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ACTIVE DRAG REDUCTION IN HYDROCARBON MEDIA USING ROTATING DISK APPARATUS

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ABSTRACT

A high precision rotating disk apparatus (RDA) is designed and employed to investigate the turbulent drag reduction characterization induced by polymeric additives. For the past few decades, polymers have been used widely as drag reducer agents in a pipeline and RDA successfully due to its viscoelastic properties that can suppress the turbulent at high ranges of Reynolds number. In this study, drag reduction efficacy of diesel fuel in a rotating disk apparatus is investigated using high molecular weight polyisobutylene polymer as drag reducing agent. Dependence of drag reduction on different parameters such as: polymer concentration and rotational disk speed (RPM) are also investigated. In addition, the mechanical stability of this polymer with time was studied by measuring torque values for 300 sec at a fixed rotational speed (2000 rpm). It was observed that the drag reduction of diesel fuel increases withthe rotational disk speed and polymer concentration till a critical concentration at which the maximum drag reduction achieved. The maximum DR obtained was about 19.197% at Re = 902062 and PIB concentration of 150 ppm.

Keywords: drag reduction, polyisobutylene, rotating disk apparatus, diesel fuel.

1. INTRODUCTION

The main concept of drag reduction phenomenon is to reduce the pressure drop of fluids flowing through a pipe by adding a minute amount of additives. That means the fluids with additives needs a lower pressure drop than that of fluids without any additives to maintain the same flow rate (Armstrong & Jhon, 1984; Cadot, Bonn, & Douady, 1998; Tabor & Gennes, 2007). Drag reduction (DR) has extensive applications in engineering areas such as; transportation of oil, wastewater treatment, firefighting, transport of solids in water, heating and cooling rings, hydraulic and jet machinery, and biomedical applications (Dodge & Metzner, 1959; Gasljevic, Aguilar, & Matthysz.ast, 2001; Gyr & Bewersdorff, 1995). Different types of additives such as flexible long-chain macromolecules, colloidal surfactants, and insoluble fibers or particles suspensions have been widely used as drag reducing agent in both pipelines and RDA systems. Among all these additives, long-chain polymers show a good ability to reduce the friction drag forces. Polyisobutylene (PIB) is one of these polymers, which is widely used in pipelines regime as drag reducing agent with various types of solvents such as crude oil(Mowla & Naderi, 2006, 2008; Muslim & Ali, 2008), Kerosene (Shanshool, F.A., & Slaiman, 2011), and gas oil (Shanshool & Haider, 2008; Shanshool & Slaiman, 2012). Different ranges of PIB molecular weights were used in these studies. Furthermore, the effects of polymer concentration, polymer molecular weights, pipe length, pipe diameter, and liquid flow rate on DR efficiency were investigated. The results and other details of these studies are illustrated in Table-1.

Table-1. The details of previous studies of PIB in pipeline system.

Authors	Year	PIB molecular weight	PIB concentration (ppm)	Solvent type	Reynolds number (Re)	Maximum % DR
(Mowla & Naderi, 2006)	2006	———	0 - 30	Crude oil	6446 - 28112	40%
(Muslim & Ali, 2008)	2008	———	10 - 50	Crude oil	———	22.23%
(Mowla & Naderi, 2008)	2008	———	4, 8, 12, and 18	Crude oil	36326 - 74978	45%
(Shanshool & Haider, 2008)	2008	2.9, 4.1, and $5.9*10^6$	10 - 70	Gas oil	8341 - 35747	18.7%
(Shanshool et al., 2011)	2011	2.5, 4.1, and $5.9*10^6$	10 - 50	Kerosene	———	9%
(Shanshool & Slaiman, 2012)	2012	2.6, 4.1, and $5.9*10^6$	10 - 50	Gas oil	———	———

ARPN Journal of Engineering and Applied Sciences

The RDA employed in this study is usually used to simulate the external flow which is including the flow over flat plates, as well as the flow around submerged objects (Tong, Goldburg, Huang, & Witten, 1990). In addition, it was adopted in this study because the phenomenon of DR has not been studied in external flows as extensively as in pipe flows. Most previous work of the DR induced by PIB in the RDA were performed using a smooth disk with different rotational speed, PIB concentration, PIB molecular weights in order to examine their effects on drag reduction efficiency(H.J. Choi *et al*., 1999; H.J. Choi & Jhon, 1996; C. Kim *et al*., 2000; C. A. Kim *et al*., 1997; K. H. Lee, Zhang, & Choi, 2010; K. Lee *et al*., 2002; S.T. Lim *et al*., 2002).

H.J. Choi & Jhon, (1996) studied the influence of different molecular weights of polyisobutylene (PIB) (oil-soluble) and polyethylene oxide (PEO) (water-soluble) on DR efficacy under turbulent flow using the RDA. They found a linear correlation between the DR and polymer concentration. In addition, the DR increased with polymer concentration until the optimum concentration, and at low concentration a maximum DR was obtained with high molecular weight polymers. Using the same polymer additives and solvent fluid, Kim et al.(C. A. Kim et al., 1997) studied the capability of using PIB to improve the DR properties of kerosene in RDA. Four different molecular weight ranges of PIB 9.9 x 10^5 (L-80), 1.2 x 10^6 (L-100), 1.6 x $l0^6$ (L-120) and 2.1 x $l0^6$ (L-140) were used, and all data were measured at a fixed rotational speed of 1600 rpm. The intrinsic concentration [C] was found to be an extremely useful quantity in normalizing the DR data for different molecular weights of PIB and concentrations similar to polyethylene oxide (PEO) in water.

Two different of solvents (Cyclohexane and Xylene) with different concentration of oil soluble PIB were used to examine the effect of solvent on DR characteristics in RDA (H. J. Choi et al., 1999). They also found a linear correlation between *C*/DR and polymer concentration (*C*) for different molecular weights of PIB. It was found that the intrinsic concentration an extremely useful quantity in normalizing the DR data for a homologous series of PIB, and the characteristic value (*K*) depended on the solvent system. K. Lee *et al*., (2002) studied turbulent drag reduction and mechanical molecular degradation of polyisobutylene in kerosene, and calculated the relationship between this molecular degradation and molecular weight distribution (MWD) curve. The DR percentage was decreased with time due to the mechanical molecular degradation of the polyisobutylene, and an excellent correlation between this percentage and the molecular weight or the MWD over time was noticed. S.T. Lim et al., (2002) studied the mechanical degradation and turbulent DR induced by PIB dissolved in kerosene. It was concluded that drag reduction efficiency reduced with time due to mechanical degradation of the polyisobutylene chains, and increased with increasing PIB concentration upto an optimal concentration. The influence of Reynolds number (Re), temperature of PIB– kerosene solution, and molecular weight on DR was investigated by (K. H. Lee et al., 2010). It was noticed that the DR dropped faster at higher temperature than that at lower temperature.

In this study, high molecular weight polymer of polyisobutylene was utilized to examine the effects of polymer concentration and the rotational disk velocity on DR performance of diesel fuel using RDA at high ranges of Reynolds number ($6*10^5$ – $9*10^5$). In addition, the mechanical degradation behaviour of PIB with time was also studied.

2. EXPERIMENTAL

2.1 Materials and instruments

The polymer used in the present work is polyisobutylene (linear formula: $[CH_2C(CH_3)2]_n$) with high molecular weight of 4.7 * 10^6, which purchased from Sigma Aldrich, and used without further purification. This polymer contains a 500 ppm of 2,6-di-tert-butyl-4-methylphenol as stabilizer. In addition, the main fluid used is diesel fuel purchased from Shell.

The drag reduction measurements were performed with the same Rotating Disk Apparatus (RDA) employed in our previous work (Rashed et al., 2016), which is shown in Figure-1. This instrument involves cylindrical fluid container made by a stainless steel of180 mm diameter ×110 mm height, and a removable 20 mm thick stainless steel lid to seal the solution. Maximum solution capacity of this container is about 4.2L.A smooth aluminum disk with a diameter of 14cm and thickness of 0.6 cm is immersed in the fluid and rotated with different ranges of rotational speed (0 – 3000 rpm) using an electric servo motor. The distance between the disk surface and fluid container lid is 10 mm. The RDA is connected to a computer display system for data collection and recording. A high accurate torque sensor (LONGLV-WTQ1050D, Range: 3 Nm, Output: 1.397 mv/V) was used to calculate the loaded torque on the disk. The torque values thereby transforming to readable form in the computer display system with an InduSoft Web Studio v7.1 software. Data were taken and recorded while keeping the temperature at 27 ± 0.05^{o}C. Thus, the drag reduction percentage and Reynolds number (Re) were calculated by Eq. 1 and 2, respectively (Hong et al., 2008; Hong et al., 2015; C. A. Kim et al., 2000; J. T. Kim *et al*., 2011; S. T. Lim et al., 2003; S. T. Lim et al., 2007; S. T. Lim *et al*., 2005; S.T. Lim et al., 2004; Sohn et al., 2001; Sung *et al*., 2004; Zhang et al., 2011).

$$\%DR = (Ts-Ta)/Ts\times 100 \quad (1)$$

$$NR_e = \rho\omega r^2/\mu \quad (2)$$

From the two equations above:

Ts = Torque values of pure solvent without additives.
Ta = Torque values with polymeric additives.
r = Disk radius.
ω = Angular disk speed.
μ = Fluid viscosity.
ρ = Fluid density.

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The critical Reynolds number value is 3×10^5, which is represent the transition from laminar to turbulent flow in RDA (H. J. Choi *et al*., 2000; Hoyt, 1972; Little *et al.*, 1976).

2.2 Experimental procedure

All the experiments were performed in a constructed rotating disk apparatus, testing two different variables which are:

1) Polymer concentration (50, 100, 150, 200, and 300 ppm).

2) Rotational disk velocity (2000 – 3000 rpm), were corresponding to Re of ($6*10^5$ - $9*10^5$).

Firstly, the polymer solutions with different concentrations were prepared by weight the specific amount of PIB dependence on the required concentration, and dissolved in 4.5 L of pure diesel. The samples were left for 24 hours until dissolved exactly, and tested using a constructed rotating disk apparatus. The experimental procedure starts by measuring the torque values of pure diesel (without additives) for all rotational disk speed ranges (2000-3000 rpm). Then the pure diesel was changed by one of the polymer solutions and the torque values were measured for all rotational speeds. This procedure is repeated for the restpolymer concentrations, which are mentioned above. The recorded data were directly collected from the computer display system and analyzed.

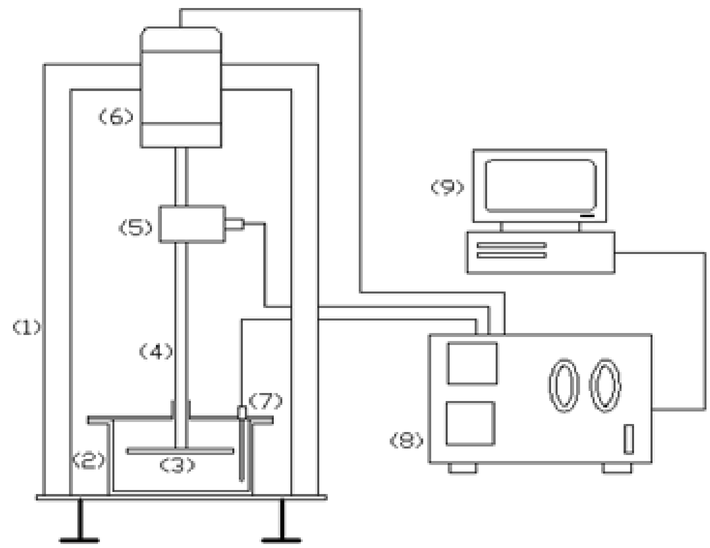

Figure-1. Schematic diagram of the rotating disk apparatus for drag reduction measurement: (a) Outside frame, (2) Fluid container, (3) Rotating disk, (4) Disk holding shift, (5) Torque sensor, (6) Electric motor, (7) thermocouple, (8)Controller interface, and (9) PC.

3. RESULTS AND DISCUSSIONS

The torque results as a function of Re for various polyisobutylene concentrations using smooth disk are shown in Figure-2. As shown, torque is increased with Re for the pure solvent and all polymer concentrations. The minimum torque value indicates a higher drag reduction performance depending on the drag reduction calculation equation (Eq. 1). It can be noticed that the pure diesel without any additives has a higher torque values, while the lowest values of torque can be observed with 150 ppm of PIB. That implies this concentration show the highest drag reduction performance and the pure diesel has the minimum one. These results are clearly observed in Figure-3, which represent the drag reduction as a function of Re with the same PIB concentrations used in Figure-1. From Figure-3, it was noticed that the drag reduction increase at a constant rate with PIB concentration until a specific concentration level of 150 ppm at which the maximum drag reduction achieved, similar results shown by other workers (C. A. Kim *et al*., 2000; C. A. Kim *et al*., 2002; Sohn *et al.*, 2001). That concentration is usually referred to as the saturation concentration. The effect of polymer concentration on DR performance is related to two competitive mechanisms. Initially, DR increases as the concentration increases due to an increase in the number of available drag reducers. However, as the polymer concentration increases further, the solution viscosity drastically increases, leading to a decrease in the turbulent strength and an increase in the frictional drag forces. In addition, the drag reduction increased with the Reynolds number, and the maximum DR obtained was about 19.197% at Re = 902062 and PIB concentration of150 ppm.

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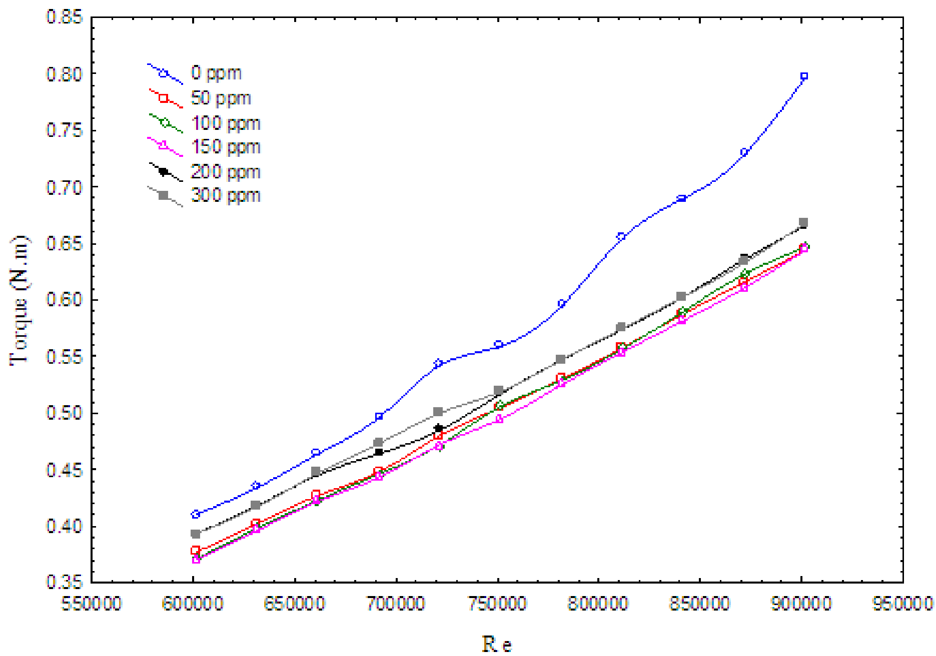

Figure-2. Torque vs. Re with different concentrations of PIB.

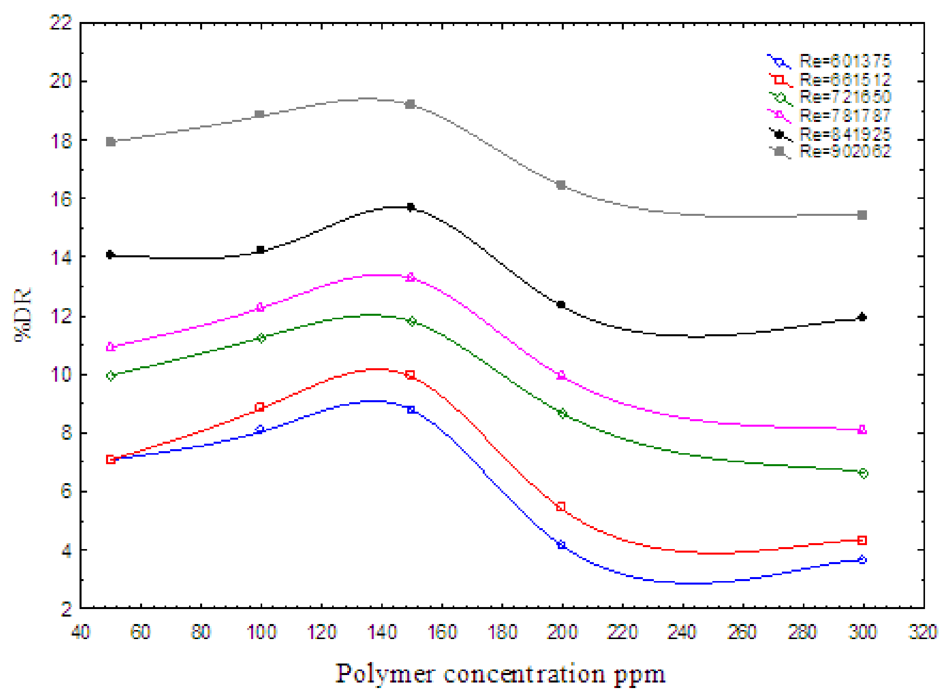

Figure-3. % DR vs. PIB concentrations with different Re.

The mechanical degradation of PIB under turbulent flow was studied by measuring the torque with time for 30 sec at a specific value of rotational speed (2000 RPM) and calculates the %DR for each second, as shown in Figure-4. We find that the %DR decreases with time for all polymer concentrations due to mechanical degradation of PIB under turbulent flow conditions, the same findings were observed by (Brostow *et al.*, 2007; Sung *et al.*, 2004; Yang *et al.*, 1991). This degradation leads to cutoff the long chains of PIB and then decreases their ability to reduce the drag friction forces. In addition, the results of this figure are proved the results of Figure-1, where the DR increased with polymer concentration till a critical value and then decreased. The maximum DR is also found with a polymer concentration of 150 ppm.

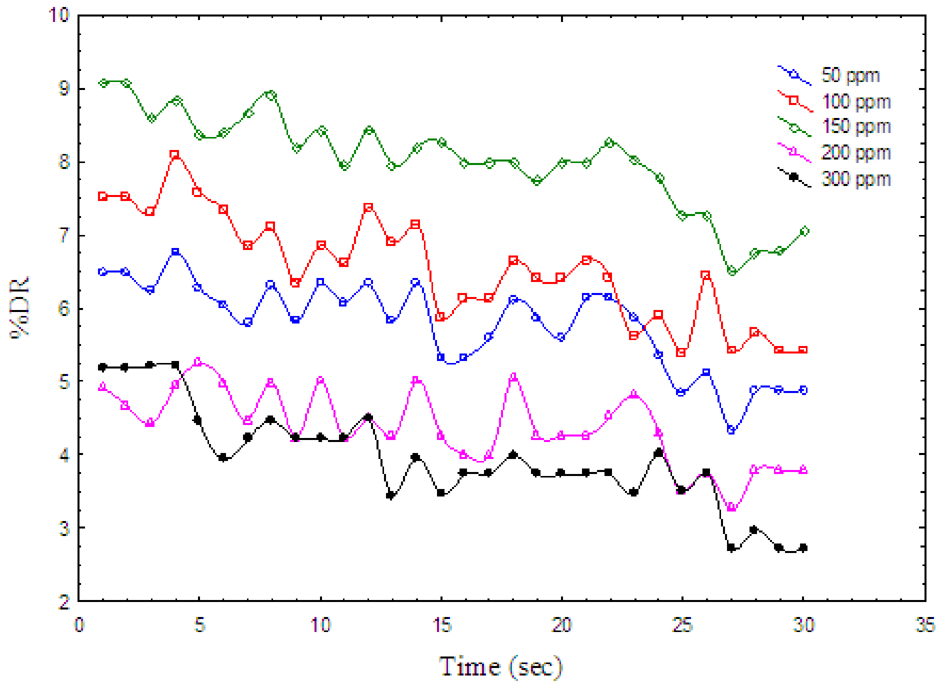

Figure-4. The mechanical stability of PIB at 2000 rpm with five different concentrations.

4. CONCLUSIONS

In conclusion, a high precise rotating disk apparatus was employed to investigate the effect of polymer concentration and angular disk velocity (rpm) on the DRefficacy of diesel fuel. High molecular weight polyisobutylene was used with five different concentrations of 50, 100, 150, 200, and 300 ppm. The mechanical degradation of this polymer was also studied by measuring the torque for 30 sec and records its values for each second. The increase in drag reduction is enhanced with the additive concentration and Reynolds number. Polyisobutylene exhibited a good ability to decrease the drag friction forces, and the highest DR obtained was about 19.197% at Re = 902062and a concentration of 150 ppm. Furthermore, decreases in %DR as a result of PIB degradation were found.

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REFERENCES

Armstrong R. and Jhon M. S. 1984. A Self-Consistent Theoretical Approach To Polymer Induced Turbulent Drag Reduction. Chemical Engineering Communications, 30(1-2), 99-111. doi:10.1080/00986448408911118.

Brostow W., Lobland H. E. H., Reddy T., Singh R. P. and White L. 2007. Lowering mechanical degradation of drag reducers in turbulent flow. Journal of Materials Research. 22(01): 56-60. doi:10.1557/jmr.2007.0003.

Cadot O., Bonn D. and Douady S. 1998. Turbulent drag reduction in a closed flow system: Boundary layer versus bulk effects. Physics of Fluids, 10(2): 426. doi:10.1063/1.869532.

Choi H. J. and Jhon M. S. 1996. Polymer-Induced Turbulent Drag Reduction. Industrial & Engineering Chemistry Research. 35(95): 2993-2998.

Choi H. J., Kim C. A. and Jhon M. S. 1999. Universal drag reduction characteristics of polyisobutylene in a rotating disk apparatus. Polymer. 40(16): 4527-4530. doi:10.1016/S0032-3861(98)00869-6.

Choi H. J., Kim C. A., Sohn J. and Jhon M. S. 2000. An exponential decay function for polymer degradation in turbulent drag reduction. Polymer Degradation and Stability. 69(3): 341-346. doi:10.1016/S0141-3910(00)00080-X.

Dodge D. W. and Metzner A. B. 1959. Turbulent flow of non-newtonian systems. AIChE Journal. 5(2): 189-204. doi:10.1002/aic.690050214.

Gasljevic K., Aguilar G. and Matthysz.ast E. F. 2001. On two distinct types of drag-reducing fluids, diameter scaling, and turbulent profiles. Journal of Non-Newtonian Fluid Mechanics. 96(3): 405-425. doi:10.1016/S0377-0257(00)00169-5.

Gyr A. and Bewersdorff H. W. 1995. Drag reduction of turbulent flows by additives. Fluid Mechanics and Its Applications, 32, 234 p. doi:10.1007/978-94-017-1295-8.

Hong C. H., Choi H. J. and Kim J. H. 2008. Rotating disk apparatus for polymer-induced turbulent drag reduction. Journal of Mechanical Science and Technology. 22(10): 1908-1913. doi:10.1007/s12206-008-0731-z.

Hong C. H., Choi H. J., Zhang K., Renou, F. and Grisel, M. 2015. Effect of salt on turbulent drag reduction of xanthan gum. Carbohydrate Polymers. 121, 342-347. doi:10.1016/j.carbpol.2014.12.015.

Hoyt J. 1972. A Freeman Scholar Lecture: The Effect of Additives on Fluid Friction. Journal of Fluids Engineering. 94(2): 258-285.

Kim C., Kim J., Lee K., Choi H. and Jhon M. 2000. Mechanical degradation of dilute polymer solutions under turbulent flow. Polymer. 41(21): 7611-7615. doi:10.1016/S0032-3861(00)00135-X.

Kim C. A., Jo D. S., Choi H. J., Kim C. B. and Jhon M. S. 2000. A high-precision rotating disk apparatus for drag reduction characterization. Polymer Testing, 20(1): 43-48. doi:10.1016/S0142-9418(99)00077-X.

Kim C. A., Lee K., Choi H. J., Kim C. B., Kim K. Y. and Jhon M. S. 1997. Universal characteristics of drag reducing polyisobutylene in kerosene. Journal of Macromolecular Science Pure and Applied Chemistry, A34, 705-711. doi:10.1080/10601329708014996.

Kim C. A., Lim S. T., Choi H. J., Sohn J. I. and Jhon M. S. 2002. Characterization of drag reducing guar gum in a rotating disk flow. Journal of Applied Polymer Science, 83(13): 2938-2944. doi:10.1002/app.10300.

Kim J. T., Kim C. A., Zhang K., Jang C. H. and Choi H. J. 2011. Effect of polymer-surfactant interaction on its turbulent drag reduction. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 391(1-3): 125-129. doi:10.1016/j.colsurfa.2011.04.018.

Lee K. H., Zhang K. and Choi H. J. 2010. Time dependence of turbulent drag reduction efficiency of polyisobutylene in kerosene. Journal of Industrial and Engineering Chemistry. 16(4): 499-502. doi:10.1016/j.jiec.2010.03.027.

Lee K., Kim C. A., Lim S. T., Kwon D. H., Choi H. J. and Jhon M. S. 2002. Mechanical degradation of polyisobutylene under turbulent flow. Colloid and Polymer Science. 280(8): 779-782. doi:10.1007/s00396-002-0690-3.

Lim S. T., Choi H. J., Biswal D. and Singh R. P. 2004. Turbulent drag reduction characteristics of amylopectin and its derivative. E-Polymers. 4(1): 751-760.

Lim S. T., Choi H. J., Lee S. Y., So J. S. and Chan, C. K. 2003. λ-DNA induced turbulent drag reduction and its characteristics. Macromolecules. 36(14): 5348-5354. doi:10.1021/ma025964k.

Lim S. T., Hong C. H., Choi H. J., Lai P.-Y. and Chan C. K. 2007. Polymer turbulent drag reduction near the theta point. Europhysics Letters (EPL). 80(5): 58003. doi:10.1209/0295-5075/80/58003.

Lim S. T., Lee K., Kim C. A., Choit H. J., Kim J. G. and Jhon M. S. 2002. Turbulent Drag Reduction and Mechanical Degradation of Polyisobutylene in Kerosene. J. Ind. Eng. Chem. 8(4): 365-369.

Lim S. T., Park S. J., Chan C. K. and Choi H. J. 2005. Turbulent drag reduction characteristics induced by calf-thymus DNA. Physica A: Statistical Mechanics and Its Applications. 350(1): 84-88. doi:10.1016/j.physa.2004.11.034.

Little R. C., Patterson R. L. and Ting R. Y. 1976. Characterization of the drag reducing properties of poly(ethylene oxide) and poly(acrylamide) solutions in external flows. Journal of Chemical and Engineering Data. 21(3): 281-283.

Mowla D. and Naderi A. 2006. Experimental study of drag reduction by a polymeric additive in slug two-phase flow of crude oil and air in horizontal pipes. Chemical Engineering Science. 61: 1549-1554. doi:10.1016/j.ces.2005.09.006.

Mowla D. and Naderi A. 2008. Experimental Investigation of Drag Reduction in Annular Two-Phase Flow of Oil and Air. Iranian Journal of Science and Technology. 32(B6): 601-609.

Muslim Q. and Ali A. 2008. Drag Force Reduction of Flowing Crude Oil by Polymers Addition. The Iraqi Journal for Mechanical and Material Engineering. 8(2): 149-161.

Rashed M. K., Mohd M. A., AbdulBari H. A. and Halim S. I. 2016. Investigating the effects of Surfactants on drag reduction performance of diesel fuel in a rotating disk apparatus. Journal of Purity, Utility Reaction and Environment. 5(1): 18-30.

Shanshool J., F.A., M. and Slaiman I. N. 2011. The influnace of mechanical effects on degradation of polyisobutylene as drag reducing agent. Petroluem and Coal. 53(3): 218-222.

Shanshool J. and Haider M. T. 2008. Effect of Molecular Weight on Turbulent Drag Reduction with Polyisobutylene. In The First Regional Conference of Engineering and Sceince. 11: 52-59.

ARPN Journal of Engineering and Applied Sciences

Shanshool J. and Slaiman I. N. 2012. Mechanical Degradation Kinetics of Poly (iso-butylene) in a Turbulent Flow. In Proceedings of International Conference on Engineering and Information Technology. Toronto, Canada.

Sohn J. I., Kim C. A., Choi H. J. and Jhon M. S. 2001. Drag-reduction effectiveness of xanthan gum in a rotating disk apparatus. Carbohydrate Polymers. 45(1): 61-68. doi:10.1016/S0144-8617(00)00232-0.

Sung J. H., Kim C. A., Choi H. J., Hur B. K., Kim J. G. and Jhon M. S. 2004. Turbulent Drag Reduction Efficiency and Mechanical Degradation of Poly(Acrylamide). Journal of Macromolecular Science, Part B. 43(2): 507-518. doi:10.1081/MB-120029784.

Tabor M. and Gennes P. G. De. 2007. A Cascade Theory of Drag Reduction. Europhysics Letters (EPL). 2(7): 519-522. doi:10.1209/0295-5075/2/7/005.

Tong, P., Goldburg, W. I., Huang, J. S. and Witten, T. A. 1990. Anisotropy in turbulent drag reduction. Physical Review Letters. 65(22): 2780.

Yang K. S., Choi H. J., Kim C. B. and Jhon M. S. 1991. A study of drag reduction by polymer additives in rotating disk geometry. Korean J. Rheol. 3(1): 76.

Zhang K., Choi H. J. and Jang C. H. 2011. Turbulent drag reduction characteristics of poly(acrylamide-co-acrylic acid) in a rotating disk apparatus. Colloid and Polymer Science. 289(17-18): 1821-1827. doi: 10.1007/s00396-011-2502-0.