

Research Article

Drag Reduction Characteristics of Polyacrylamide in a Rotating Disk Apparatus

^{1,2}Hayder A. Abdul Bari, ¹Zainab Yousif and ¹Zulkefli Bin Acoob

¹Faculty of Che. and Natural Reso. Eng., Universiti Malaysia Pahang, Kuantan, Pahang, Malaysia

²Centre of Excellence for Adva. Res. in Fluid Flow (CARIFF) Universiti Malaysia Pahang, 26300 Kuantan, Malaysia

Abstract: The drag reduction efficiency of Polyacrylamide has been tested in this study with different parameters using rotating disc apparatus. The polymer is tested at various concentrations (500, 700, 1000, 1500 and 2000) ppm and under turbulent conditions at different rotation speed up to 3000 rpm. The results show that maximum percent of drag reduction is (28, 30, 33, 35 and 36) % for the above concentrations respectively. The mechanical degradation of the polymer with time is also investigated and analyzed using empirical exponential decay function. The fractional exponential decay equation was found to fit the experimental data of low polymer concentration, while better fitting of single exponential decay model is found for experimental data of higher polymer concentration. The drag reduction decrease with increasing polymer concentration.

Keywords: Degradation, drag reduction, polyacrylamide, polymer, RDA

INTRODUCTION

Drag reduction is one of the most famous issues that have been studied and investigated in the last years for its economical importance. Many materials used to as a drag reducer like, polymers surfactants, solid materials but among all of them polymers are considered the most effective drag reducing agent.

The addition of small amount of flexible polymer into turbulent flows was known to reduce drag. Drag reduction ability is mainly influenced by the molecular parameters of the dissolved polymer material such as chain flexibility and aggregation.

Polymeric drag reducing agents are considered as successful and commercially feasible additives for enhancing the flow in strategic pipelines. Despite their advantages, their resistance to mechanical degradation and high forces during transportation introduce a new problem to the drag reduction system where polymeric additives should be injected again after certain distances to regain its drag reduction ability.

Mechanical degradation refers to the polymer bond rupture. Many researchers investigated degradation of polymer, (Brostow, 1983; Horn and Merrill, 1984; Moussa and Tiu, 1994), from their results it could be found that degradation depends on many conditions including polymer Molecular Weight (MW), Molecular Weight Distribution (MWD), temperature, polymer-solvent interactions, polymer concentration, turbulent

intensity, method of preparation and storage and flow geometry.

Sohn *et al.* (2001) studied the drag reduction of xanthan gum in a rotating disk apparatus using ultrasonic irradiation, they found that drag reduction efficiency is closely related to molecular parameters, such as stress level, temperature, polymer species, molecular weight and polymer-solvent interactions.

Sung *et al.* (2004) examined the mechanical degradation kinetics of poly (ethylene oxide) with two different molecular weight, they found that higher molecular weight polymers showed less mechanical degradation than that of low molecular weight.

Nakano and Minoura (1975) concluded that polymer chain scission enhanced in good solvent than that in poor solvent. They also concluded that the interaction between molecular be weak at low concentration (Kim *et al.*, 2000) Mechanical degradation of dilute polymer solutions under turbulent flow, they adopted the theoretical model for molecular degradation in turbulent flow proposed by Brostow *et al.* (1990).

Virk *et al.* (1967) examined Polyethylene Oxide (PEO) as a drag reducer in water flowing in a pipe, he found a universal drag reduction relationship, which was later simplified by Little (1971). The universal drag reduction equation was found to be independent of concentration, molecular weight and flow geometry.

Corresponding Author: Zainab Yousif, Faculty of Che. and Natural Reso. Eng., Universiti Malaysia Pahang, Kuantan, Pahang, Malaysia

This work is licensed under a Creative Commons Attribution 4.0 International License (URL: <http://creativecommons.org/licenses/by/4.0/>).

Another universal drag reduction curve for intrinsic concentration and intrinsic drag reduction was made by Dschagarowa and Menning (1977).

Choi and Jhon (1996) investigated the concentration dependence of drag reduction for many polymers using a Rotating Disk Apparatus (RDA) with different solvents and concentrations. Correlations between polymer concentration, drag reduction index and viscosity-average molecular weight were founded (Choi *et al.*, 2000).

In this study we will study the characteristic behavior of Polyacrylamide as a drag reducer agent including investigation of the effect of concentration, rotation speed on drag reduction efficiency, as well as its mechanical degradation and stability with time at turbulent condition using Rotating Disc Apparatus (RDA).

MATERIALS AND METHODS

Polyacrylamide used as drag reducer: Different concentration of Polyacrylamidewere prepared in distilled water. The concentrations tested for polymer are 500, 1000, 1500 and 2000 ppm. All samples were stored in a container at room temperature for one day to get dissolved properly. The Brookfield viscometer in the concentric cylinder mode is used to determine the rheological properties of the test samples.

Drag reduction measurements were implemented using Rotating Disc Apparatus (RDA). The RDA consists of a simple disk, made of aluminum with a diameter of 18 cm and a height of 1.9 cm, so that drag reduction efficiency can be evaluated. The disk could be rotated at a radius of $a = 8$ cm and a thickness of $b = 0.3$ cm (Fig. 1). Heidolph Company, ModelRZR 2102 has manufactured the rotor system, enclosed by constant speed. With this rotor system, the rotational speed of the disk could be controlled from 0 up to a

maximum of 3000 rpm. The used volume of solution necessary to fill the entire container is about 1200 cm^3 .

Computer control unit combining high speed data sampling with controlled disk and rotational speed are integrated in the RDA system to measure fluid friction from laminar to turbulent flow accurately. The rotating disk apparatus could calculate both skin and form friction in which the internal flow shows the frictional drag reduction while external flow shows total drag that includes both flow over flat plates (skin friction) and flow around submerged particles (form friction). Nevertheless, frictional part is only related to drag reduction phenomenon.

The drag reduction efficiency of any drag reduction agent can be represented as given below:

$$\%Dr = \frac{T_w - T_c}{T_w} \times 100 \quad (1)$$

where, T_w and T_c are the torques output for the (polymer and surfactant combines) measured on both sides of the disk, rotating at the same rpm in the water with and without additives with surfactant and polymers, respectively.

The Reynolds number of the disk can be determining by:

$$N_{Re} = \frac{\rho R^2 \omega}{\mu} \quad (2)$$

where,

μ : The fluid viscosity

ρ : Fluid density

R and ω : The radius of the disk and the angular velocity, respectively.

Turbulence is yield by using the rotary disk apparatuses, for $N_{Re} > 3 \cdot 10^5$.

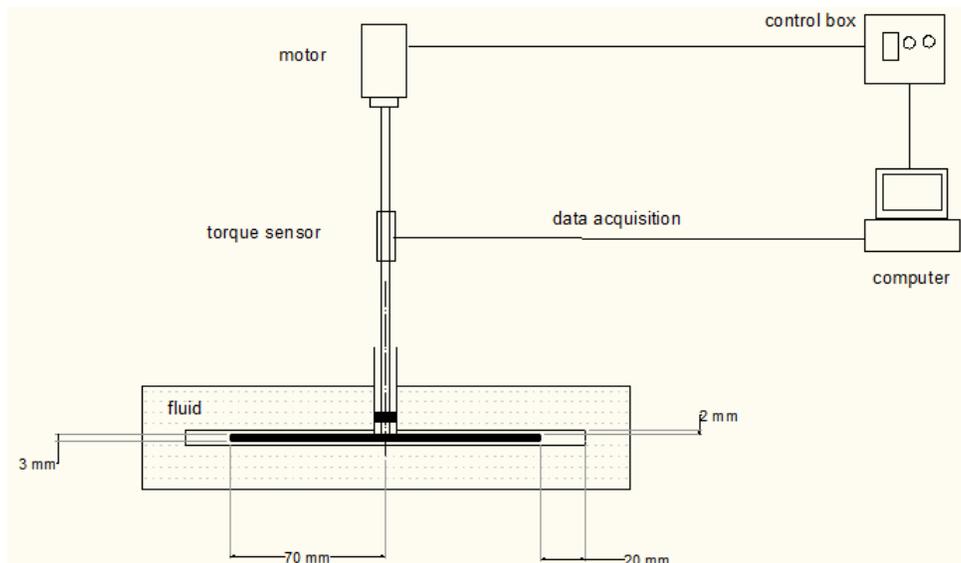


Fig. 1: Schematic of (RDA) rotating disk apparatus

RESULTS AND DISCUSSION

It's well known that Polyacrylamide is an important drag reducer agent, its drag reduction efficiency dependence on Reynolds number at different concentration is shown in Fig. 2. This figure illustrates that the percent drag reduction is larger at higher polymer concentration than that at lower one. This behavior is induced to the contribution of viscosity behavior with concentration increasing from individual polymer molecular. Indeed, these values of drag reduction percentages increase with increasing rotation speed till they reach maximum values of (28, 30, 33, 35 and 36) % for polymer concentration (500, 700, 1000, 1500 and 2000) ppm respectively. This increasing is reduced at higher Reynolds number values and reaches to nearly constant values of (23 and 25) % for (1500 and 2000) ppm, respectively, while it continues to decrease for (500, 700 and 1000) ppm concentration. This decreasing may be attributed to the degradation of polymer at higher velocity.

In order to study this degradation, the rotating disc apparatus used in this study measures the changes in drag reduction as a function of time as well as the stability of this polymer at high turbulent condition. Figure 3 shows the dependence of drag reduction percentage with time for different polymer concentration at certain rotation speed of 3000 rpm. This figure illustrates that the polymer is more shear stable drag reduction agent at higher concentration (1500 and 2000) ppm more than that at lower concentration (500, 700 and 1000) ppm. This stability can be explained if we know that the drag reduction is a function of molecular weight, chain linearity and flexibility and molecular expansion in solute (Kim *et al.*, 1986).

This result confirms with that obtained from Fig. 2, i.e., the drag reduction seems to be related with shear

force and elongation straining, in which a breakage of main chain of the polymer caused by mechanical energy (Sohn *et al.*, 2001). Similar behavior has shown by other workers (Jun *et al.*, 2004; Choi *et al.*, 2000).

More investigation on the time dependent of drag reduction can be achieved using the following single relaxation model made by (Bello *et al.*, 1996):

$$DR(t)/DR(0) = \exp(-t/\lambda_s) \quad (3)$$

where,

DR(t), DR(0) = Percent drag reduction efficiency at time t and time t = 0 respectively.

λ_s = An adjustable parameter (not a true relaxation time)

$(1/\lambda_s)$ = The drag reduction activity, i.e., the rate of degradation.

The λ_s values obtained, from applying Eq. (3) on the experimental data and using a least square method (Fig. 4), are 666.6 min^{-1} and 312.1 min^{-1} for (2000 and 1500) ppm with correlation coefficient 0.9 and 0.95, respectively. A low fitting of data with this equation achieved at lower concentrations (500, 700 and 1000) ppm, in spite of the successful applicability of this single exponential decay model. Therefore, a modified form of single exponential decay function made by William and Watt as shown in the following equation:

$$DR(t)/DR(0) = \exp(-(t/\lambda_f)^{1-n}) \quad (4)$$

where,

λ_f = Defined as an observed time scale of the relaxation process

n = A fractional exponent, i.e., the degree of non-exponentiality.

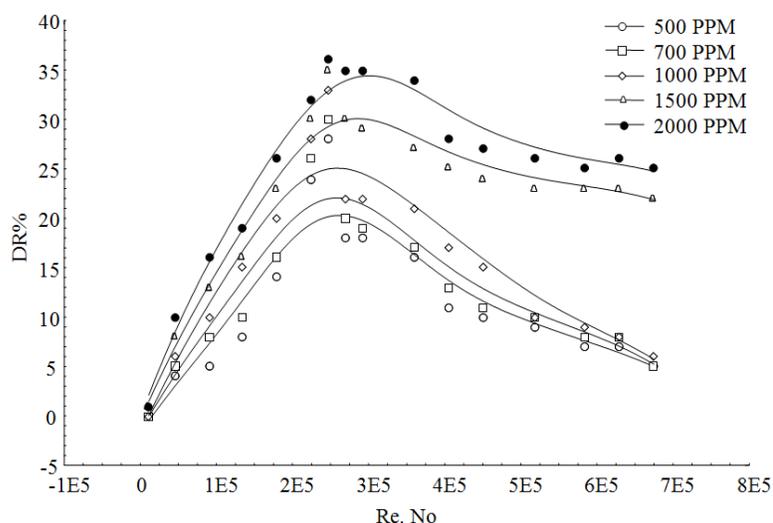


Fig. 2: The percentage of drag reduction with Reynolds number at different polymer concentration

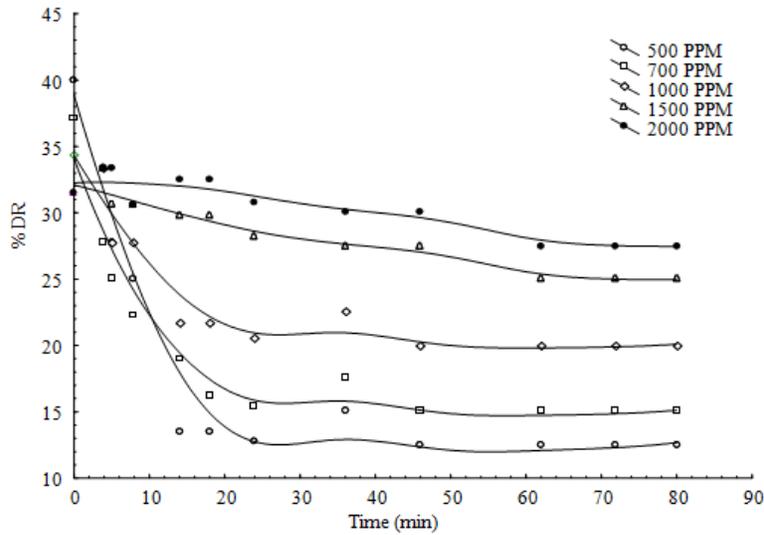


Fig. 3: The effect of time on percent drags reduction for different polymer concentration at 3000 rpm

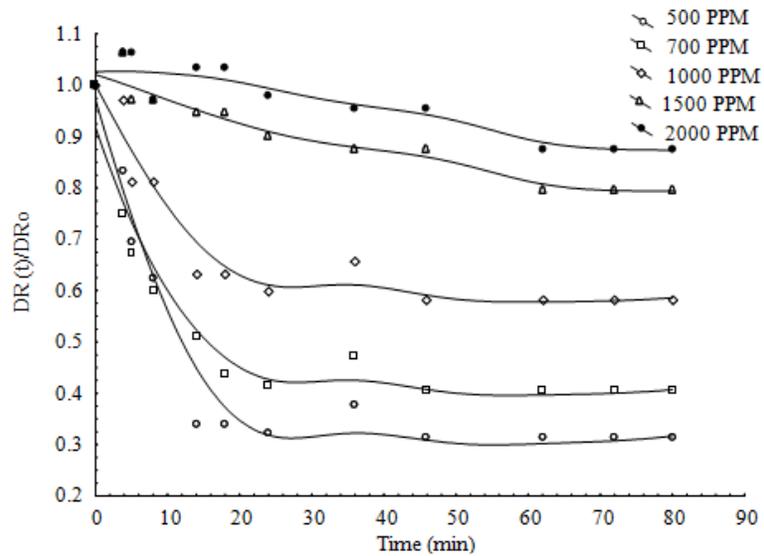


Fig. 4: Drag reduction efficiency values at various polymer concentration applying Eq. (3) and (4) at 3000 rpm

This equation fits the lower concentration experimental data. The λf obtained are 34.4 min^{-1} , 52.9 min^{-1} and 66.6 min^{-1} for 500, 700 and 1000 ppm with correlation coefficient 0.8, 0.88 and 0.86 respectively. It could be noticed from λs and λf values obtained that they are increase with increasing polymer concentration which means that the rate of degradation decrease with increasing concentration. The same result is also obtained by the work of Jun *et al.* (2004).

Figure 5 shows the shear viscosity of the polymer as a function of applied shear rate. It could be clearly noticed that increasing shear rate leads to increase in viscosity, this is due to the shear thickening behavior of this polymer. Also, increasing concentration caused increasing and extending of polymer concentration leading to increase in viscosity.

As we mentioned before that the drag reduction efficiency is related to polymer concentration. This relation is introduced through a universal correlation for drag reduction made by Choi *et al.* (1999) as reported in Eq. (5):

$$\frac{c}{DR} = \frac{K[C]}{DR_{max}} + \frac{c}{DR_{max}} \quad (5)$$

The above equation is a three parameter empirical relationship between drag reduction and concentration at fixed rotation speed and its valid for both pipe and rotating disc (Kim *et al.*, 1997; Choi and Jhon, 2000). In which C is concentration, DR_{max} is maximum drag reduction of polymer and $[C]$ is the intrinsic concentration which represents by:

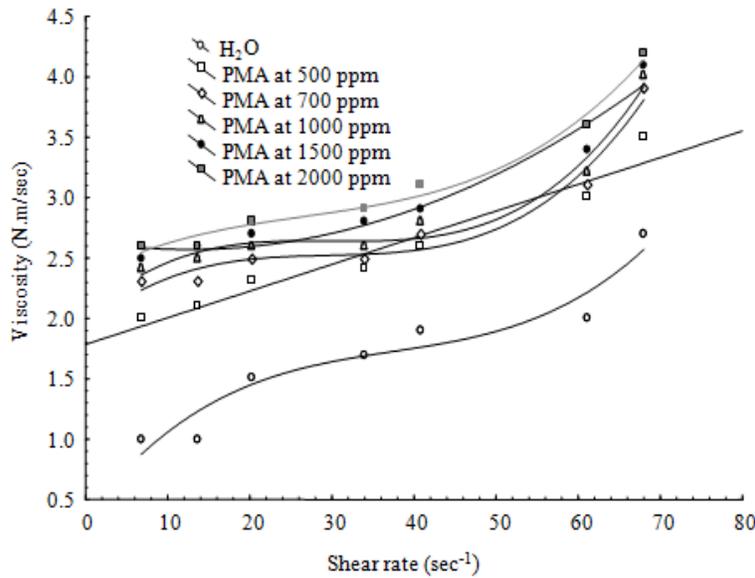


Fig. 5: The effect of shear rate on viscosity for different concentrations of PAA

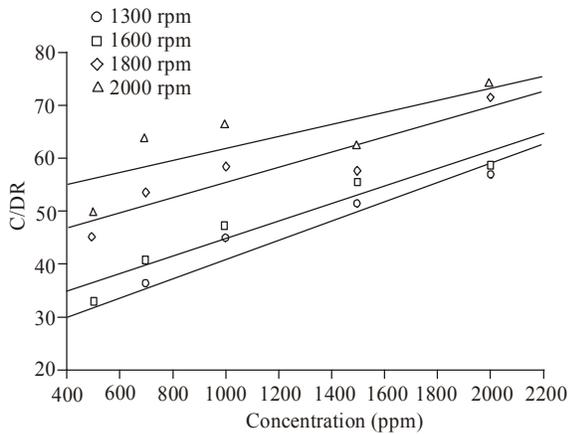


Fig. 6: Polymer concentration with C/DR at different rotation speed

Table 1: The values of K, (C), (DR) and DR_{max} at different rotation speeds

	Rotation Speed (rpm)			
	1300	1600	1800	2000
(C)	22.8	28.6	41.0	50.4
DR_{max}	54.3	60.9	67.5	88.4
(DR)	2.3	2.1	1.6	1.7
K	16.7	12.8	5.2	6.9

$$[C] = \frac{DR_{max}}{[DR]} \quad (6)$$

where,

$$[DR] = \text{The intrinsic drag reduction defined as } [DR] = \lim_{c \rightarrow 0} \frac{DR}{c}$$

Eq. (5) can be rewritten in the form of Eq. (7), (Choi *et al.*, 1999):

$$\frac{DR/C}{[DR]} = \frac{1}{K+C/[C]} \quad (7)$$

Figure 6 shows the linear relation of C and C/DR at different rotation speed in turbulent condition. The reciprocal of the slope and the intercept of these linear relation give the values of DR_{max} and [C] respectively.

Applying Eq. (7), different values of K are obtained. The computed values of K, [C], [DR] and DR_{max} are tabulated in Table 1.

Its noticed from this table that intrinsic values of concentration and DR_{max} increase with increasing rotation speed. While the values of intrinsic drag reduction and the constant K decrease with increasing velocity and they seems to be closer at 1800 and 2000 rpm. Hunston and Zakin (1980) illustrated that the material which have the largest values of DR_{max} and smallest values of [C] is the more efficient one.

The above result confirms that good drag reduction occurs at higher concentration and this is also compatible with the results obtained from Fig. 2 in which the higher concentration has the largest values of drag reduction.

CONCLUSION

This study presented the combined effect of turbulent flow and polymer concentration on the percent drag reduction efficiency. This efficiency increases with increasing rotation speed till it reaches a maximum value then it decreases with increasing velocity. Indeed the drag reduction efficiency decrease with increasing time due to polymer degradation and this degradation lowered at high concentration. The degradation of high concentration fits with the single exponential decay model while low concentration fits with the fractional exponent modl.

REFERENCES

- Bello, J.B., A.J. Müller and A.E. Sáez, 1996. Effect of intermolecular cross links on drag reduction by polymer solutions. *Polym Bull.*, 36(1): 111-118.
- Brostow, W., 1983. Drag reduction and mechanical degradation in polymer solutions in flow. *Polymer*, 24(5): 631-638.
- Brostow, W., H. Ertepinar and R.P. Singh, 1990. Flow of dilute polymer solutions: Chain conformations and degradation of drag reducers. *Macromolecules*, 23: 5109-5118.
- Choi, H.J. and M.S. Jhon, 1996. Polymer-induced turbulent drag reduction. *Ind. Eng. Chem. Res.*, 35(9): 2993-2998.
- Choi, H.J., C.A. Kim and M.S. Jhon, 1999. Universal drag reduction characteristics of polyisobutylene in a rotating disk apparatus. *Polymer*, 40(16): 4527-4530.
- Choi, H.J., C.A. Kim, J.I. Sohn and M.S. Jhon, 2000. An exponential decay function for polymer degradation in turbulent drag reduction. *Polym. Degrad. Stabil.*, 69(3): 341-346.
- Dschagarowa, E. and G. Menning, 1977. *Rheol. Acta*, 16: 309.
- Horn, A.F. and E.W. Merrill, 1984. Midpoint scission of macromolecules in dilute solution in turbulent flow. *Nature*, 312: 140-141.
- Hunston, D.L. and J.L. Zakin, 1980. Flow-assisted degradation in dilute polystyrene solutions. *Polym. Eng. Sci.*, 20(7): 517-523.
- Kim, C.A., K. Lee, H.J. Choi, C.B. Kim, K.Y. Kim and M.S. Jhon, 1997. Universal characteristics of drag reducing polyisobutylene in kerosene. *J. Macromol. Sci. A*, 34(4): 705-711.
- Kim, C.A., J.T. Kim, K. Lee, H.J. Choi and M.S. Jhon, 2000. Mechanical degradation of dilute polymer solutions under turbulent flow. *Polymer*, 41(21): 7611-7615.
- Kim, O.K., T. Long and F. Brown, 1986. An unusual coil deformation of polyacrylic acid induced by high shear flow. *Polym. Commun.*, 27: 71-73.
- Little, R.C., 1971. Drag reduction in capillary tubes as a function of polymer concentration and molecular weight. *J. Coll. Interf. Sci.*, 37(4): 811-818.
- Moussa, T. and C. Tiu, 1994. Factors affecting polymer degradation in turbulent pipe flow. *Chem. Eng. Sci.*, 49(10): 1681-1692.
- Nakano, A. and Y. Minoura, 1975. Effects of solvent and concentration on scission of polymers with high-speed stirring. *J. Appl. Polym. Sci.*, 19(8): 2119-2130.
- Sohn, J.I., C.A. Kim, H.J. Choi and M.S. Jhon, 2001. Drag-reduction effectiveness of xanthan gum in a rotating disk apparatus. *Carbohydr. Polym.*, 45(1): 61-68.
- Sung, J.H., S.T. Lim, C.A. Kim, H.J. Chung and H.J. Choi, 2004. Mechanical degradation kinetics of poly(ethylene oxide) in a turbulent flow. *Korea-Aust. Rheol. J.*, 16(2): 57-62.
- Virk, P.S., E.W. Merrill, H.S. Mickley, K.A. Smith and E.L. Mollo-Christensen, 1967. The Toms phenomenon: Turbulent pipe flow of dilute polymer solutions. *J. Fluid Mech.*, 30(2): 305-328.