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Increasing the Flow Capacity and Reducing Drag in Microtubes Using Drag-Reducing Polymers

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ABSTRACT

Decreasing pressure losses in microtubes is an important subject, especially when an increase in the flow capacity is required. In the same pumping power, decreasing the pressure drops coincides with increasing the fluid flow rate passing through a microtube. The current study aims to examine how the water pressure drop across a microtube can be affected by the addition of small concentrations of different drag-reducing polymeric agents. A kind of the laminarization behaviour was found by the addition of the selected polymer to the turbulent flow. The effect of the concentration of the drag-reducing agent (DRA) on the observed viscosity and drag values are reported. Moreover, the effects of different types of drag-reducing agents on the friction factor are obtained at the best concentration in the range of examined concentrations. Under this condition the percentage of the drag reduction and increase in the capacity of the flow were respectively 33 % and 36 %. The obtained results show that more drag reduction occurs at a higher flow rate for 20 ppm of the polyacrylamide with a high molecular weight.

1. Introduction

Many researches were undertaken with the aim of studying the pressure drop in various chemical engineering application processes [1, 2]. As a practical method, the addition of minute concentrations of drag-reducing agents (in the ppm order) to the turbulent fluid flow may avoid negative consequences of pressure losses in the pipeline. By suppressing the energy content of the turbulent eddies, the drag-reducing agent (DRA) reduces the consumed power of the pump at a constant flow rate or increases the piping system capacity at a constant pressure drop without any changes in the pipeline conditions. This effect is particularly important when the maximum allowable operating pressure (MAOP) is a discouraging parameter [3, 4]. Drag reducing agents are divided into various categories, such as long-chain polymers, surfactants, suspensions of particles, fibres and micro-bubbles, as well as compliant coatings [3, 4]. However, fluid soluble polymers with ultrahigh molecular weight (more than 10^6Da) are classified as paramount drag-reducing agents [3, 4].

The first attempts for employing DRAs were carried out by Toms [3, 4] and Mysles [5] in their individual studies. The smart specifications of DRAs have attracted many researchers to study the drag reduction effect both experimentally and theoretically [6-13].

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Virk [7] conducted one of the most valuable studies on the drag reduction. He investigated the effect of adding polymers to the Newtonian flow and found that the the thickness of the wall layer would increase in the presence of DRA. This increased thickness may extend the velocity profile of the wall layer, and in turn, decrease the friction factor of the turbulent flow.

Karami and Mowla [14] proposed a mathematical model to investigate the effects of various experimental parameters on the drag reduction. They found that the drag reduction increased with the concentration and molecular weight of DRA, the flow rate and temperature of the fluid, as well the relative roughness of the pipe. Their model matched the experimental data appropriately. In a statistical study, Karami et al. [15] showed that the most effective parameters in the drag reduction were the Reynolds number and the concentration of the polymers.

Kamel and Shah [16] conducted some experiments on ASP700 as a drag reducer and observed that 80 % of the drag reduction occurred only with using 0.07 V % of this material. In another study, Zadrazil et al. [17] used polyethylene oxide (PEO) as a drag reducer in the water flow for their experiments and found that the DR % was increased with the concentration of the additive having been increased. Varnaseri and Peyghambarzadeh [18] investigated the effect of the polyacrylamide drag reducing agent on the friction factor and the heat transfer coefficient in laminar, transitional and turbulent flow regimes in circular pipes with different diameters and they reached 50 % of the DR. Effects of a new drag reducing agent named CPA, of which the field test showed the maximum drag reduction rate of 25 %, on the natural gas pipeline transportation were investigated by Ma et al. [19]. Moreover, several studies were carried out in order to observe the effect of various parameters, e.g. types of DRPs, the concentration of DRA, pipe diameters, on the drag reduction [20-24].

In recent years, the application of microscale devices have been found in many fields. The application of the microtube is the same as of the conventional pipes. The main differences between these two are associated with the viscous heat dissipation. Due to the significantly large surface to volume ratio of the microscales, in some cases, this effect may cause measurable increases in the liquid temperature. Therefore, the liquid flow is subjected to very high shear rates caused by the applied pressure even for low Reynolds numbers. Recent investigations have suggested the presence of an apparent slip at the wall; such a slip may occur locally when the shear rate exceeds a critical value, below which the no-slip condition is valid. Conversely, in microtubes, the increase in temperature due to the viscous heat dissipation alters the liquid properties, particularly the dynamic viscosity, and hence changes the friction number [25].

Nonetheless, applications of the microscale are outspread quickly because of attractive features such as a higher mass, heat and momentum transfer coefficient, which is important in the practical applications. One of the first attempts to apply the microchannel in a single phase was conducted by Tuckerman and Pease [26]. Nowadays, many of the conventional engineering apparatus could be successfully replaced by microchannels [27]. Knowing the hydrodynamic of microchannels has critical importance to understand the behaviour of the flow as well as the friction factor under various conditions [28-32]. Rahimi et al. [33] conducted an experimental and modelling study on the hydrodynamics of the water flow in serpentine rectangular microchannels and developed correlations to predict the friction factor.

Alteration of the application of the microchannels is an interesting subject among researchers [34, 35], due to an increase in surface forces, the pressure drop of the channels may be increased and create some difficulties for the fluid flow [27]. The application of the microstructures under the turbulent flow regime is restricted. The main problem is a resulted high pressure drop in the turbulent regime. Therefore, it is difficult to use these types of channels for high capacity fluid transportations [31]. Nowadays, overcoming this problem is a big challenge for many researchers, and some methods, including covering the surface of the channel with a compliant coating which is a conventional way, have beeen proposed to resolve it [36-38].

Ushida et al. [39-41] conducted some experiments to investigate the effects of some additives to the micro apparatus. They found that nanobubbles decreased the amount of the pressure drop of the flow in the micro orifices (with the inner diameter of less than 50 µm) and capillary tubes (with the inner diameter of less than 70 µm). They also showed that the combination of nanobubbles-polymers was not as efficient as a pure polymer solution. They related the effect to the lower elastic stress of nanobubbles-polymers. Their study was restricted to low Reynolds numbers with a range of very high concentrations.

Despite the importance of this subject, most of the investigations have been carried out to find the effect of DRA in the large-scale tube and pipes. In this study, the idea of using the polymeric DRA is employed for micro-scale systems, which are more involved with high operational pressure drops. The current study employs three different water-soluble polymers to investigate their effects on the amount of the pressure drop and the consequent increase in capacity in a microtube. The injection of small concentrations (ppm) of these agents well demonstrates the delay in the occurrence of the turbulent fluid flow regime. The experimental achievements of this study show that by addition of DRA to the flow, the capacity of the tube can be increased and more fluid can be transported. Therefore, as a novel achievement, the present study uses the positive effect of the polymer to avoid high pressure losses through the microtube, it can be seen as a smart way to increase the capacity of the fluid inside the microtubes.

2. Drag reduction definition

Drag reducing agents are the additives which effectively decrease the friction of the flow in the vicinity of the solid surfaces. The ability of these additives to control the friction losses depends strongly on their resistance against degradation and high solubility in the working fluid. The injection of DRA to the pipeline prevents the vortex formation by damping various turbulent eddies and consequently reduces the head losses in the flow. Most of the researchers have observed the drag reduction effect only under turbulent conditions where the Reynolds number (Re) was above 2300 in pipe flows. Understanding the mechanism of the drag reduction is not clarified exactly and remains a big challenge to researchers [14]. Nevertheless, in general, there are three hypotheses to this effect. The first group of hypotheses relates the drag reduction to the commensurability of the linear scale of turbulence and the radius of gyration of macromolecules. The coincidence of the frequency of turbulent fluctuations and the reciprocal of the relaxation time of the polymer molecule is assumed in the second group of hypotheses. The third group of hypotheses is based on the redistribution of the energy balance of the turbulent flow in the presence of polymer additives [42].

The percentage of the drag reduction (DR %) is the criteria to show the ability of any drag reducing agent that is defined as follows (Equation 1) under constant flow rates:

$$DR\,\% = \left(1 - \frac{f_{DRA}}{f_{No-DRA}}\right) \times 100 \qquad (1)$$

where f_{DRA} and $f_{No\text{-}DRA}$ are friction factors in the presence of DRA and the working fluid respectively, which are directly related to the pressure drop of the pipeline.

The friction factor is defined in terms of the Reynolds number and the relative roughness of the pipe described by numerous equations. Virk [7] proposed a general equation for the drag reduction in the smooth pipes based on the Prandtl-Karman (P-K) equation. The Prandtl-Karman relation has been defined in equation (2) for a turbulent flow:

$$1/\sqrt{f} = 4\log(\mathrm{Re}\sqrt{f}) - 0.4 \qquad (2)$$

It has been well demonstrated that very small concentrations of DRA are needed to create a significant change in the drag reduction [43, 44]. Based on different experimental studies, the drag reduction rapidly increases with increase in the concentration of the DRA until it meets a maximum drag reduction asymptote [45]. The drag reduction also tends to increase with increasing the applied Reynolds number, and the phenomena show a higher DR % at a more turbulent flow [1, 14]. Based on the P-K equation, Virk [7] developed an equation for the drag reduction in the presence of a diluted polymeric solution, in the presence of the maximum drag reduction profile (the MDR asymptote).

3. Material and methods

An experimental apparatus, schematically depicted in Figure 1, has been employed to study the drag reduction in the microtube. The experimental setup consisted of a centrifugal pump to transfer the working fluid into a microtube. The employed tube was a conventional industrial copper tube with 780μm of the inner diameter and 50cm of length. The pressure drop was measured by using two BD pressure transducer sensors (@ BD | SENSORS GmbH) monitored by a digital indicator. The uncertainty for the measurement of the pressure drop was about 0.5 percent. Since the diameter of the pipe was small enough to install the pressure transducers on the pipe directly, the inlet and outlet of the microtube are installed on two vessels, and the pressure transducers are installed on the vessels to measure the pressure. The calibration experiments show a reliable pressure measurement with this system. The positions of the two points of the pressure measurement are based on the required distance from the inlet and outlet of the microtube. The first point was selected in the position where the fully developed condition was insured (based on the highest Dodge Metzner Reynolds number [46]). The second point was selected with an assured distance from the outlet to avoid the exit effects.

In order to investigate the effect of drag reduction, three water-soluble polymeric solutions were prepared and injected by a syringe pump. The injection point was approximately 64 cm prior to the entrance of the tube to ensure the complete dissolving. The injection rate was adjusted by a controlling loop. Injecting is a good alternative to decrease the possibility of any mechanical degradation because it avoids the induced degradation of the polymer through the pump. The only degradation that may occur is due to the negligible effects of the wall of the tube.

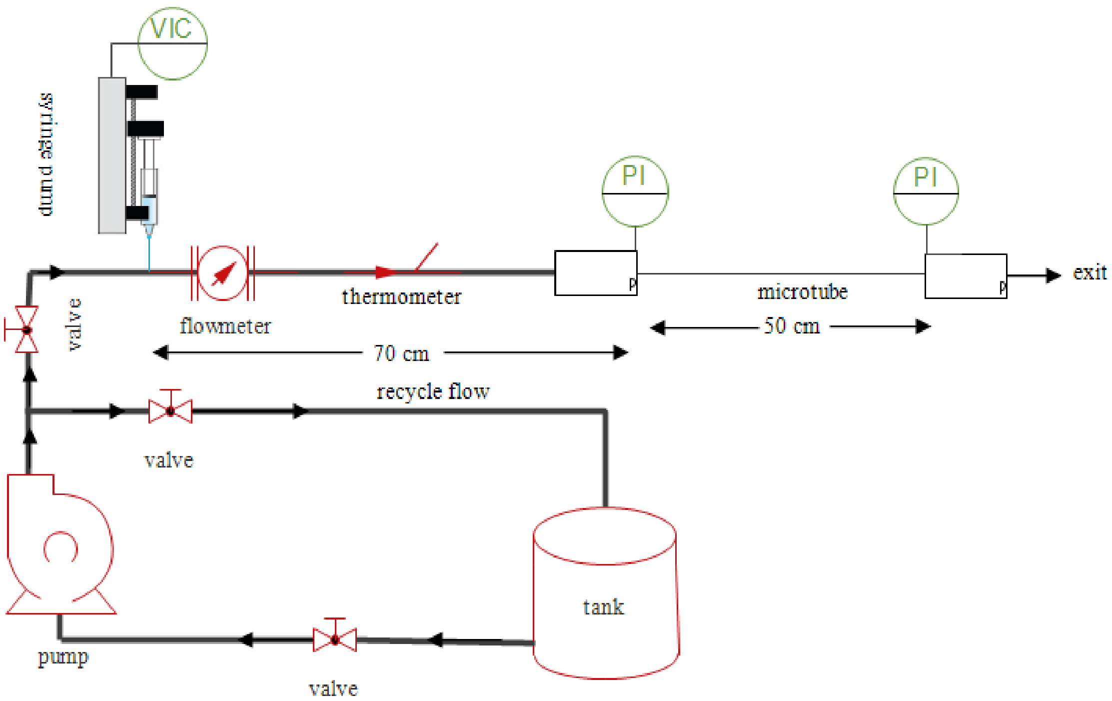
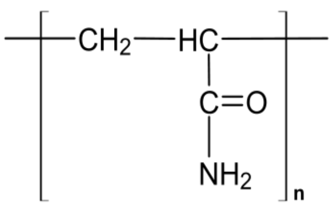
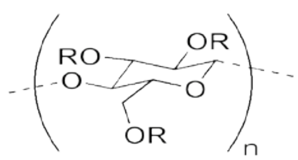


Figure 1. A schematic view from the employed experimental apparatus.

The three employed DRAs were two different types of polyacrylamide (PAA) with 22000 kDa (PAA1) and 18000 kDa (PAA2) of the molecular weight and Carboxymethyl cellulose (CMC) as a food-grade additive with a low molecular weight. These agents were precisely dissolved in water under ultrasound waves. The employed method assures a complete dissolution. The chemical structures of these agents are depicted in Figure 2. After the preparation of the solutions, the additives were injected with a controlled rate to the working fluid to investigate the drag reduction effect.



(a)



R = H or CH_2CO_2H

(b)

Figure 2. Chemical structures of a) Polyacrylamide (PAA) and b) Carboxymethyl cellulose (CMC) as drag reducer polymers.

The desired concentrations of the DRAs were adjusted by the ratio of the flow rate of the master solution to the working fluid. The concentration of additive drag reducing agents is evaluated more appropriately if it has no significant effect on the viscosity and density of the working fluid. In order to consider how the addition of the polymers changes the fundamental specifications of the fluid, like viscosity, some experiments were carried out to measure the viscosity of the diluted polymeric solution by a rotational rheometer (Rholab QC) at 25 ºC. The obtained results are presented in the Figure 3 for PAA1. Based on Figure 3a, there is no considerable change in the viscosity for lower concentrations. However, the deviations from the viscosity of water are more significant at higher concentrations, and some non-Newtonian behaviour are observed. The changes of the viscosity show shear thinning behaviour, which means the viscosity of the fluid decreases by the increase of the shear rate. By the way, the Figure 3b shows the amounts of shear stress in terms of the applied shear rate. As the figure reveals, by addition of the polymer to the flow, some nonlinear behaviours are found due to the resulted non-Newtonian behaviour.

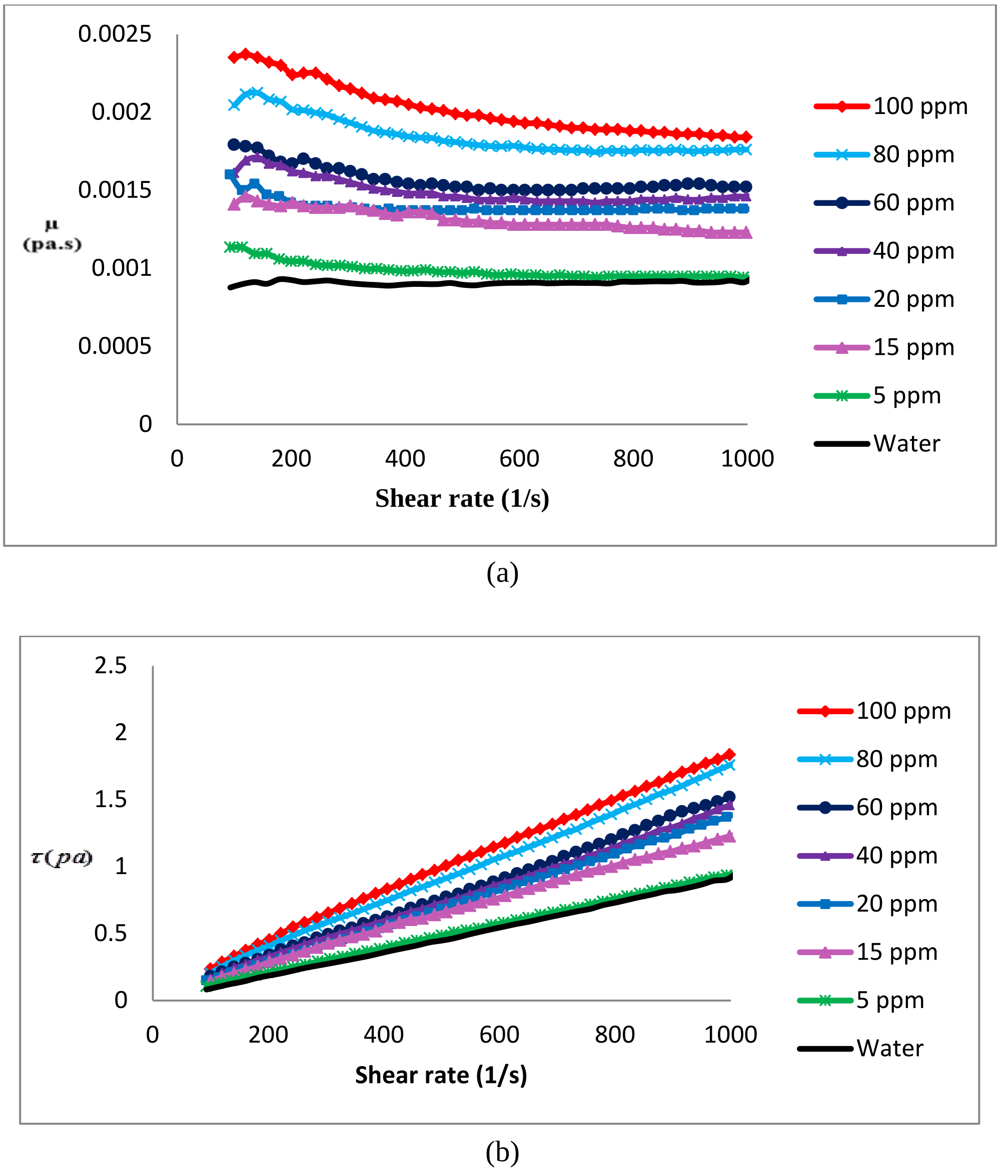
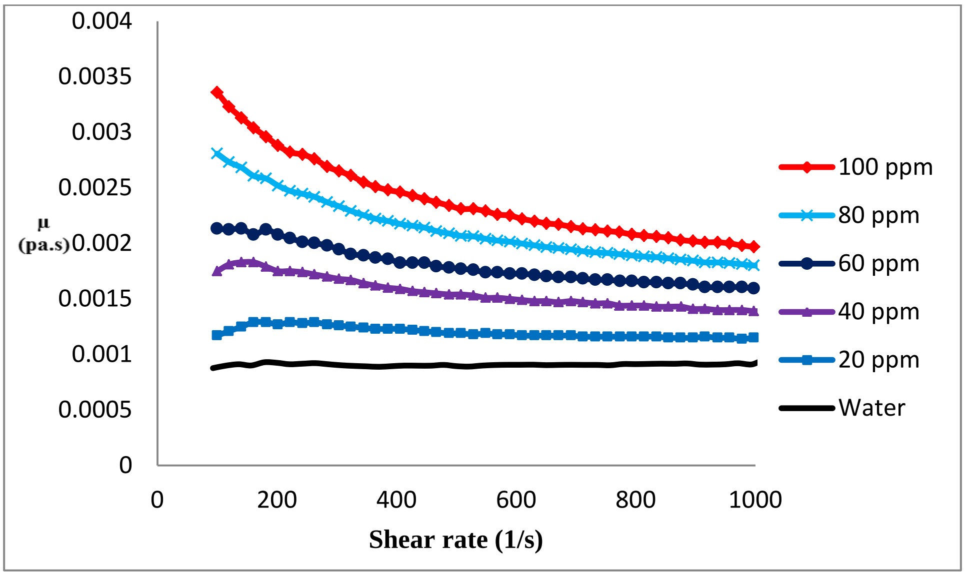
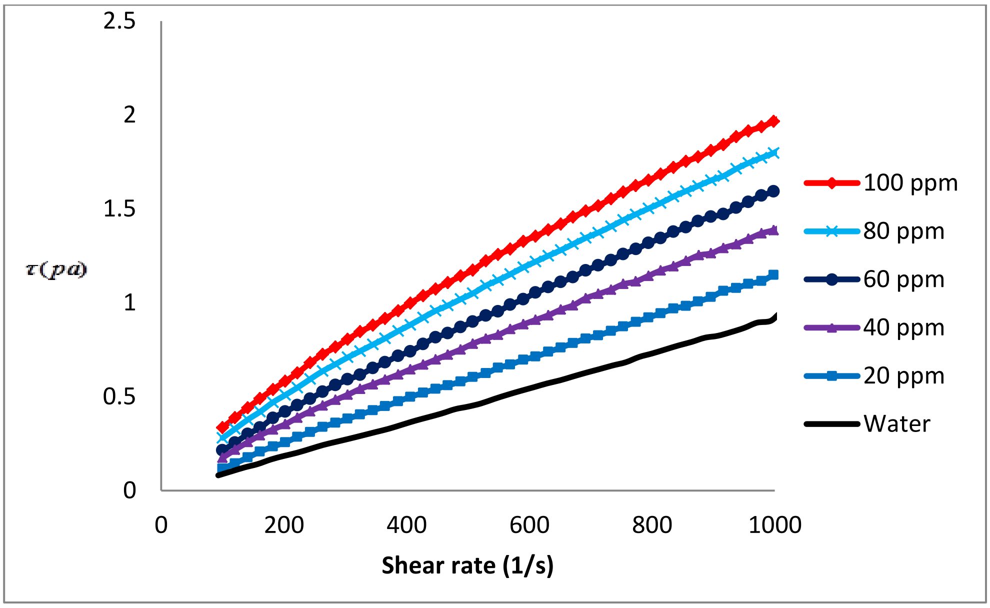


Figure 3. Effects of adding various concentrations of PAA1 on the (a) viscosity and (b) the resulted shear stress of the diluted solution.

The obtained viscosity pattern of CMC was found to be slightly different from that of PAA, as depicted at Figures 4a-b, and non-Newtonian behaviour was more obvious, especially at higher concentrations.



(a)



(b)

Figure 4. Effects of adding various concentrations of CMC on the (a) viscosity and (b) the resulted shear stress of the diluted solution.

The resulted shear stress (τ) of the non-Newtonian fluid is related to the applied shear rate ($\dot{\gamma}$) by the following power-law equation:

$$\tau = k\dot{\gamma}^n \qquad (3)$$

where n and k are the flow behaviour and consistency indices of the treated fluid respectively. The amounts of the two indices can be obtained by the log-log plot of the shear stress in terms of the shear rate, in which the slope of the plots simply shows the flow behaviour index (n) while the consistency index (k) can be found by the intercept of the plots. Table 1 summarizes the resulted Rheological behaviour of the flow at various concentrations of the PAA1 and CMC. The same result with PAA1 may be expected with PAA2.

An obvious non-Newtonian behaviour is observed for CMC compared to PAA, as it was expected from viscosity curves.

In order to obtain the turbulent flow as the desired condition for drag reduction, the flow rates of the water were adjusted between 1 mL/s to 2.5 mL/s, which provided the Reynolds number of 1460 to 4374. To check the turbulence intensity of the flow in the microtube, Figure 5 illustrates the diagram of the "f.Re" values in terms of Re. The sudden change in the slope of the diagram means the onset of turbulence.

Table 1
The obtained flow behaviour index (n) and the consistency index (k) of the none-Newtonian fluid at various polymer concentrations.

Polymer	Concentration (ppm)	n	k (kg/m.s^{2-n})
PAA	5	0.927	0.00155
	15	0.922	0.00212
	20	0.962	0.00175
	40	0.931	0.00229
	60	0.929	0.00242
	80	0.911	0.00319
	100	0.874	0.00436
CMC	20	0.948	0.00164
	40	0.864	0.00356
	60	0.851	0.00447
	80	0.796	0.00739
	100	0.762	0.01020

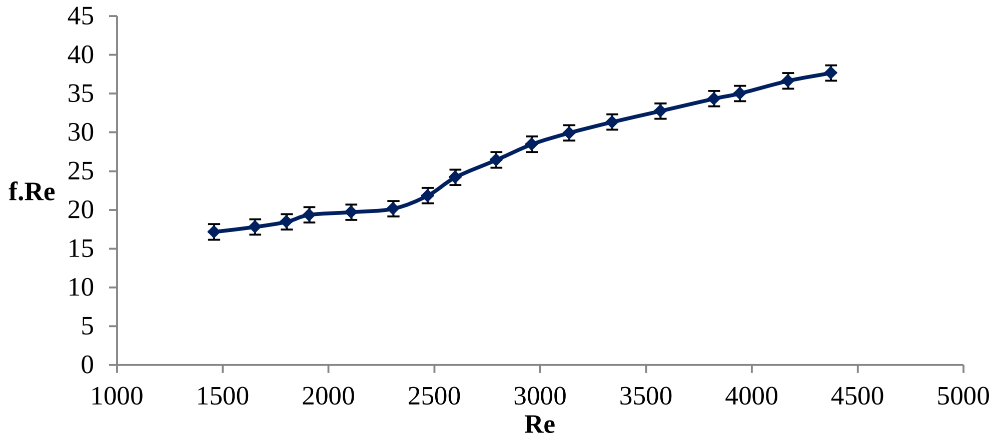


Figure 5. Values of f.Re at various Reynolds numbers for the water flow.

The main idea of the onset of turbulence is laid in the Hagen-Poiseuille law which suggests that the pressure drop of the laminar flow in the pipes varies linearly with the velocity of the fluid. While in the case of turbulent flows, there is no proportional relation, and the pressure drop varies with $V^{1.5-2}$, so a sharp change may be expected. This point is exactly the critical Reynolds number which converts laminar flow to the turbulent one. Converting the parameters to the friction factor and Reynolds number suggests a similar behaviour. This sudden change in the slope indicates that the internal flow undergoes a transition from the laminar to the turbulent regime, so the conventional theory still works for the flow in microtubes [47].

The amount of the friction factor, f, is calculated based on the fanning formula as follows:

$$f = \frac{\Delta P . d}{2\rho v^2 L} \qquad (4)$$

where V and ρ are the average bulk velocity and the density of water respectively. d is the diameter of the tube, and L is the distance between two points where the pressure drop (ΔP) was measured.

4. Results and discussion

By the injection of DRA to the working fluid, the amount of the friction factor is decreased, as expected. Various parameters may control the drag reduction. These are mainly the concentration of DRA, the type of DRA, and the applied flow rate. Every parameter may have a significant effect to decrease the friction factor and increase the flow capacity by the alteration of the performance of the polymer.

4.1. Effects of concentration on the drag reduction

The concentration of DRA may play an important role in the drag reduction. Although the effect of concentration is investigated for conventional pipes [1], there is not any insight on microtubes. In order to check the influence of this parameter, various concentrations of the three employed DRAs have been investigated in this study.

As Figure 6 reveals, the increased concentration of the polymers first increases and then decreases the amounts of the drag reduction. The best concentration shows that the higher DR % may vary with the employed Reynolds number. At more turbulent flows, the solubility of the polymers would be increased, and this solubility may let more molecules contribute to damp turbulence vortices, and hence, increase the amount of the drag reduction as well as changing the best condition. The highest amount of the drag reduction was found at 20 ppm for PAA and 60 ppm for CMC. A higher amount of concentration beyond the best point may induce the viscose resistant forces against the flow and hence decrease the drag reduction ability of the polymer. The latter result is confirmed by conventional pipe studies [1].

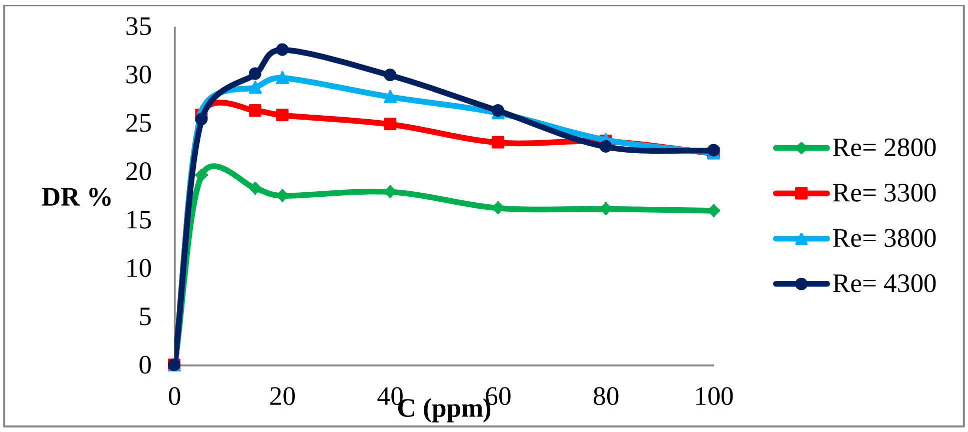


Figure 6. Variations of the DR % with the concentration of PAA1.

Figures 7 to 9 show the changes in the friction factor for two different types of PAA as well as CMC respectively. By the addition of the polymer to the flow, the friction factor of the flow is decreased significantly, and an enhanced performance may be observed with a higher deviation from the turbulent water curve.

As Figure 7 shows, by the injection of PAA1 to the flow, a remarkable tendency to continue the laminar behaviour may be found. The pure water flow has higher friction factors compared to the diluted polymeric solutions with a normal laminar to turbulent trend. By the addition of a small concentration of DRA, for example 5 ppm, the amount of the friction factor is decreased significantly at a higher Re number, and the tendency to continue the laminar behaviour may be observed. At higher concentrations of PAA1 around the best condition of 20 ppm, the researchers observed that the friction factor tended to continue the laminar behaviour of the water flow even at higher Reynolds numbers. The increase of the concentration beyond 20 ppm may increase the friction slightly, but the laminarization behaviour is still confirmed.

A similar behaviour could be found for PAA2, as it is shown in Figure 8. The ability of DRA is increased first, until 20 ppm, and then it is decreased at higher concentrations. All the concentrations show a tendency to continue the laminar behaviour.

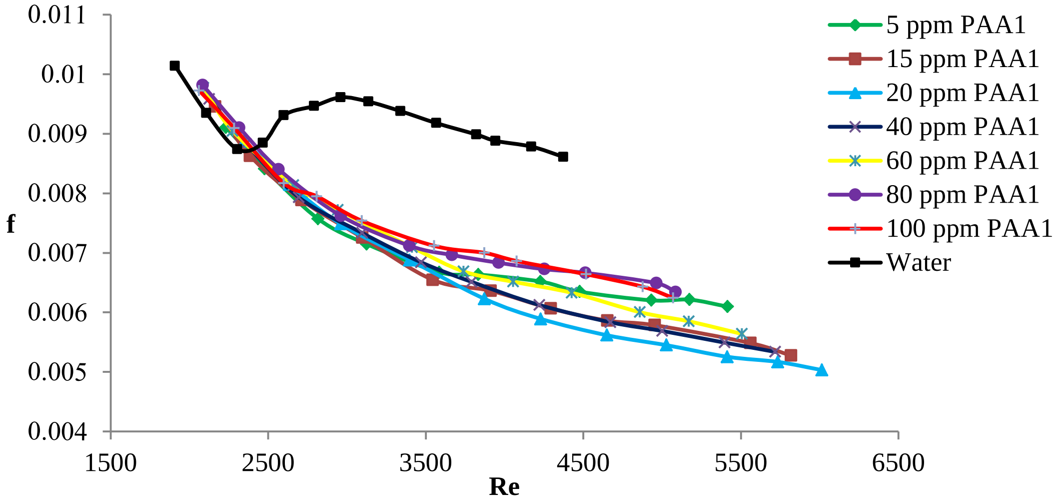


Figure 7. The effect of the concentration of PAA1 on the calculated friction factor.

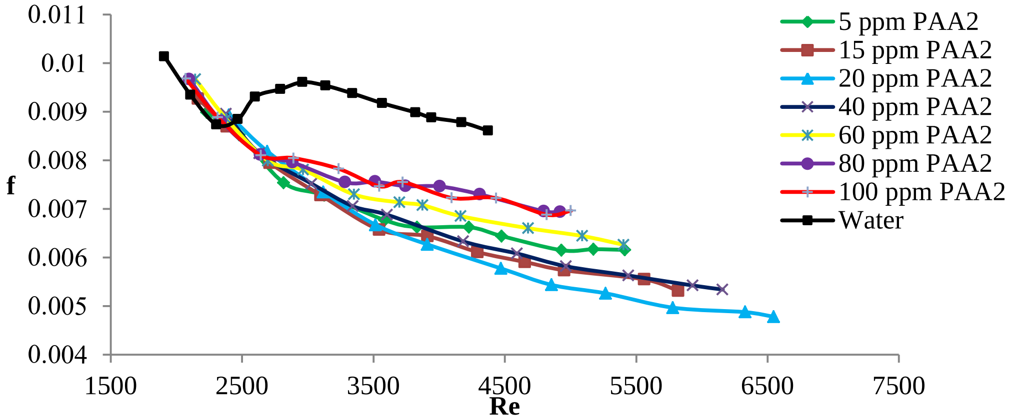


Figure 8. The effect of the concentration of PAA2 on the calculated friction factor.

Figure 9 shows the obtained data for CMC. A similar laminarization behaviour is understood. The best concentration, in this case 60 ppm, demonstrates the best performance, while other concentrations show slight deviations. In this case, the deviancy is more obvious compared to PAAs.

Changing the pattern of the flow from a turbulent to a laminar regime after the injection of DRA could be justified by the dynamics of the drag reduction. As former studies revealed, DRA could thicken the buffer sub-layer and let viscous effects grow [6].

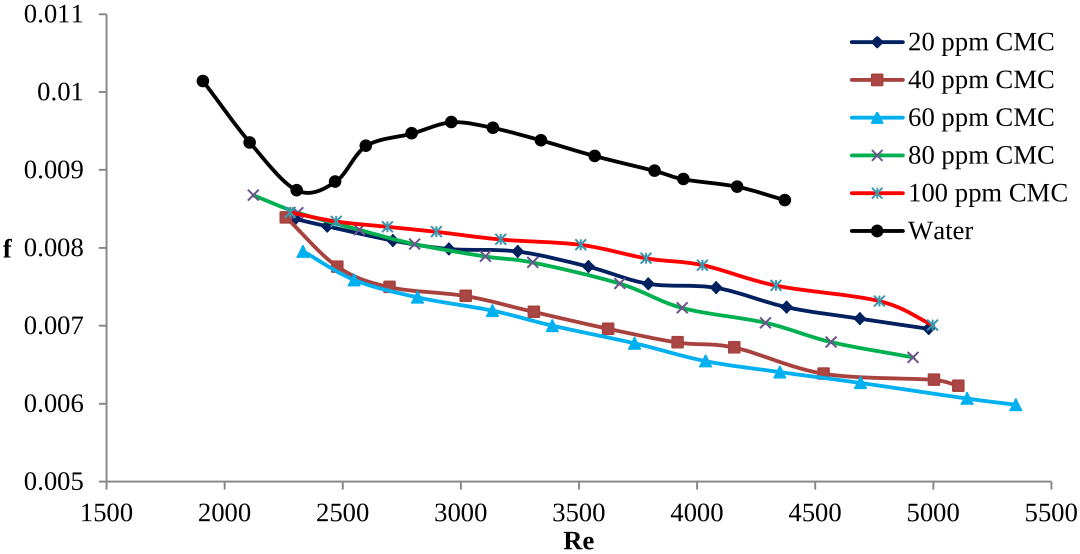


Figure 9. The effect of the concentration of CMC on the calculated friction factor.

The thickened sub-layer causes a more laminarization of the flow. This lets the laminar behaviour to be continued even at higher Re numbers. Also, Kostic [47] suggested that the addition of polymers decreases the turbulent energy-dissipation, thereby laminarizing the turbulent flow.

This is a very important achievement in the case of the microfluidic flow where the high flow rate with a low friction factor may be required. In this study, the maximum achieved DR % was 32.6 % for 20 ppm of PAA1 at the Reynolds number of 4300, which seems an acceptable amount for this very low concentration.

4.2. Effect of the type of polymers on the drag reduction

Different types of polymeric DRA may have an important effect on the friction factor. In most cases, the molecular weight, length of chain and solubility of the polymer have significant influences on the drag reduction [1].

In the current study, two various grades of PAAs and one type of CMC are prepared as three water-soluble polymeric solutions to compare their effects as drag reducers. The polymeric solutions were injected into the flow based on volumetric ratios. The observations showed no significant difference between PAA1 and PAA2 at lower concentrations, although the data showed that PAA1, the polymer with the higher molecular weight, had a better performance at higher concentrations. This increased performance may be due to the ability of the relative long chains of the molecules to damp the resulted vortices in the turbulent flow.

Figure 10 illustrates the obtained results for 20 and 60 ppm concentrations of the studied DRAs. The figure contributes to the comparison of the capability of various agents as drag reducers. The results show a better effect for PAA compared with CMC. The better performance of PAA may be explained by the higher molecular weight and better solubility of PAA in water compared to thoes of CMC. The structures of these two polymers, according to the Figure 2, offer an appropriate polarity for both PAA and CMC. The obtained results show 24.9 % as the maximum drag reduction for CMC. However, this value is slightly lower than the maximum DR % for PAAs, but CMC is a food-grade additive polysaccharide with no such undesirable effect on the health as the contamination of water, especially at low concentrations.

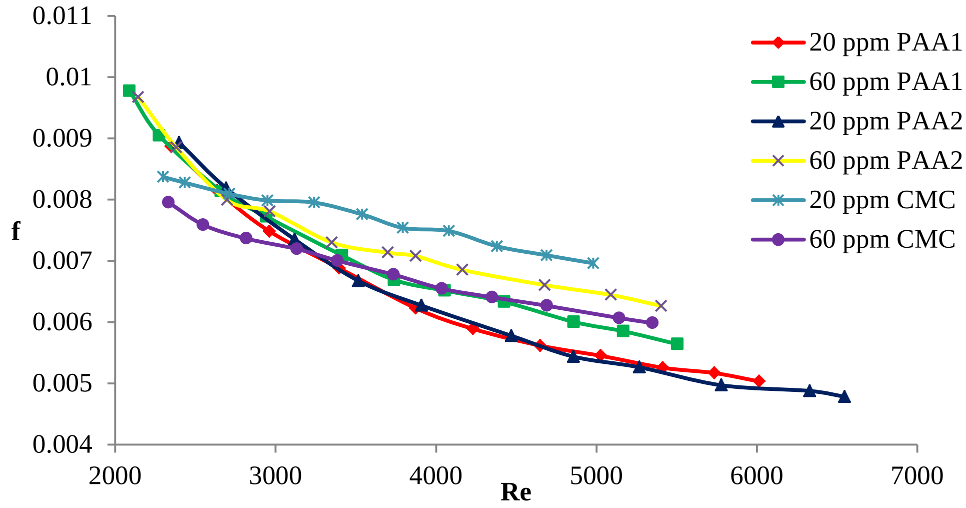


Figure 10. The comparison between the effects of different types of drag-reducing agents on f values at their best concentration.

4.3. Effect of the flow rate on the drag reduction

In theory, the higher turbulent flow results in a better drag reduction effect. The increased drag reduction amount is due to increasing the solubility of the polymers in the water and the resulted challenges between the fluctuated turbulence eddies and DRA molecules. In the turbulence flow, the nonlinear inertia overcomes viscous effects. By suppressing the turbulence vortices, the thickness of the buffer sub-layer may increase and, in turn, more drag reduction occurs [7]. This increased sub-layer may justify the laminarization behaviour, as discussed earlier, and hence a lower friction factor after injecting DRA. Increasing the flow rate, and the consequent turbulent intensity of the fluid, makes polymeric DRAs more soluble in the fluid and enhances their performance. The employed flow rates depend strongly on experimental restrictions such as the pipe diameter. In this study, the maximum flow rate was selected as 2.29 mL/s for water due to safety considerations and to avoid passing the allowable operating pressure.

As Figure 11 depicts, the data obtained from this study prove that increasing the turbulence intensity of the fluid leads to more drag reduction. The figure is developed for PAA1, and all other additives show similar behaviours. The figure also depicts the effect of the concentration of the polymeric agents on the DR %. It is clear that increasing the concentration leads to a lower DR %, as discussed above. Increasing the Reynolds number may also result in the mechanical degradation. This negative effect was found for 5 ppm of PAA at relatively high turbulence conditions. Other concentrations did not show such the effect in the employed range of the Reynolds numbers in this study. The better condition is a higher DR %, which is obtained by a higher flow rate and the best concentration.

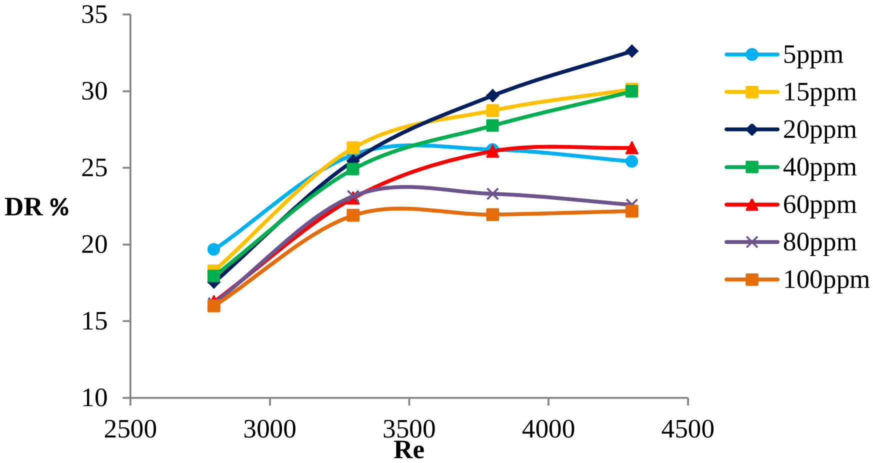


Figure 11. The amount of the DR % using various concentrations of PAA1 with the increase in the Reynolds number.

Addition of DRA to the turbulent flow also allowed the system to increase its capacity, so a higher flow rate could be achieved. This issue will be discussed more in detail in the next section.

4.4. Effect of DRA on the flow capacity

In order to investigate the potential of DRAs in increasing the capacity of the flow in the microtube, some of the experiments have been conducted at a constant pressure drop, and then the amount of the increased capacity was studied by comparing the resulted data. This phenomenon could be easily confirmed by the investigation of the projected velocity of the flow. The addition of DRA to the flow shows an increased projection velocity which demonstrates the ability of the polymer to increase the capacity of the fluid at a constant pressure drop.

Figure 12 graphically shows that the maximum obtainable flow rate of pure water is 2.29 mL/s with a 264.3 kpa pressure drop, and the experimental apparatus could not provide a higher flow rate. However, the addition of the drag reducing polymers to the working fluid changes the capacity of the system and allows more fluid to be cycled with the same energy consumption by the pump. According to the obtained results by the experiments, the addition of 20 ppm of PAA to the fluid increases the capacity of the system up to 2.8 mL/s with a 221.8 kpa pressure drop. The comparison of the obtained results shows about 36 % increase in capacity at a 221.8 kpa constant pressure drop. A similar effect would occur for all other concentrations of PAAs and CMC.

Since the addition of the polymers theoretically leads to damping the turbulence bursts and to thickening the laminar sub-layer of the flow, or a partial laminarization of the flow, the mean velocity of the fluid may be increased. The resulted velocity profile tends to show a convex form rather than a plug shape of the turbulent regime, as reported in previous studies in the literatures [42].

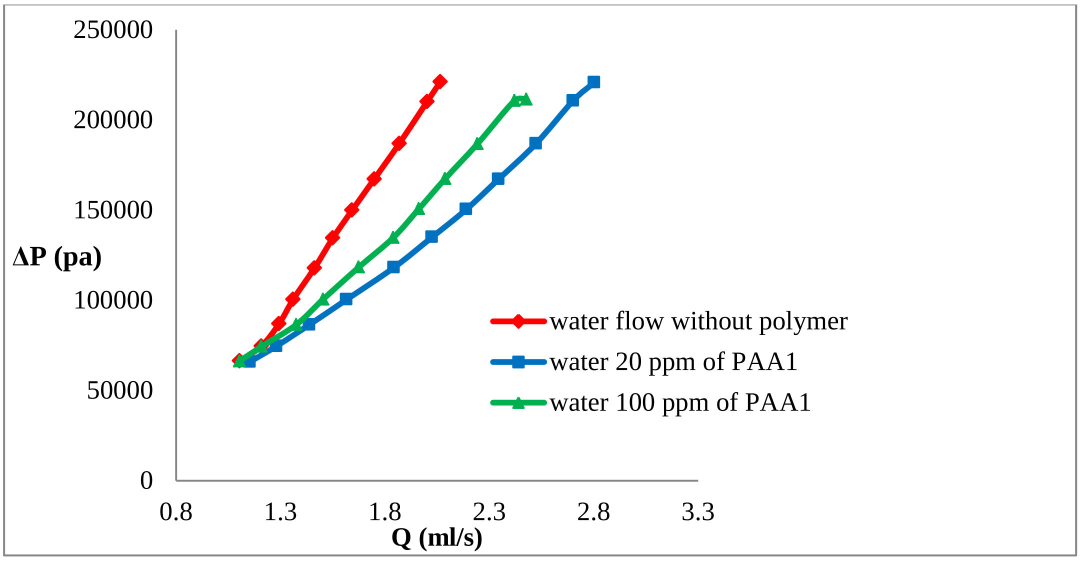


Figure 12. The variation of the pressure drop with the flow rate for water, 20 ppm and 100 ppm of PAA1.

Subsequently, the addition of DRA to the fluid allows the pump to direct more energy to transport the fluid rather than damping the random motion of vortices. Therefore, this effect increases the capacity of the microtube without passing the maximum allowable operating pressure.

5. Conclusions

In the present study, the drag reduction effect was investigated by the injection of small concentrations of three polymeric solutions to the flowing water in a microtube. This study has been conducted experimentally by considering the effect of the concentration of the different polymers on the turbulent flow. The maximum obtained drag reduction percentage is approximately 33 %, obtained for 20 ppm of PAA. The obtained results show that by increasing the concentration of PAA and CMC, the DR % had an ascending trend first, and then it would decrease. This increase followed by the decrease may be due to competitions between the ability of polymers as drag reducers and viscose effects at higher concentrations due to imposed stresses by the polymers. The effect of the concentration of the DRAs and the Re number of the flow on the DR % is parallel with the observed results developed for conventional pipes which are precisely addressed by the researchers [3, 4, 14, 15].

Another valuable result of this study is increasing the capacity of the system up to 36 %. This improvement means that by the addition of DRA to the flow, the capacity would be increased at constant pressure drops. This is a valuable result, especially in the case of microchannels, where the higher flow rates may be appreciated while the maximum allowable operating pressure is a disadvantage.

Nomenclature

CMC	carboxymethyl cellulose.
d	diameter of microtube [m].
DRA	drag reduction agent.
DR %	drag reduction percent.
f	fanning friction factor.
f_{DRA}	fanning friction factor in the presence of DRA.

$f_{No\text{-}DRA}$	fanning friction factor without DRA.
k	consistency index in the power law fluids [kg/(m.s^{2-n})].
L	distance between the two points measuring pressure [m].
MDR	maximum drag reduction.
n	flow behaviour index in the power law.
PAA	polyacrylamide.
P–K	Prandtl–Karman equation.
Q	flow rate [m^3/s].
Re	Reynolds number.
V	average bulk velocity [m/s].
ΔP	pressure drop [pa].
μ	viscosity of the fluid [pa.s].
$\dot{\gamma}$	shear rate [1/s].
ρ	density of water [kg/ m^3].
τ	shear stress [pa].

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