An experimental study on friction reducing polymers in turbulent pipe flow

Ozmen, Yucel; Boersma, Bendiks Jan

DOI
10.1016/j.oceaneng.2023.114039

Publication date
2023

Document Version
Final published version

Published in
Ocean Engineering

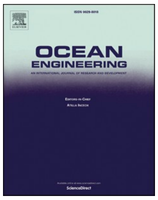
Citation (APA)
Ozmen, Y., & Boersma, B. J. (2023). An experimental study on friction reducing polymers in turbulent pipe flow. *Ocean Engineering*, *274*, Article 114039. https://doi.org/10.1016/j.oceaneng.2023.114039

Ocean Engineering 274 (2023) 114039

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



An experimental study on friction reducing polymers in turbulent pipe flow

Yucel Ozmen [a,*], Bendiks Jan Boersma [b]

[a] Department of Mechanical Engineering, Karadeniz Technical University, Trabzon, 61080, Turkey
[b] Laboratory for Energy Technology, Mechanical Engineering Faculty, Delft University of Technology, 2628 CD, Delft, the Netherlands

ABSTRACT

An experimental study was conducted to search the reduction of friction in fully developed turbulent pipe flow using different types of polyacrylamides as friction reducing polymers. Pressure drop measurements determined the friction reduction. Three different polymer types Superfloc A110, Superfloc A130 and Superfloc A150 were used to examine the effect of polymer concentration, Reynolds number and polymer type on friction reduction. The Darcy friction factor was obtained for each polymer type at the polymer concentration ranging from 0 to 500 wppm and a Reynolds number range of 10000-80000.

It was observed that friction factor decreased with increment in polymer concentration and Reynolds number for each polymer. Higher molecular weight polymers are more effective at reducing friction. With increasing concentration of polymer, the measured data approaches the Virk asymptote, which represents the maximum friction reduction limit by the polymers. The percentage of friction reduction increased with increasing concentration of polymer up to 100 wppm for each polymer type and then began to decrease for polymer concentrations higher than 100 wppm. An empirical formula was obtained to calculate the Darcy friction factor as a function of Reynolds number and polymer concentration for Superfloc A110.

1. Introduction

Dissolving a small amount of high molecular weight polymer in a liquid can greatly reduce frictional drag in turbulent pipe or duct flows. This event is known as friction reduction and was first reported by Toms in 1948 (Toms, 1948). Since then, interest in friction reduction has increased due to its widespread use in industry. Polymer additives benefit a variety of applications including very long-distance transportation of liquids, firefighting operations, domestic plumbing, irrigation systems and underwater objects. In order to better understand the observed effect, many experimental and numerical studies have been carried out on the decrease in resistance caused by the polymer in turbulent flow. The first experimental studies on this subject were made by Toms (1948) and Virk (1975). Virk showed significant differences for polymers in laminar and turbulent flows. While no decrease in friction was observed in laminar flows, a significant decrease in was obtained in turbulent flow. He was the first to demonstrate the existence of a maximum friction reduction limit independent of pipe diameter and polymer type in a turbulent pipe flow, this limit is known as the Virk asymptote. Numerous studies reveal that the potential of polymers to reduce friction in a turbulent flow is strongly affected by the molecular weight of the polymer, the polymer type, the polymer concentration, the polymer degradation, the preparation type of the solutions, the solvent properties, the solution temperature, the turbulent intensity, Reynolds number, geometry of flow, roughness and size of the pipe and the types of pumps used (Den Toonder et al., 1995). After the first observations on the friction reducing polymers, various studies have been carried out in this area. Achia and Thompson (1977) and Oldaker and Tiederman (1977) worked the effect of polymer additives on turbulent structures near the wall in pipe flow and noted that the addition of the polymers suppressed the formation of streaks. Harder and Tiederman (1991) stated that the addition of polymer produced a reduction in Reynolds shear stress and the polymer effect only appeared at high polymer concentrations. Sasaki (1991) revealed that the increase in flexibility in additives negatively affects the decrease in resistance. Japper-Jaafar et al. (2009) studied the effects of Reynolds number and concentration on resistance reduction in a large-scale circular pipe flow. They reported that as the solution concentration increased, the friction reduction efficiency increased and was slightly dependent on the Reynolds number. Costalonga et al. (2018) conducted an experimental study to provide a direct quantitative comparison of friction reducing polymers between tubes and annular channels. They found that reducing friction is a function of dimensionless time. Zhang et al. (2018) stated that both the viscosity and flexibility of the polymeric fluid affect the friction reduction. Matras and Kopiczak (2016) investigated the friction reduction effectiveness of adding both high molecular weight polymer and surfactants to the solvent. They stated that the addition of high molecular weight polymers and surfactants reduces friction in turbulent flow. Ptasinski et al. (2001) showed that an increase in viscosity can increase the thickness of the buffer zone, resulting in an increase in flow rate.

---

* Corresponding author.
E-mail addresses: yozmen@ktu.edu.tr (Y. Ozmen), B.J.Boersma@tudelft.nl (B.J. Boersma).

https://doi.org/10.1016/j.oceaneng.2023.114039
Received 19 May 2022; Received in revised form 13 January 2023; Accepted 20 February 2023

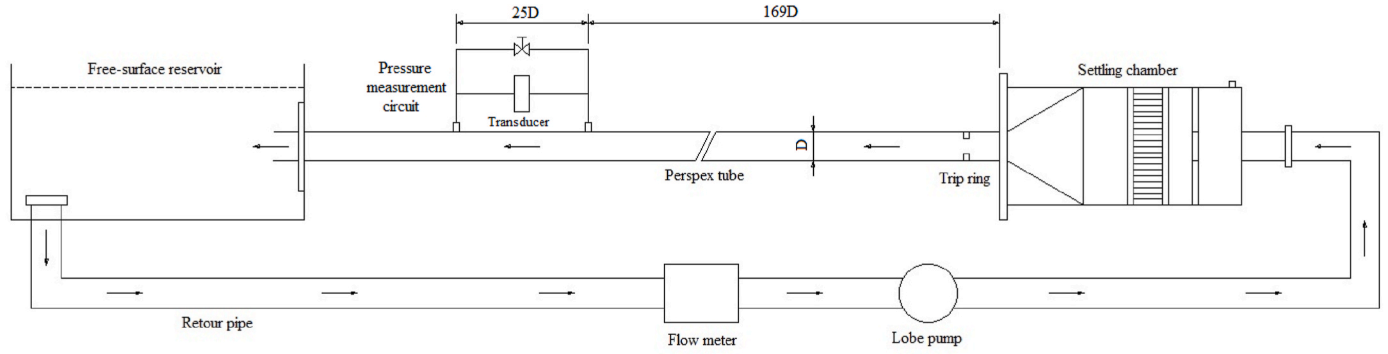


Fig. 1. Schematic diagram of the pipe flow facility.

Table 1a
Carreau parameters for five polymer solutions of Superfloc A110 **at T = 20 °C.**

solution	100 wppm	200 wppm	300 wppm	400 wppm	500 wppm
Temp. (°C)	20.0	20.0	20.0	20.0	20.0
η_o (mPas)	0,00225	0,004031	0,006922	0,009829	0,01150
η_∞ (mPas)	0,001012	0,001012	0,001012	0,001012	0,001012
n	0,9	0,845	0791	0,76	0,78
λ (s)	0,4335	0,4585	0,4035	0,5185	0,4785

Table 1b
Carreau parameters for five polymer solutions of Superfloc A130 **at T = 20 °C.**

solution	100 wppm	200 wppm	300 wppm	400 wppm	500 wppm
Temp. (°C)	20.0	20.0	20.0	20.0	20.0
η_o (mPas)	0,002054	0,003713	0,00513	0,007015	0,009948
η_∞ (mPas)	0,001012	0,001012	0,001012	0,001012	0,001012
n	0,9	0,845	0,81	0,768	0785
λ (s)	0,4785	0,4985	0,4985	0,4785	0,4785

Table 1c
Carreau parameters for five polymer solutions of Superfloc A150 **at T = 20 °C.**

solution	100 wppm	200 wppm	300 wppm	400 wppm	500 wppm
Temp. (°C)	20.0	20.0	20.0	20.0	20.0
η_o (mPas)	0,001876	0,00349	0,004767	0,007606	0,01125
η_∞ (mPas)	0,001012	0,001012	0,001012	0,001012	0,001012
n	0,93	0,82	0,82	0,74	0,73
λ (s)	0,3785	0,4585	0,4585	0,4585	0,4585

Petrie et al. (2003), in their study examining the effect of surface roughness on the friction reduction provided by the addition of polymer in the boundary layer on a flat plate, stated that the friction reduction is greater on rough surfaces. A review article on friction reduction of polymer solutions in turbulent flow was compiled by Graham (2004). Somandepalli et al. (2005) investigated the downstream occurrence of friction reduction in a turbulent boundary layer. The polymer entrainment reduction of a turbulent pipe flow under the effect of Coriolis force has been experimentally studied by Omrani et al. (2012). The results showed that the friction factor increased monotonically but gradually increased with rotation. Friction reduction increased with concentration, but was unaffected by rotation. Vural et al. (Zeybek Vural et al., 2014) investigated effects of polymers in reducing friction in turbulent pipe flow. They noted that the velocity fluctuations near the wall were affected from the presence of the polymer. Rowin et al. (2021) developed a novel coating that bonds drag-reducing polymers to metallic surfaces. They observed maximum drag reduction of 19% in a turbulent channel flow. One of the most critical problems in friction reduction applications with polymer addition is degradation of polymers. This effect is due to the high shear stresses in turbulent flow and can lead to a significant loss of the ability of the polymers to reduce friction. A study examining the parameters affecting polymer degradation was carried out by Den Toonder et al. (Den Toonder et al., 1995). They stated that the type of pump used in the system has a great effect on the degradation of the polymer and that a disc pump should be preferred in order to prevent degradation in pumping the polymer solution. A brief review of the mechanical degradation of linear polymers in turbulent flows is presented by Soares (2020). In parallel with experimental research, some studies (Ptasinski et al., 2003; Robert et al., 2010; Resendea et al., 2018) are based on the computational solution of viscoelastic equations, especially the FENE-P model. Direct numerical simulations (DNS) are suitable for evaluating different models and analyzing friction reduction mechanisms of polymers. However, the high computational costs make the simulations undesirable for high Reynolds numbers. Therefore, approaches such as Large Eddy Simulation (LES) and Reynolds Mean Navier-Stokes (RANS) are evaluated in solving these problems.

Despite numerous experimental, theoretical and numerical studies in this field for more than half a century, due to the complexity in physics, no result has emerged that fully explains this phenomenon. Some detailed experimental studies are needed to explain the actual physical mechanics of friction reducing polymers. Most of the experimental work on friction reducing polymers has been performed at low Reynolds numbers. But industrial applications are at high Reynolds numbers. Therefore, this study aims to examine friction reducing polymers in a wide Reynolds number range. The present study investigates the effects of polymer type (molecular weight), Reynolds number and concentration of polymer on friction reduction by pressure difference measurements of a turbulent pipe flow.

2. Characteristics of turbulent pipe flow

For fully developed turbulent flow in a horizontal pipe of diameter D, the relationship between wall shear stress, τ_w and axial pressure drop, ΔP is given by

$$\tau_w = \frac{D}{4}\frac{\Delta P}{\Delta x} \tag{1}$$

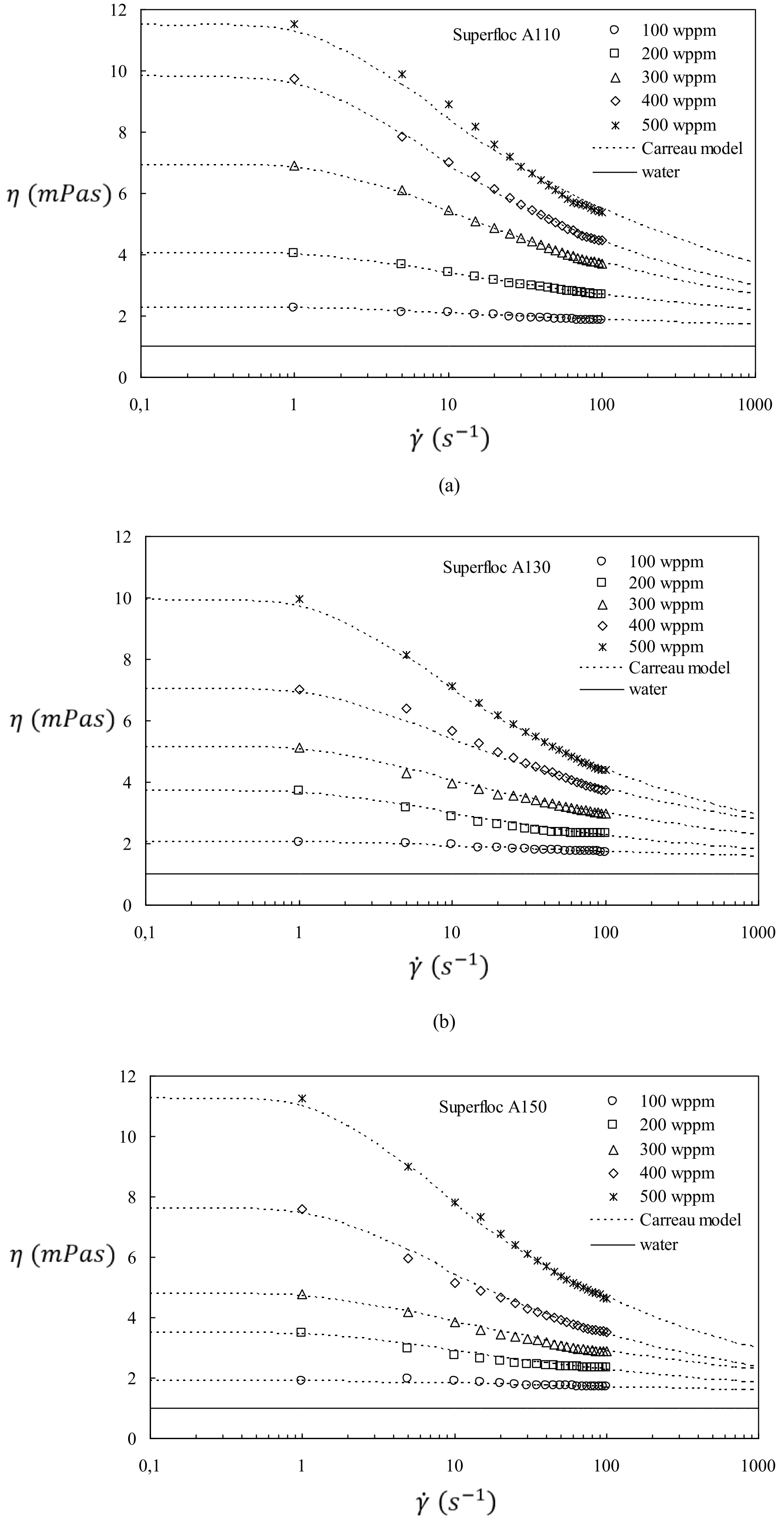
where $\Delta P/\Delta x$ is the pressure gradient. The shear stress at the wall is scaled with the mean kinetic energy of flow per unit volume to express non dimensional Fanning friction factor f. This factor is given by

$$f = \frac{\tau_w}{\frac{1}{2}\rho U_b^2} \tag{2}$$

The Darcy friction factor is four times the Fanning friction factor,

$$f_{Darcy} = 4\, f_{Fanning} \tag{3}$$

The Reynolds number is given as follows, defined by the bulk mean velocity in the pipe and the diameter of pipe.



(a)

(b)

(c)

Fig. 2. Viscosity as a function of shear rate at different concentration. (a) Superfloc A110 (b) Superfloc A130 (c) Superfloc A150.

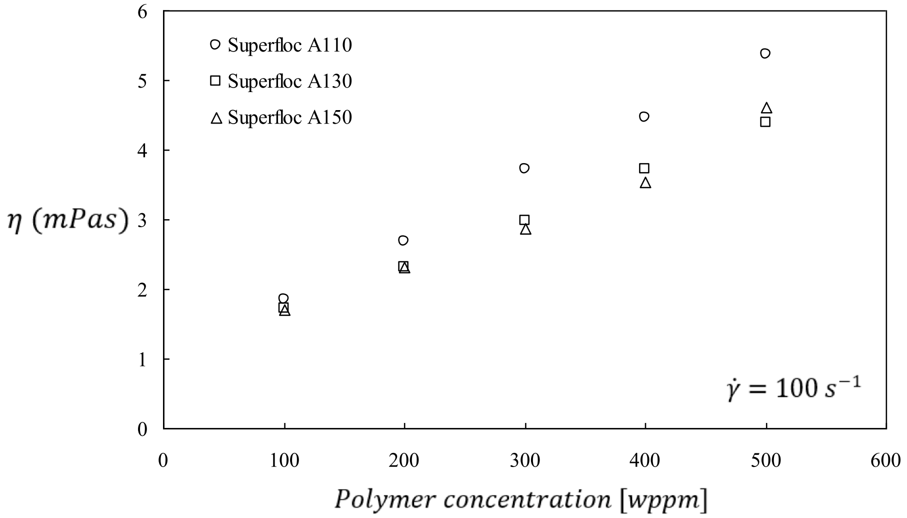


Fig. 3. The effect of polymer type on the viscosity at different concentration.

$$Re = \frac{\rho U_b D}{\eta} \tag{4}$$

where η is constant viscosity of the fluid (Ptasinski et al., 2001).

For turbulent flow in smooth and rough pipes, some comparable empirical equations have been established in the literature. A common formula which is known as Colebrook relation valid over the Reynolds number range of $4000 < Re \leq 10^8$ and is given below:

$$\frac{1}{\sqrt{f_{Darcy}}} = -2\log\left(\frac{\varepsilon}{3,7D} + \frac{2,51}{Re\sqrt{f_{Darcy}}}\right) : \text{Colebrook equation} \tag{5}$$

The effect of the friction reduction increases with increment in polymer concentration and reaches the asymptotic value. Adding additional polymer has no effect on this value. Virk (1975) obtained the following equation in which the friction reduction is not affected by the properties of the polymer.

$$\frac{1}{\sqrt{f_{Fanning}}} = 19.0\log\left(Re\sqrt{f_{Fanning}}\right) - 32,4 \text{ or } f_{Fanning} = 0,58Re^{-0,58} \tag{6}$$

The amount of friction reduction is determined by the difference in pressure drop between solvent and polymer solution at the same Reynolds number.

$$DR\% = \frac{\Delta P_N - \Delta P_P}{\Delta P_N} \bullet 100\% = \frac{f_N - f_P}{f_N} \bullet 100\% \tag{7}$$

'N' and 'P' are used for the Newtonian and the polymeric fluid respectively.

3. Experimental setup

3.1. Flow facility

The experiments were carried out at the circulatory pipe flow facility of the Aero and Hydrodynamics Laboratory at TU Delft, a schematic diagram of which is shown in Fig. 1. Important components of the pipe system are the settling chamber, measurement pipe, pressure measurement circuit, the flow meter, the pump, the reservoir and the return pipe. The measuring pipe consists of a horizontal pipe with a length of 9 m and an inside diameter of 40 mm. The pipe is made of transparent plexiglass and has a circular cross section. A lobe pump, Nakakin Sanitary Rotary Pump (RM-series) was used to pump the working fluid through the system. This pump type is preferred because it reduces the amount of mechanical degradation (Ptasinski et al., 2001). After the pump, the flow passes through a flow corrector and a settling chamber. The settling chamber is designed to provide a smooth and uniform flow in the pipe. In this study, a fully developed turbulent flow was required, the flow was forced into turbulence through a trip ring just after the entrance of the pipe. This trip ring provides a sudden contraction of the pipe diameter and causing a large disturbance and a direct transition to turbulence. The total system volume is approximately 95 L. The pressure drop over the turbulent pipe was measured at a distance of 1 m between 169D and 194D from the settling chamber. A membrane differential pressure transducer was used (Validyne, Model DP 15–20) for pressure measurements. A pressure measurement circuit was formed to measure the stable values of pressure drops. The pressure transducer was connected to the pressure holes having a diameter of 1 mm over the pipe through two small hoses with a valve in between which made possible to prevent overloading the membrane. The working principle of the sensor is based on the deflection of a thin stainless steel membrane as a result of the pressure difference at both side of the membrane. The pressure transducer was used with a Validyne carrier demodulator (Model CD15), which produces a ±10 V DC analog output proportional to the full scale pressure range. The pressure range of the transducer is 0–860 Pa (0–88 mmWC). For the calibration of the pressure transducer, a Betz micro-manometer was utilized with air as medium. A linear relationship between the pressure and output voltage was found with a negligible hysteresis. Pressure drop measurements were taken by using LabVIEW. The pressure data was very noisy and therefore a low pass filter (Kronh-Hite, Model 3202 R) was used at 20 Hz. It was observed that when the signals from the pressure transducer were integrated for a period of 30 s, the signals became stable and the measurement time of 30 s was sufficient to accurately determine the pressure drop and friction factor.

For the measurement of the flow rate an ultrasonic flow meter (Kronhe UFM 500 and a signal converter UFC 500 K) was used where the signal converter was mounted on the primary head. The relative measurement error of the pressure drop measurements was 0.5% and the maximal error in the flow rate was 0.25%.

3.2. Polymer solution

The polymers types used in these study are Superfloc A110, Superfloc A130 and Superfloc A150 which are anionic polyacrylamide flocculants from Cytec Industries. Polyacrylamides are high molecular weight polymers. The molecular weights of these polymers are $6 - 8 \times$

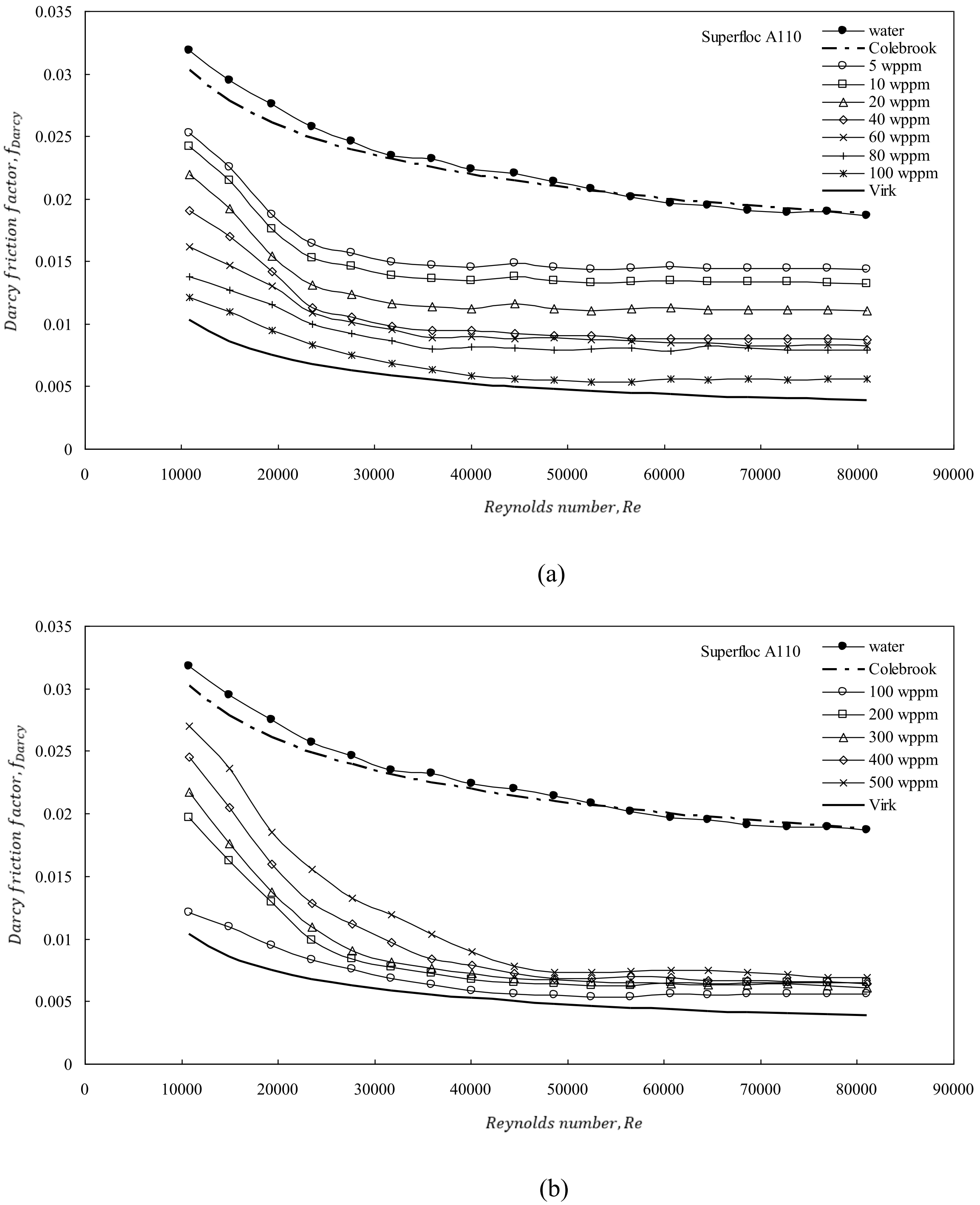
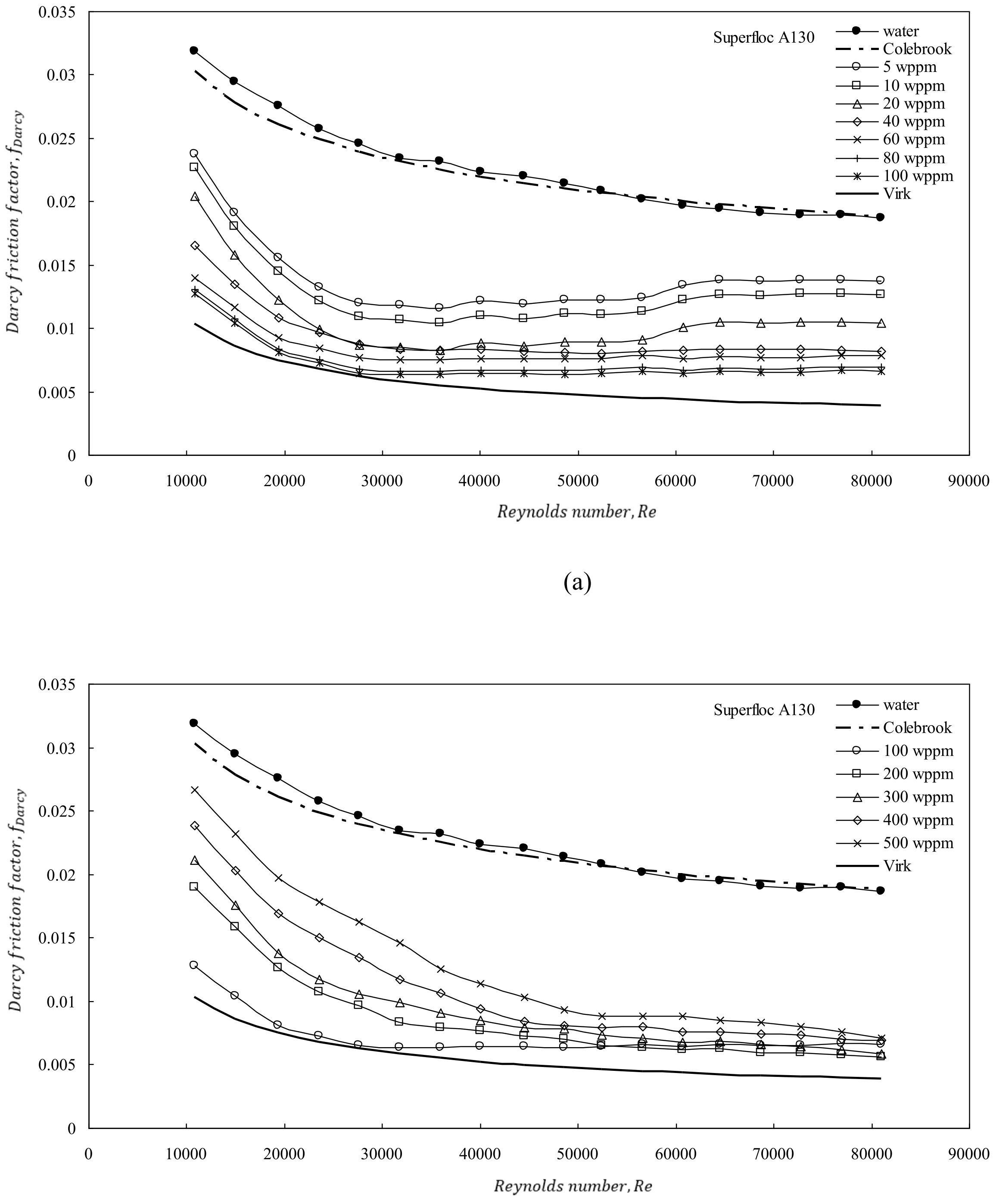


Fig. 4. Darcy friction factor versus Reynolds number at different concentrations of Superfloc A110 polymer.

10^6g/mol, $10 - 15 \times 10^6$g/mol and $12 - 15 \times 10^6$g/mol respectively. The most important advantage of these polymers is that they are highly resistant to mechanical degradation (Den Toonder et al., 1995). These polymers are added to the water according to the procedure described below. Before the actual experiments the solutions are prepared by first creating a solution with a relatively high fixed concentrations of Superfloc A110-150 in water.

First a 10000 wppm master solutions were obtained in a mixing vessel for three different types of polymer as follows. A 5 L container filled with tap water. 50 g of dry powder polymer was dissolved in the water for each polymer type. This process is done by the slow addition of polymers to water in a container that is mixed in a continuous rotation. After mixing for about 10 h, the mixture is left alone for about a day to let small air bubbles to move away from the container. At the end of this process, the resulting solution was found to be quite clear. Afterwards, the master solution was added to the free-surface reservoir and was simultaneously diluted with fresh water until the desired concentration was achieved. Slowly mixing by a mixer in the reservoir with free surface and pumping of the solution at a low flow rate through the entire setup is continued until the solution becomes homogeneous. After this the solution is ready for the measurements. These 10000 wppm



(a)

(b)

Fig. 5. Darcy friction factor versus Reynolds number at different concentrations of Superfloc A130 polymer.

solutions thus prepared were used in the pipe system for a period of 1–2 weeks. Different volumetric amounts of the master solution are diluted in 95 L of water in the experimental setup to obtain the polymer concentrations to be examined within the scope of the study.

3.3. Rheological characterization of polymers

In the experiments, three polymer types were used as Superfloc A110, Superfloc A130 and Superfloc A150 with the range of 0–500 wppm polymer concentration. For each of these polymer types with different concentrations, some fluid parameters were determined by means of rheometric measurements. The viscosity η was measured as function of the shear rate $\dot{\gamma}$ in a viscometer. The relation between the shear rate and viscosity is given with Carreau model (Bird et al., 1987):

$$\eta(\dot{\gamma}) = \eta_{\infty} + (\eta_0 - \eta_{\infty})\left[1 + (\lambda\dot{\gamma})^2\right]^{(n-1)/2} \tag{8}$$

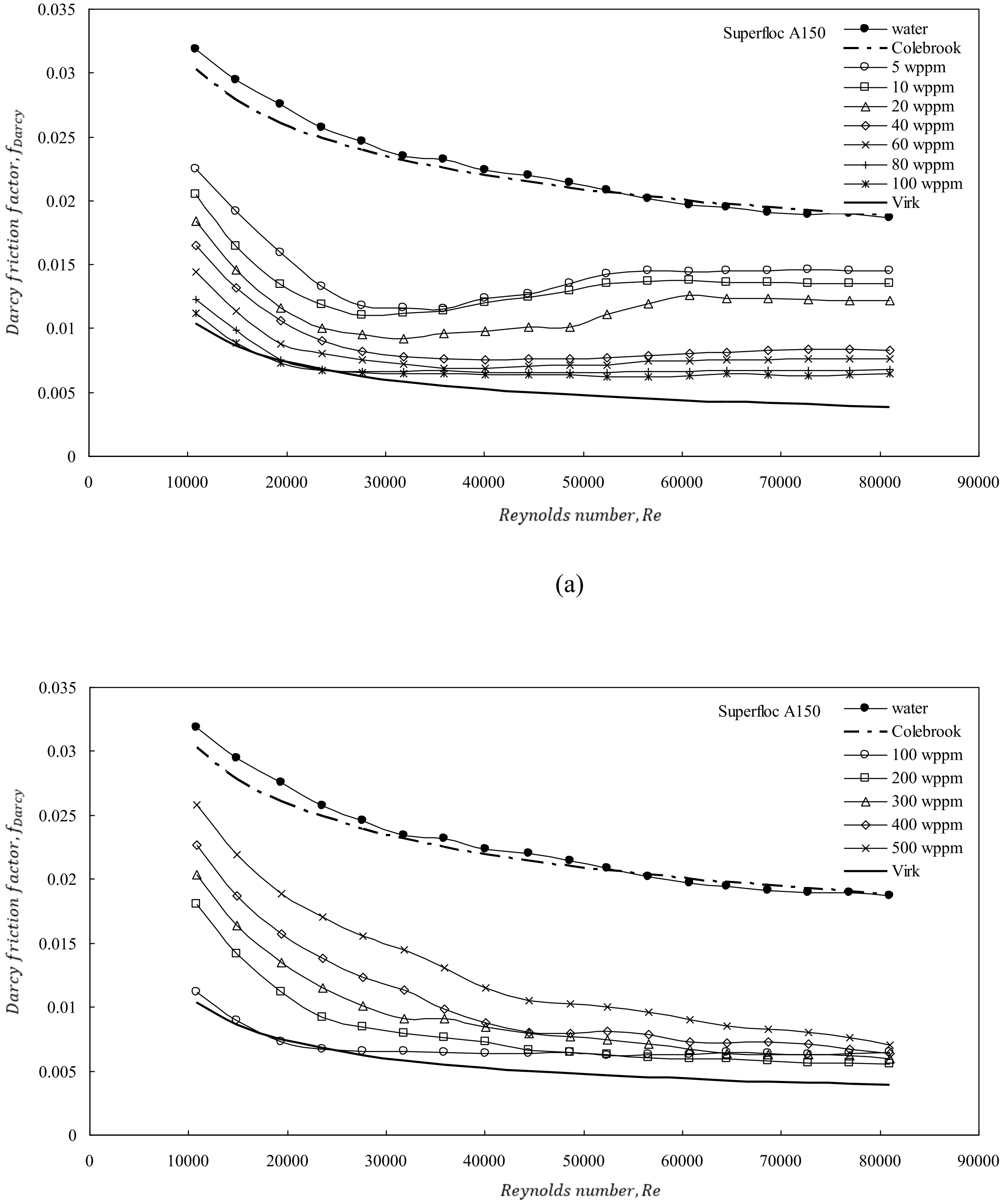
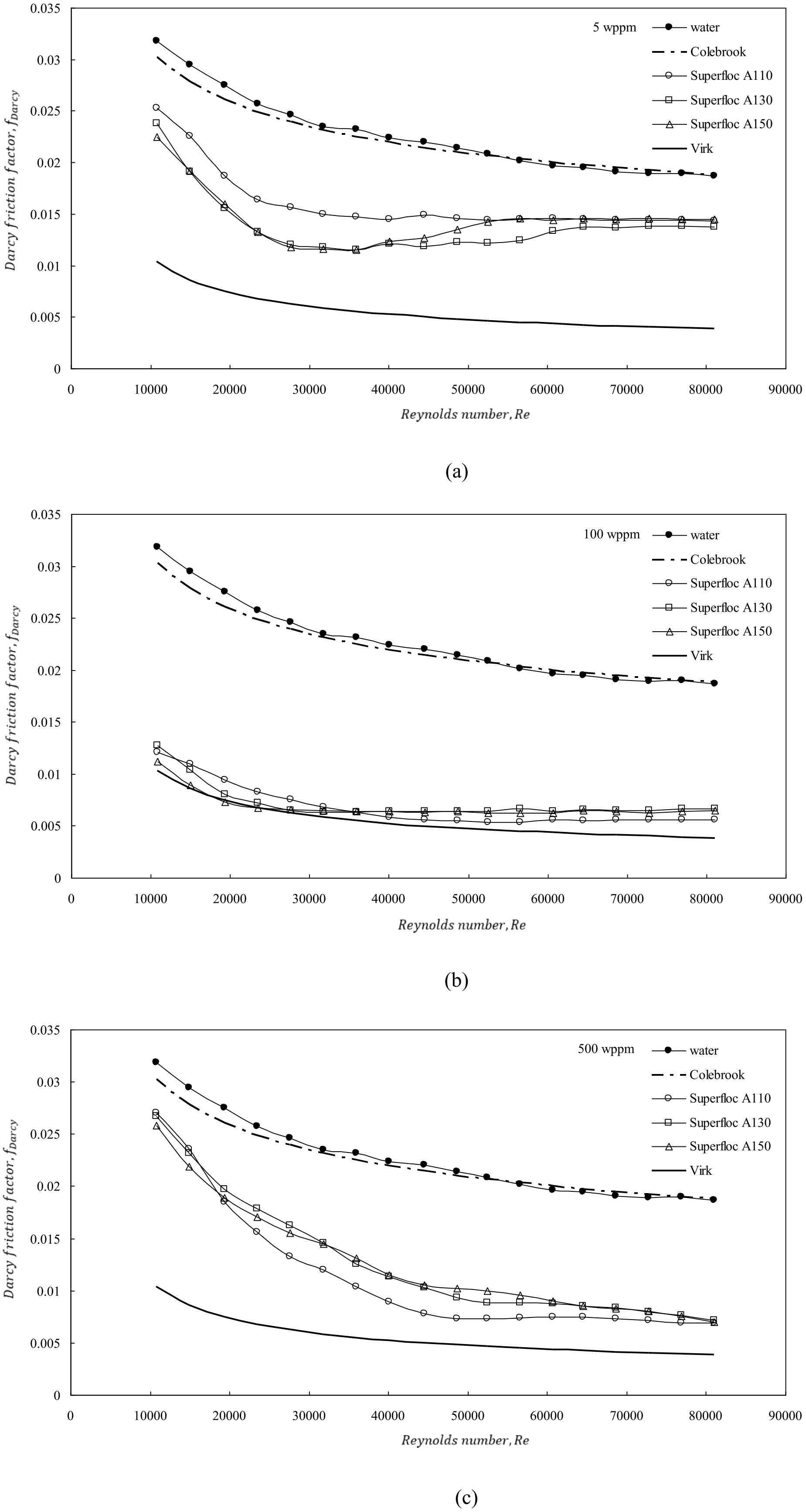


Fig. 6. Darcy friction factor versus Reynolds number at different concentrations of Superfloc A150 polymer.

where η_0 is the zero shear viscosity, η_∞ is the infinite shear viscosity, λ is a time constant and n is the power law index. The viscosity of the solvent is used as the infinite shear viscosity. Viscosity changes are plotted with the Carreau model for all polymer types studied. The Carreau parameters for three polymer types are given in Table 1a–c and viscosity curves are presented in Fig. 2a–c. As it is not possible to reach very high shear rates in the viscometer, it is assumed in the fitting procedure that $\eta_\infty = \eta_{solvent} = \eta_{water}$. It is clear from the figures that all polymer solutions show significant shear thinning behavior and that the effect becomes stronger with increasing concentration. Viscosity measurements of Ptasinski et al. (2001) for Superloc A110 polymer type agree well with the results of this study. Fig. 3 illustrates the effect of different concentrations of polymer type on viscosity for a shear rate of 100. It is seen that the viscosity increases with increment in polymer concentration for each polymer type. The elongation of polymer molecules causes an increase in viscosity. The increase in viscosity of Superfloc A110 polymer

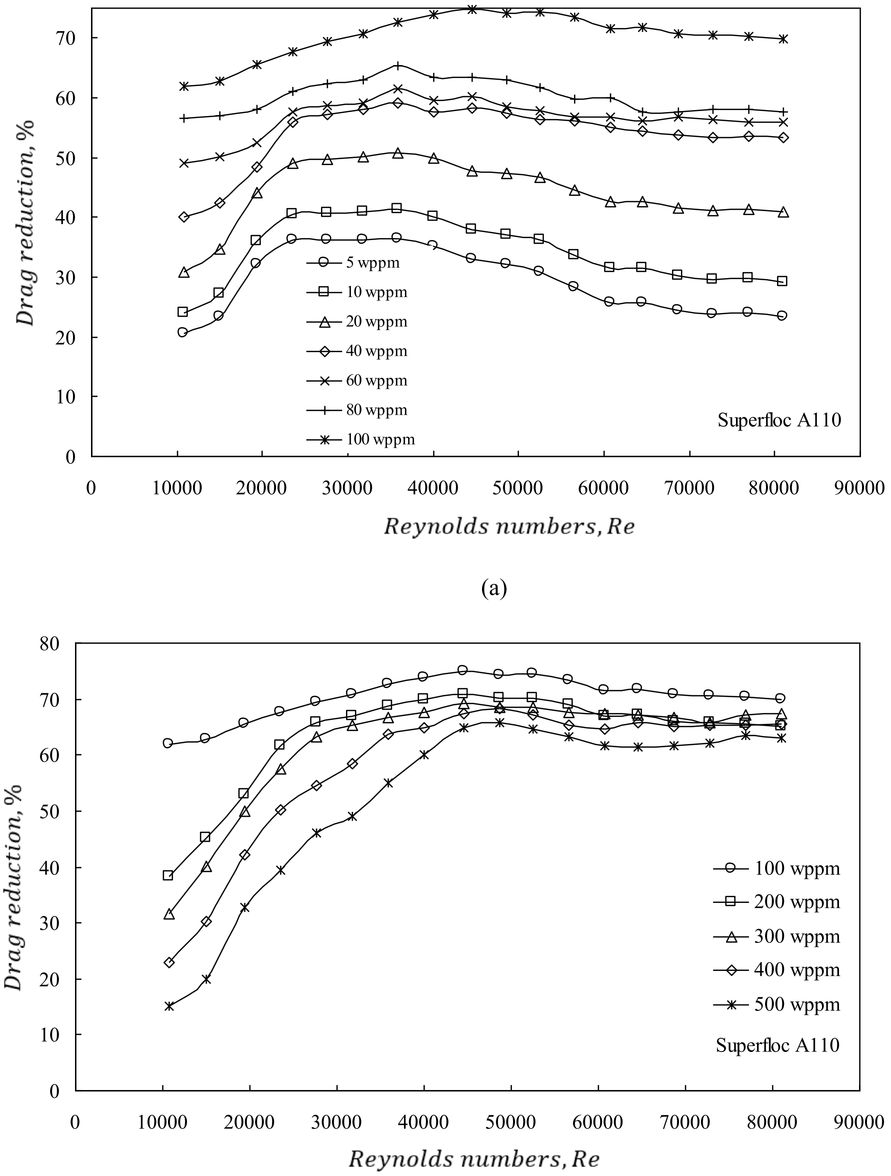


(a)

(b)

(c)

Fig. 7. Darcy friction factor versus Reynolds number at different polymer types. (a) 5 wppm (b) 100 wppm (c) 500 wppm.



(a)

(b)

Fig. 8. Drag reduction versus Reynolds number at various concentrations of Superfloc A110 polymer.

is higher than for the other two polymer types because of the difference among the molecular weights of polymer types.

4. Results and discussion

In the measurements, friction reduction was obtained with pressure drop acquired in turbulent pipe flow. To ensure that the pressure taps are in the fully developed flow zone, the entry length, l_e (Zeybek Vural et al., 2014), was checked with the following empirical relation,

$$\frac{l_e}{D} = 4.4(\mathrm{Re})^{1/6} \tag{9}$$

For the highest bulk Re of approximately 80000, l_e becomes 29D (D = 40 mm). The distance from the entry section of the first pressure tap (169D) is much larger than entry length (29D) and pressure drop measurements are thus taken in fully developed turbulent flow region. Polymer solutions were checked to see whether the polymer chains are destroyed by the pump during measurements. It was observed that shear thinning behaviors of polymer solutions remained the same for several days after being used in the flow facility. Therefore it was concluded that this pump does not destroy the polymer chains and the polymers are not degraded. Pressure drop measurements were conducted for three polymer types as Superfloc A110, Superfloc A130 and Superfloc A150 at the range of 0–500 wppm polymer concentration and at the range of 10000–80000 Reynolds numbers. Experimental results were presented as plot of f_{Darcy} against Re_D. Figs. 4–6 show the effect of polymer concentrations with the plots of the Darcy friction factors versus Reynolds numbers for Superfloc A110, Superfloc A130 and Superfloc A150 respectively. The results were compared with friction factor obtained from Colebrook equation for water. Good agreement was found between the experimental data of this study and Colebrook relation when the solvent was pure for each polymer type. Virk asymptote also was given in the figures to show effect of polymer concentration ratio on friction factor. Plots of Reynolds number versus Darcy friction factor at different polymer concentrations rates occurred in a region bounded between an

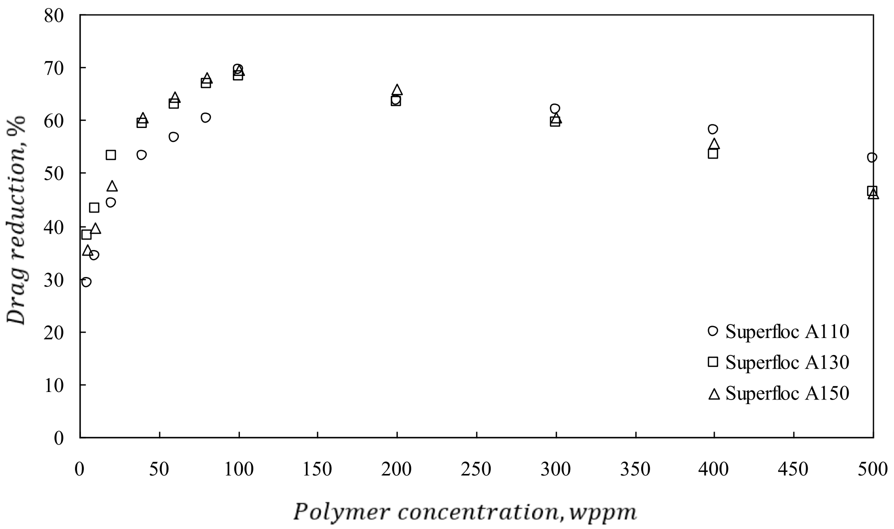


Fig. 9. The effect of polymer type on the friction reduction at different concentrations.

Table 2
Values of coefficients for proposed empirical formula.

a_1	- 4.279
a_2	- 0.014
a_3	5.110×10^{-5}
a_4	-5.361×10^{-8}
a_5	7660.989
a_6	48.317
a_7	- 0.047
Correlation coefficient	0.89

upper limit defined by the Colebrook equation and maximum friction reduction curve for each polymer type. Fig. 4a and b shows the effect of polymer concentration ratio on the friction factor with different Reynolds number for Superfloc A110. It was observed that the friction factor decreased with increment in concentration of polymer and with increasing Reynolds number. This event was explained by the elastic-sublayer model theory. The sublayer started to grow with increasing concentration of additive (Virk, 1975). After the addition of polymer, the Darcy friction factor decreased with increasing concentration of polymer, friction factor data points approach the Virk asymptote. For the polymer concentration of 100 wppm, the friction factor reaches to the Virk asymptote (Fig. 4a). For the polymer concentration higher than 100 wppm, the friction factor start to increase with increasing concentration of polymer by moving away from Virk asymptote (Fig. 4b). Higher concentration of polymer than 100 wppm started to affect solvent properties. Breaking-up of long-chain polymers changed the rheological properties of polymers and its friction reduction capacity. Ptasinski et al. (2001) noted that friction reduction reached a limit and a further increment in the polymer concentration did not change the friction factor for the Superfloc A110. This study showed that further increment in polymer concentration caused a friction increase. The Darcy friction factor decreased rapidly with increasing concentration of polymer to a saturation value (100 wppm), and then slowly increases with further increases in concentration. The saturation limits on friction reduction was reached when the effect of polymer was observed in the entire cross section of the pipe (Katerpallir and White, 2000). The maximum resistance reduction occurred when the Reynolds shear stresses were mostly damped, and fluctuating polymer stresses were the main mechanisms that perpetuated the turbulence (Min et al., 2003). While the friction factor was decreasing with increasing Reynolds number up to its moderate values, Reynolds number did not have any effect on friction factor for higher then its moderate values. At each polymer concentration, as the Reynolds number increases, the friction factor decreases and finally becomes constant with respect to the Reynolds number. The decreasing behaviors of friction factor for Superfloc A130 and Superfloc A150 polymers were almost the same with Superfloc A110 (Figs. 5 and 6). The effect of polymer concentration ratio on friction reduction also appeared as a lower friction factor at any Reynolds number for Superfloc A130 and Superfloc A150 polymers. Fig. 7a–c shows the effect of polymer type on the Darcy friction factor at the three different polymer concentration as 5 wppm, 100 wppm and 500 wppm, respectively. The molecular weights of studied polymer types in this study were similar. The molecular weight of Superfloc A110 was a bit lower than the other polymer types. This small difference between the polymer types enabled us to examine the effect of molecular weight on the friction factor. Superfloc A130 and Superfloc A150 have the same molecular weight. This also gave the possibility to test the sameness of friction factors for them. Fig. 7a shows the effect of different Reynolds number and polymer type on the friction factor at a polymer concentration of 5 wppm. It was observed that there was a difference for friction factor between the Superfloc A110 and the Superfloc A130 & Superfloc A150. The friction factors of Superfloc A130 and Superfloc A150 were the same and lower than the friction factor of Superfloc A110 because of the difference between the molecular weights. Higher molecular weight polymers were found to be more effective at reducing friction. Fig. 7a shows that the friction factor decreases with increasing molecular weight of polymer, resulting in an increase in friction reduction. It is known from literature that one of the many parameters influencing friction factor is the molecular weight. Very high molecular weight flexible polymers with long linear chain structures are the best polymer friction reducers. Fig. 7b shows the friction factors of the three different polymer types near the Virk asymptote at the polymer concentration of 100 wppm. This concentration is called as optimum concentration for each polymer type. There was no clear difference among the friction factor distributions. The abilities of reaching to the maximum friction reduction asymptote were almost the same for three different polymer types. For the polymer concentration of 500 wppm, again, there is a friction factor difference between the Superfloc A110 and the others. Friction factors of Superfloc A130 and Superfloc A150 were the same and higher than the friction factor of Superfloc A110 (Fig. 7c).

Fig. 8a and b represent the effect of the Reynolds number and polymer concentration rates on friction reduction for Superfloc A110. From Fig. 8a, it was observed that the percent resistance reduction

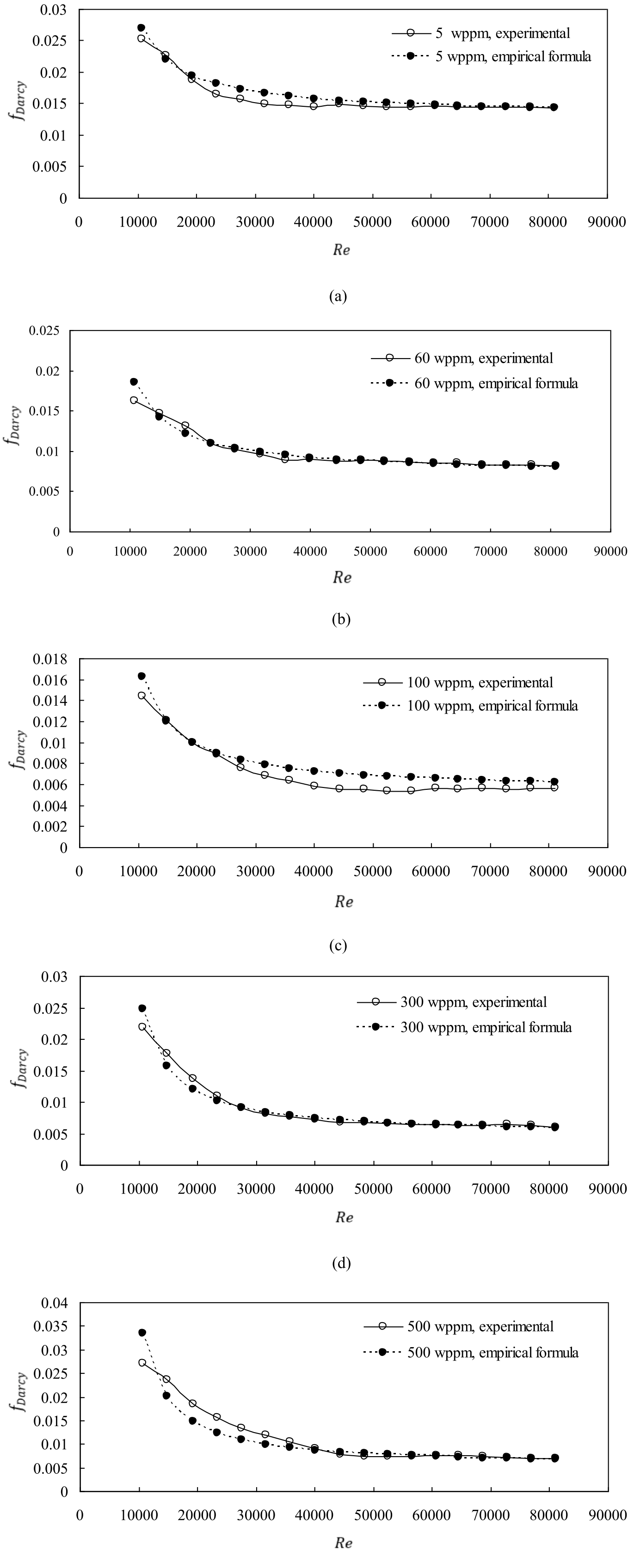


Fig. 10. Darcy friction factor versus Reynolds number at different concentrations of Superfloc A110 polymer. (a) 5 wppm (b) 60 wppm (c) 100 wppm (d) 300 wppm (e) 500 wppm.

increased with increment in polymer concentration. The percentage of friction reduction increased with increment in polymer concentration in the system until maximum friction reduction was achieved at 100 wppm polymer concentration. Maximum friction reduction occurs at higher Reynolds number with increment in polymer concentration. The reduction in friction provided by the addition of polymer is due to the viscosity of the polymer solution. The polymer stabilizes the turbulent boundary layer, resulting in less turbulent energy production and therefore less energy loss (Drappier et al., 2006). Increasing the concentration of the polymer solutions increased the amount of friction reduction, since the friction reduction was caused by the sum of the contributions of the individual polymer molecules (Kima et al., 2011). The longer polymer chain provided more chances for mixing and interaction with the flow. It was confirmed that the elongation of the polymer chain is critical for the reduction of friction. The most effective friction reducing polymers were essentially linear with maximum elongation for a given molecular weight. As the Reynolds number increased up to the middle values, the percentage of friction reduction also increased and then began to decrease slightly at higher Reynolds numbers than the middle Reynolds numbers. Similar findings were reported in the studies of (Kamel and Shah, 2009; Abubakar et al., 2014). Increasing the Reynolds number meant increasing the degree of turbulence in the pipe, which gave the friction reducer a better environment to be more effective. It was clear that higher polymer concentration gave greater resistance reduction and this became increasingly evident in highly turbulent flows. Friction reduction is related to the degree of turbulence controlled by the solution velocity (Anees Khadom and Abdul-Hadi, 2014). For higher than polymer concentration of 100 wppm, friction reduction percentage started to decrease with increasing concentration of polymer because the polymer started affecting solvent properties (Fig. 8b). This drop in friction reduction percentage due to increasing concentration of polymer was more pronounced up to moderate Reynolds number. Long chain polymer molecules started to be broken in the solution because of the occurred high shear stress in the turbulent flow. Although not shown, the effects of Reynolds number and polymer concentration on friction reduction for Superfloc A130 and Superfloc A150 polymers were almost identical to Superfloc A110. It was found that the percentage of friction reduction increased with increment in polymer concentration and solution Reynolds number for each polymer type. The highest maximum friction reduction percentage was obtained with 100 wppm Superfloc A-150 as 74%. Fig. 9 shows the effect of different concentrations of polymer types on friction reduction. It is observed from the figure that the friction reduction increases with increment in polymer concentration up to 100 wppm for each polymer type and then starts to decrease for polymer concentrations higher than 100 wppm. Similar findings are reported in the study of (Choi and Jhon, 1996). Friction reduction percentage of Superfloc A110 was a bit lower from the other two polymer types because of the difference between the molecular weights.

The results of this study show that the Darcy friction factor is affected by parameters such as Reynolds number and polymer concentration. By regarding the difficulties of measuring the pressure drop, an empirical formula was proposed to literature for Superfloc A110 which is the most used polymer type in polymer based studies. By applying non-linear multiple regression analysis to the experimental data of the Superfloc A110, the dependence of the Moody friction factor with polymer concentration and Reynolds number is fitted as follows,

$$f_{Darcy} = \exp\left(a_1 + a_2 C + a_3 C^2 + a_4 C^3 + \left(a_5 + a_6 C + a_7 C^2\right) / \mathrm{Re}\right) \tag{10}$$

where f_{Darcy} is Darcy friction factor, C is polymer concentration (wppm) and Re is Reynolds number. The values of constants a_1, a_2, a_3, a_4, a_5, a_6 and a_7 which give the best fitting of experimental data were given in Table 2. Correlation coefficient of the equation is obtained as 0.89. Fig. 10a–e shows the relationship between the observed values of the Darcy friction factor taken from the experimental data and the values estimated from the correlation for polymer concentrations of 5 wppm, 60 wppm, 100 wppm, 300 wppm and 500 wppm, respectively. The results of the correlations show good agreement between the observed and estimated Darcy friction factor values. It appears that this formula can be easily used over wide polymer concentration and Reynolds number ranges to estimate the Darcy friction factor with high accuracy. This equation can be generalized to other types of polymers.

5. Conclusions

Polymer friction reduction in fully developed turbulent pipe flow was investigated experimentally. The effect of the Reynolds number, polymer types and polymer concentration on the friction reduction were the variables of study. All polymer solutions used in this study showed significant shear thinning behavior and that their effects became stronger with increasing concentration. The Darcy friction factor decreased with increment in polymer concentration and with increasing Reynolds number for each polymer type. The friction factor decreased rapidly with increasing concentration of polymer to a saturation value at the polymer concentration of 100 wppm and then slowly increased with further increases in concentration. As the Reynolds number increased, the friction factor decreased and reached a constant level. Higher molecular weight polymers were found to be more effective at reducing friction. The friction reduction percentage increased with increasing concentration of polymer up to 100 wppm for each polymer type and then began to decrease for polymer concentrations higher than 100 wppm. Maximum resistance reduction occurs at higher Reynolds number with increasing concentrations of polymer. The highest maximum friction reduction percentage was obtained as 74% with 100 wppm of Superfloc A-150. An empirical formula was obtained for Superfloc A110 showing the relationship between Darcy friction factor, Reynolds number and polymer concentration. The formulas can be easily used over wide Reynolds number and polymer concentration ranges to estimate the friction factor with a high degree of accuracy.

Authorship statement

Y. Ozmen, Conception and design of study, acquisition of data, analysis and/or interpretation of data, drafting the manuscript, revising the manuscript critically for important intellectual content. B. J. Boersma: Analysis and/or interpretation of data, drafting the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgement

Authors of this paper would like to thank Scientific and Technological Research Council of Turkey for postdoctoral scholarship support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oceaneng.2023.114039.

Nomenclature

C	Polymer concentration ppm
D	Pipe diameter m
DR	Drag reduction
ε	Roughness mm
f_{Darcy}	Darcy friction factor
$f_{Fanning}$	Fanning friction factor
l_e	Entry length m
n	Dimensional power law index
N	Newtonian
P	Polymeric
ΔP	Pressure drop Pa
$\Delta P/\Delta x$	Constant pressure gradient
Re	Reynolds number
U_b	Bulk mean velocity m/s
ρ	Density of the fluid kg/m^3
τ_w	Wall shear stress Pa
η	Constant viscosity Pa·s
η_0	Zero-shear-rate viscosity Pa·s
η_∞	Infinite-shear-rate viscosity Pa·s
$\dot{\gamma}$	Shear rate
λ	Time constant

References

Abubakar, A., Al-Hashmi, A.R., Al-Wahaibi, T., Al-Wahaibi, Y., Al-Ajmi, A., Eshrati, M., 2014. Parameters of drag reducing polymers and drag reduction performance in single-phase water flow. Adv. Mech. Eng. 6, 202073.

Achia, B.U., Thompson, D.W., 1977. Structure of the turbulent boundary in drag-reducing flow. J. Fluid Mech. 81, 439–464.

Anees Khadom, A.A., Abdul-Hadi, A.A., 2014. Performance of polyacrylamide as drag reduction polymer of crude petroleum flow. Ain Shams Eng. J. 5 (3), 861–865.

Bird, R.B., Armstrong, R.C., Hassager, O., 1987. Dynamics of Polymer Liquids, 1 second ed. John Wiley, New York.

Choi, H.J., Jhon, M.S., 1996. Polymer-induced turbulent drag reduction. Ind. Eng. Chem. Res. 35, 2993–2998.

Costalonga, M.L., Loureiro, B.V., Soares, E.J., 2018. Drag reducing flows by polymer solutions in annular spaces. J. Fluid Eng. 140, 1–8.

Den Toonder, J.M.J., Draad, A.A., Kuiken, G.D.C., Nieuwstadt, F.T.M., 1995. Degradation effects of dilute polymer solutions on turbulent drag reduction in pipe flows. Appl. Sci. Res. 55, 63–82.

Drappier, J., Divoux, T., Amarouchene, Y., Bertrand, F., Rodts, S., Cadot, O., Meunier, J., Bonn, D., 2006. Turbulent drag reduction by surfactants. Europhys. Lett. 74, 362–368.

Graham, M.D., 2004. Drag reduction in turbulent flow of polymer solutions. Rheol. Rev. 143–170.

Harder, K.J., Tiederman, W.G., 1991. Drag reduction and turbulent structure in two-dimensional channel flows. Phil. Trans. Roy. Soc. Lond. 336, 19–34.

Japper-Jaafar, A., Escudier, M.P., Poole, R.J., 2009. Turbulent pipe flow of a drag-reducing rigid "rod-like" polymer solution. J. Non-Newtonian Fluid Mech. 161, 86–93.

Kamel, A., Shah, S.N., 2009. Effects of salinity and temperature on drag reduction characteristics of polymers in straight circular pipes. J. Pet. Sci. Eng. 67 (1), 23–33.

Katerpallir, S., White, C., 2000. The onset of drag reduction by dilute polymer additives, and the maximum drag reduction asymptote. J. Fluid Mech. 409, 149–164.

Kima, J.T., Kima, C.A., Zhanga, K., Jangb, C.H., Choia, H.J., 2011. Effect of polymer–surfactant interaction on its turbulent drag reduction. Colloids Surf. A Physicochem. Eng. Asp. 391, 125–129.

Matras, Z., Kopiczak, B., 2016. The effect of surfactant and high molecular weight polymer addition on pressure drop reduction in pipe flow. Braz. J. Chem. Eng. 33 (4), 933–943.

Min, T., Choi, H., Yoo, J.Y., 2003. Maximum drag reduction in a turbulent channel flow by polymer additives. J. Fluid Mech. 492, 91–100.

Oldaker, D.K., Tiederman, W.G., 1977. Structure of the turbulent boundary layer in drag reducing pipe flow. Phys. Fluids 20, 133–144.

Omrani, P.S., Delfos, R., Boersma, B.J., 2012. Polymer induced drag reduction in a turbulent pipe flow subjected to a Coriolis force. Flow, Turbul. Combust. 89, 589–599.

Petrie, H.L., Deutsch, S., Brungart, T.A., Fontaine, A.A., 2003. Polymer drag reduction with surface roughness in flat-plate turbulent boundary layer flow. Exp. Fluid 35, 8–23.

Ptasinski, P.K., Nieuwstadt, F.T.M., , Brule, B. H. A. A. V. D., Hulsen, M.A., 2001. Experiments in turbulent pipe flow with polymer additives at maximum drag reduction, flow. Turbulence and Combustion 66, 159–182.

Ptasinski, P.K., Boersma, B.J., Nieuwstad, F.T.M., Hulsen, M.A., van Den Brule, B.H.A.A., Hunt, J.C.R., 2003. Turbulent Channel flow near maximum drag reduction: simulations, experiments and mechanisms. J. Fluid Mech. 490, 251–291.

Resendea, P.R., Afonsob, A.M., Cruz, D.O., 2018. An improved k-ε turbulence model for FENE-P fluids capable to reach high drag reduction regime. Int. J. Heat Fluid Flow 73, 30–41.

Robert, A., Vaithianathan, T., Collins, L.R., Brasseur, J.G., 2010. Polymer-laden homogeneous shear-driven turbulent flow: a model for polymer drag reduction. J. Fluid Mech. 657, 189–226.

Rowin, W.A., Asha, A.B., Narain, R., Ghaemi, S., 2021. A novel approach for drag reduction using polymer coating. Ocean Eng. 240, 109895.

Sasaki, S., 1991. Drag reduction effect of rod-like polymer solutions. I. Influences of polymer concentration and rigidity of skeletal back bone. J. Phys. Soc. 60, 868–878.

Soares, E.J., 2020. Review of mechanical degradation and de-aggregation of drag reducing polymers in turbulent flows. J. Non-Newtonian Fluid Mech. 276, 104225.

Somandepalli, V.S.R., Hou, Y.X., M, G., 2005. Mungal, streamwise evolution of drag reduction in a boundary layer with polymer injection. In: Proc. 2nd Int. Symp. On Sea Water Drag Reduction Busean, Korea.

Toms, B., 1948. Observation on the flow of linear polymer solutions through straight tubes at large Reynolds numbers. Proc. Int. Rheol. Congr. 2, 131–141.

Virk, P.S., 1975. Drag reduction fundamentals. AIChE J. 21, 625–656.

Zeybek Vural, S., Bayram, G., Uludag, Y., 2014. Experimental investigation of drag reduction effects of polymer additives on turbulent pipe flow using ultrasound Doppler velocimetry. Turk. J. Chem. 38, 142–151.

Zhang, X., Duan, X., Muzychka, Y., 2018. Analytical upper limit of drag reduction with polymer additives in turbulent pipe flow. J. Fluid Eng. 140 (5), 051204.