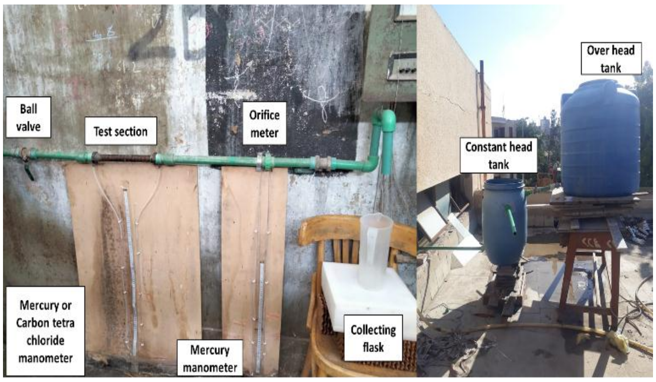


Figure 2. Photograph of experimental apparatus.

The tests were done carefully to produce a stable packing of the beads and to prevent the effects of changing porosity on the pressure drop as the flow rate is varied. The experimental work is carried out to measure the pressure drop and flow rate using polymer solutions with different concentrations of 50, 100, 150, 200, and 250 ppm, besides the flow of pure water.

B. *Fluid preparation and polymer characterization*

The polymer used in this study is a polyethylene oxide (PEO) with a molecular weight (MW) of 5×10^6 g/mole, which was purchased from Sigma-Aldrich, USA as shown in Fig.3. The concentration of polymer can be prepared with the following relation:

$$C(ppm) = \frac{m_s(mg)}{V_w(litre)} \qquad (1)$$

Where C is the desirable concentration of polyethylene oxide, which is calculated in ppm, m_s is the mass of solute, which is measured in mg, and V_w is the volume of water, which is the solvent and is measured in litres. Then, polyethylene oxide in powder form was distributed over the surface of the known amount of water in a beaker and left for 24 hours. The solution was stirred by using a magnetic bead.

Figure 3. Photograph of POE package in powder form.

To avoid polymer degradation during sample preparation, the solution was stirred slowly and quietly in one direction until the mixture became homogeneous. Then, it was left with the mixture for at least 12 hours to complete melting and homogeneity before use. These solutions were then diluted in an overhead tank to provide the desired concentration of test solution. The volume of mixture which is taken from the stock sample is calculated from the following relation:

$$V_{st} = \frac{C_n V_n}{C_{st}} \qquad (2)$$

Where V_{st} is the volume which is taken from the stock sample, C_n is the new required concentration, and C_{st} is the previously known stock concentration.

III. THEORITICAL BACKGROUND

A. *The Ergun equation (1952):*

The Blake-Kozeny and Burke-Plummer equations, which have been frequently used to predict pressure drop for Newtonian fluids flowing through packed beds, are combined in this equation. The Reynolds number Re was defined by Ergun as [14]:

$$Re = \frac{\rho U Dp}{\mu(1-\varepsilon)} \qquad (3)$$

Ergun also defined that the friction factor *f* as [14]:

$$f = \frac{Dp\, \varepsilon^3\, \Delta P}{\rho U^2 (1-\varepsilon) L} \qquad (4)$$

After conducting experiments with various flowrates and various packing materials, Ergun deduced the general form of the equation [18]:

$$f = \frac{150}{Re} + 1.75 \qquad (5)$$

Or in terms of pressure gradient [18]:

$$\frac{\Delta p}{l} = 150 \frac{\mu(1-\varepsilon)^2 U}{Dp^2 \varepsilon^3} + 1.75 \frac{(1-\varepsilon)\rho U^2}{\varepsilon^3 Dp} \qquad (6)$$

From the readings of the steady-state pressure drop through the porous media and the flow rate, the Reynolds number Re and friction factor f were computed according to the eqns. (3, 4).

B. *Drag reduction ratio (DR%)*

A drag reduction ratio is defined as the reduction of friction below that which would occur for the same flow without the drag reducing additive. The DR-effect can be obtained by measuring pressure drops with and without a drag reducing agent using the following expression [15]:

$$DR\% = \frac{\Delta P_{without\ DRA} - \Delta P_{with\ DRA}}{\Delta P_{without\ DRA}} \times 100 \qquad (7)$$

Also, it can be written in another form by calculating friction factor *f* as [15]:

$$DR\% = \frac{f_{without\ DRA} - f_{with\ DRA}}{f_{without\ DRA}} \times 100 \qquad (8)$$

IV. UNCERTAINTY ANALYSIS

To evaluate the uncertainty of the experiments, Eqn. (4) is used to get the uncertainties in friction factor. Water density and gravity acceleration are assumed to have no uncertainties. For any calculated or measured parameter (Z), such as the friction factor, the uncertainty value (E) is calculated as follows:

$$Z = f\,(x_1, x_2, x_3, \ldots\ldots\ldots, x_n). \qquad (9)$$

The uncertainty in the resultant parameter E_z is expressed as follows:

$$E_Z = \sqrt{\left(\frac{\partial Z}{X_1} E_{x1}\right)^2 + \left(\frac{\partial Z}{\partial X_2} E_{x2}\right)^2 + \cdots + \left(\frac{\partial Z}{\partial X_n} E_{xn}\right)^2} \qquad (10)$$

Where E_{x1}, E_{x2}, and E_{x3} are the uncertainties in the independent variables x_1, x_2, and x_3, respectively.

Table 1 lists the uncertainty of different measured variables. Using data given in Table 1 and from Eqn. (10), the maximum uncertainty value of friction factor as a calculated parameter is 5.1%.

Table 1. Uncertainty of measured variables

Measured variable	Uncertainty
Differential head in U-tube manometer, m	±0.001
Particle diameter, m	±0.00005
Main pipe dimeter, m	±0.00005
Length of test section, m	±0.001
Number of spheres	±10
Time, s	±0.5
Volume, m^3	±0.0001

V. RESULTS AND DISSCUSSION

A. *Water flow results*

To validate the experimental data developed in this work, the pressure drop and volume flowrate are experimentally measured for water flow, and both the Reynolds number and the total friction factor are calculated and compared with Ergun's equations (5, 6). Figure 4 demonstrates the comparison of the experimental pressure drop with the average velocity, while Fig. 5 presents the comparison of the friction factor as a function of Reynolds number. The comparison shows good agreement with the Ergun model.

B. *Polymer Solution Results:*

Many experiments were conducted to show the effect of POE concentrations (C = 50, 100, 150, 200, and 250 ppm) on friction factor and pressure drop inside the 2.45cm inner diameter pipe with a flowrate between 5.8×10^{-6} and 77×10^{-6}

m^3/s and average flow velocities have a range from 0.012 to 0.157 m/s, corresponding to Reynolds numbers ranging from 130 to 1800. All the experimental results are demonstrated in Figs. (4-6).

Figure 6 illustrates the relation between the average velocity of fluid flow and the pressure gradient for different POE concentrations. One can notice that the pressure gradient increases with the increase in the average velocity of flow. It was also discovered that as POE concentration increases, the pressure gradient decreases slightly. Figure 7 shows the Reynolds number against the friction factor for different POE concentrations. It is seen that the friction factor decreases with the increase in the POE concentration. From Figs. (6, 7), one can also conclude that the use of polymer solutions with different concentrations decreases the pressure gradient and friction factor with respect to that of pure water flow.

As shown in fig. 6, for constant values of Reynolds number, the friction factor decreases with the increase of POE concentration. From figs. (7, 8), it is concluded that there was a large reduction in friction factor at small Reynolds numbers until Re≈747, while the amount of this decrease is less at high Reynolds numbers. This confirms that the drag reducing additives are more effective in the region of (Re<747) while they are less effective in the region of (Re>747), which will be shown later in Fig. 9 for the drag reduction ratio curve.

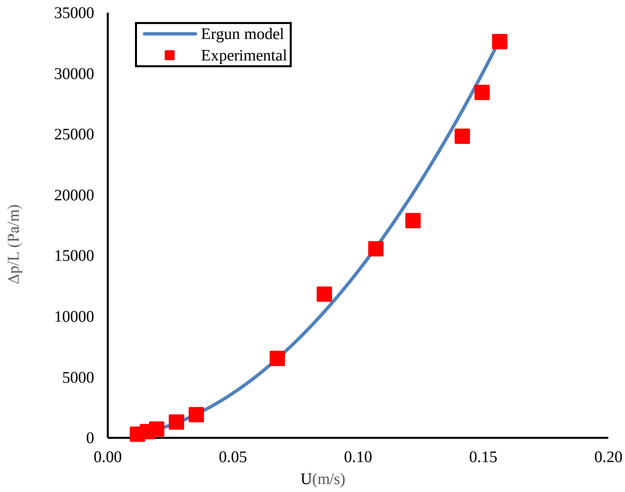


Fig. 4. Comparison between the experimental pressure gradient with the Ergun equation (6).

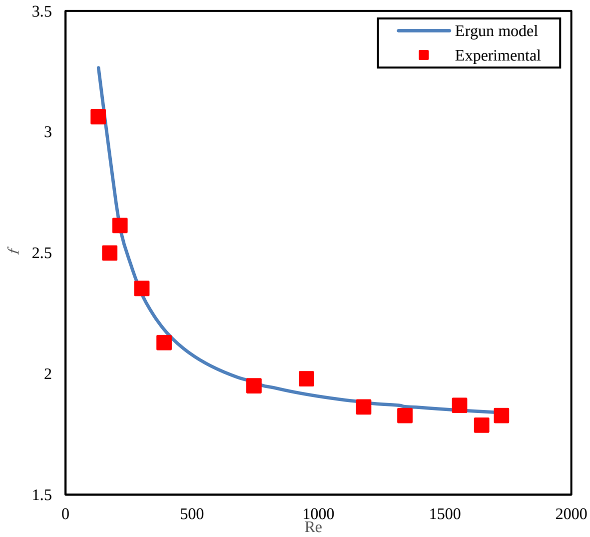


Figure 5. Comparison of the friction factor to the Ergun equation (5).

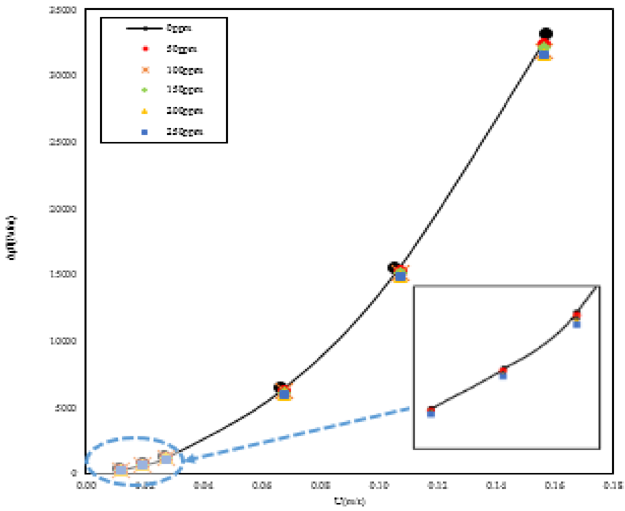


Figure 6. Pressure gradient versus average velocity at different Polyethylene oxide concentrations.

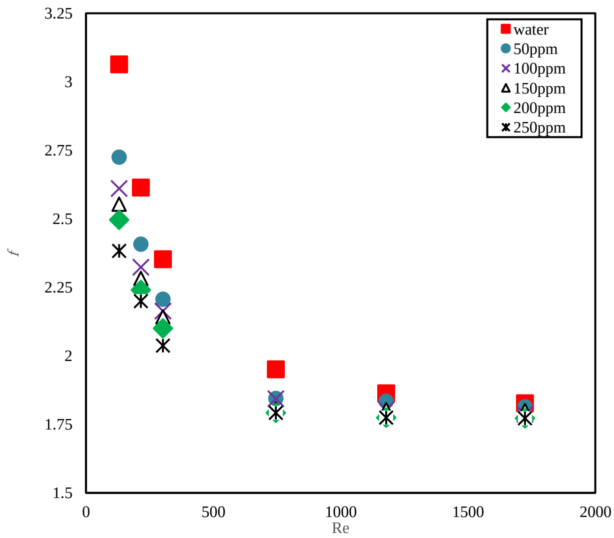


Figure 7. Reynolds number versus friction factor at different Polyethylene oxide concentrations.

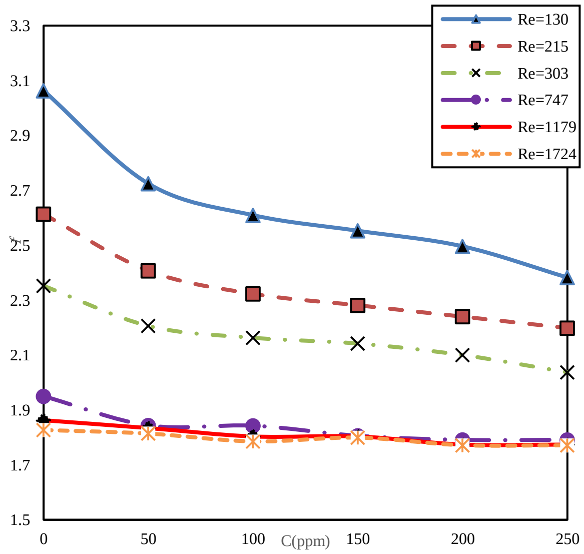


Figure 8. The effect of polymer concentration on friction factor at different values of Reynolds number.

C. *Drag reduction ratio results*

The drag reduction ratio (DR%) defined by equation (8) represents the decrease in friction factor of polymer solutions with different concentrations with respect to that of pure water flow [17]. Figure 9 demonstrates the relation between the drag reduction ratio and the average velocity of flow for different concentrations of POE solution. The drag reduction ratio increases with the increase in solution concentration. It takes higher values at small velocities (U<0.068 m/s) compared to its values at high velocities (U>0.068 m/s). It reaches about 22.3% at C = 250 ppm and velocity U = 0.012 m/s. As a result, it is possible to conclude that the drag reducing additives are more effective at low velocities and less effective at high velocities, as mentioned previously.

The experimental results of the drag reduction ratio as a function of POE concentration at various Reynolds numbers are shown in Fig. 8. It can be seen that the drag reduction ratio increases continuously until it reaches the maximum concentration of 250 ppm. It can also be seen that the highest value was 22.3%, which was obtained for the maximum concentration of 250 ppm.

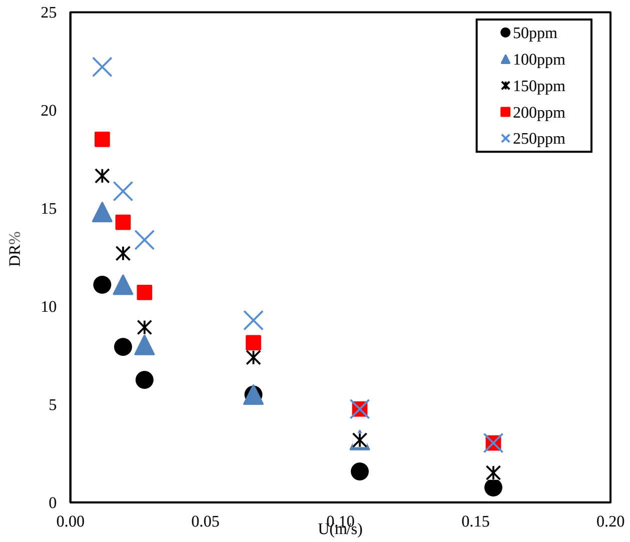


Figure 9. The effect of average velocity on drag reduction ratio DR% at various POE concentrations

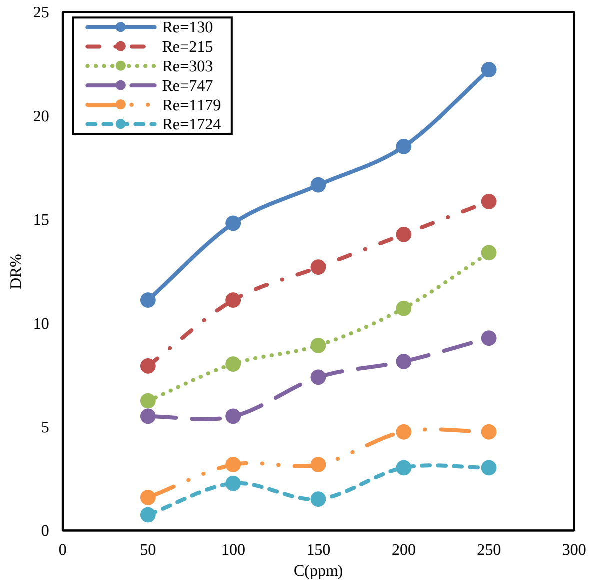


Figure 10. Effect of POE concentration on Drag Reduction ratio

DR% for different Reynolds numbers.

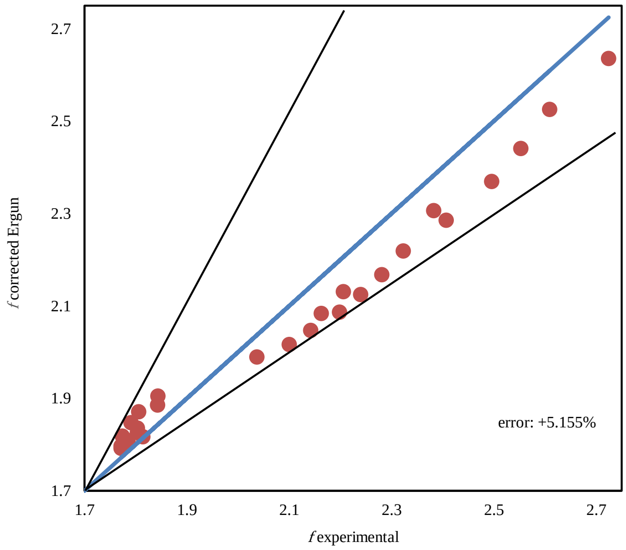


Figure 11. Experimental versus mathematical correlation results of friction factor at different POE concentrations.

D. *Non-Newtonian behavior*

The equation (11) is a correlation of the Ergun equation (5) to present the non-Newtonian and drag reduction effects, which can be expressed in dimensionless form as denoted by the friction factor:

$$f = \frac{150 + k}{Re} + 1.75 \qquad (11)$$

Where k represents the effect of drag reduction concentration. The current experimental data were used to calculate the coefficient k in eqn. (11), which was deduced to be a function of polymer concentrations as shown in eqn. (12):

$$k = -4.9\sqrt{C} \qquad (12)$$

Combining equations (11) and (12), a relationship that describes the behavior of non-Newtonian drag reducing fluid using PEO in porous media can be expressed as:

$$f = \frac{150 - (4.9\sqrt{C})}{Re} + 1.75 \qquad (13)$$

Where Reynolds number is between 130 and 1800 and polyethylene oxide concentrations are up to 250 ppm.

Figure 11 represents the relation between the values for the friction factor that were experimentally observed and those that were predicted by mathematical correlation of Ergun equation (13). It can be seen that most points are on or close to the straight line, thereby indicating a good agreement between correlated and experimental data.

VI. CONCOLUSION

Drag reduction experiments through a circular pipe packed with spheres as a porous medium were conducted. A polyethylene oxide solution with a concentration of 50, 100, 150, 200, and 250 ppm was used as a drag reducing additive for Reynolds numbers up to 1800. From the experiment results, the following conclusions can be drawn:

1. For polymer solution flow, the pressure gradient and friction factor decrease with the increase of POE concentration. The use of polymer solutions with different concentrations decreases the pressure gradient and

friction factor with respect to that of pure water flow.

2. At constant Reynolds numbers, the friction factor decreases as the concentration of POE drag reduction increases. Also, at smaller Reynolds number (Re< 747), the friction factor was greatly reduced with polymer concentration.
3. The drag reduction ratio increases with the increase in POE solution concentration.
4. The drag reducing additive is more effective in the low velocity region ($0.012 \leq U < 0.068$m/s) than in the region of high velocity ($0.068 \leq U \leq 0.157$m/s).
5. An equation that describes non-Newtonian flow behavior is derived for the friction factor as a function of POE concentration and it is expressed as:

$$f = \frac{150-(4.9\sqrt{C})}{Re} + 1.75 ,$$

For $130 \leq Re \leq 1800$ and C up to 250 ppm.

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Conflicts of Interest:

The authors declare that there is no conflict of interest.

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NOMENCLATURE

Symbols

C	Polymer concentration (-)
C_n	New required concentration (-)
C_{st}	Stock concentration (-)
$DR\%$	Drag reduction ratio (-)
Dp	Particle diameter (m)
f	Friction factor (-)
$f_{without\ DRA}$	Friction factor without drag reducing agent (-)
$f_{with\ DRA}$	Friction factor with drag reducing agent(-)
l	Test section length (m)
m_s	Solute mass (mg)
M_w	Molecular weight (g/mole)
ppm	Particle per millions
Re	Particle Reynolds number (-)
U	Average flow velocity (m/s)
V_{st}	Volume which is taken from the stock (liter)
V_w	Water volume (liter)

Greek symbols

ε	Porosity (-)
μ	Viscosity (kg/m.s)
ρ	Density (kg/m^3)
k	The parameter of drag reduction concentration effect
Δp	Pressure drop (Pa)
$\Delta p_{without\ DRA}$	Pressure drop without drag reduction agent (Pa)
$\Delta p_{with\ DRA}$	Pressure drop with drag reduction agent (Pa)
$\frac{\Delta p}{l}$	Pressure gradient (Pa/m)