



Research article

Effect of oil on the performance of biopolymers as drag reducers in fresh water flow

Lawrence C. Edomwonyi-Otu^{a,b,*}, Abdulwahid I. Dosumu^b, Nurudeen Yusuf^c^a Department of Chemical and Petroleum Engineering, Delta State University, Abraka, Nigeria^b Department of Chemical Engineering, Ahmadu Bello University, Zaria, Nigeria^c Department of Chemical and Petroleum Engineering, Bayero University, Kano, Nigeria

ARTICLE INFO

Keywords:

Drag reduction
 Natural polymers
 Oil fractions
 Reynolds number
 Guar gum
 Xanthan gum

ABSTRACT

This study looks at the effectiveness of natural polymers (biopolymers) as drag reducers in flows of oil-water mixtures. The technique of using drag reducers to minimize the frictional drag in pipeline transportation of fluids is getting more challenging and there is need to be more environmentally friendly by using natural polymers. In this report, two natural polymers: xanthan gum (XG) and guar gum (GG), were used as drag reducers in a 12-mm ID straight conduit with water. The concentration of the gums was varied from 50 to 250 ppm while 25, 0.50 and 0.75 fractions of oil were mixed with freshwater. The molecular weight of the gums was also determined to gain insight into their influence on the rheology of the fluids. The result showed that the gums (natural polymers) performed better as drag reducer in freshwater than in mixture with oil. Specifically, the drag reduction (DR) of 200 ppm GG and XG solutions at Reynolds number of 59000 in freshwater was 39% and 44% respectively, while with the addition of 50% oil fraction, it was reduced to 19% and 32% respectively. DR reduced with oil fraction. It was concluded that XG performs better in the presence of oil than GG.

1. Introduction

Frictional drag is a primary cause of energy dissipation in a pipeline system. Such friction is formed as a result of the shear stresses developed between the fluid and the pipe wall [1]. Pumping systems used to reduce this friction constitute high ratio of global energy demand [2]. Therefore, efforts are being made by different researchers [3, 4, 5, 6] to look for substitutes such as the addition of certain polymeric materials to fluid flows in order to reduce frictional drag and in turn reduce pumping requirements during simulation and field applications [7]. This approach referred to as drag reduction (DR) [5] was first developed by Toms who observed significant DR when he added a few parts per million (ppm) of polymethylmethacrylate into monochlorobenzene solution [8].

The exact mechanism of the interaction of the material with the fluid that brings about drag reduction is still subjected to research and debate despite numerous experiments conducted [9]. Lumley [10] believed that DR is caused by the stretching of polymer chains. Here, when the randomly coiled polymer chain stretches, the effective viscosity increases, thereby reducing the wall friction and increasing the dimension of the buffer sub-layer resulting in the observed DR. Little et al. [11]

examined more mechanisms which supported Lumley hypothesis. Virk [12] believed that the contact of the polymer solution with the turbulence caused DR. He also put forward that increasing the maximum kinetic energy of the inner flow might have influence on DR. The postulation by Bermann [13] which focused on the examination of numerous molecular models indicated that maximum stretching of polymer molecule is irrelevant in DR.

Few researchers gave enhanced insight of DR mechanism using numerical simulation approach. Terrapon et al. [14] proved that the energy extorted from the near-wall vortices is the result of the stretching of the polymer molecules around the vortices. This approach has also been corroborated to explain the organized holding and discharge of power to the flowing fluid by the polymeric substances [15, 16]. The storage and the discharge of energy happen at the vortices close to the wall and at the regions closest to the wall respectively. Furthermore, this approach was applied to prove that the mixing of polymer serves as a DR relaxation process [17]. Den-Toonder et al. [18] applied direct simulation to check the functions of stress/shear rate anisotropy and elasticity on DR. The prevailing understanding is that as the polymer extend, the directional variation in viscous effect causes structural changes in turbulence and disorderliness that results to DR.

* Corresponding author.

E-mail address: uceclce@ucl.ac.uk (L.C. Edomwonyi-Otu).

It has been proven that natural polymeric additives are comparably resistant to degradation to their synthetic counterparts [7, 19]. Although, there are few natural polymeric additives well known for their performance as drag reducing agents (DRAs) in single phase flow, studies investigating these polymers in enhancing multiphase oil-water flows are limited in open literature [20, 21]. The use of natural gums has not been investigated on multiphase flows. Hence, in this study, the effect of oil on the performance of two natural polymeric additives, namely guar gum and xanthan gum, in freshwater were investigated and compared.

2. Materials and methods

2.1. Materials

Guar gum (GG) and xanthan gum (XG), both >95% purity, were obtained off the shelf in powdered form and used without further purification. A master solution of 10,000 ppm was prepared separately from each polymer samples. This was achieved by measuring 30 g of each samples with the aid of electronic balance (CWS Series, 180 g max.). Each sample was gently poured into 3 L of tap water in a 10-liter vessel while being gently stirred to avoid lump formation and for homogeneous delivery of the polymeric substances while in the polymer-water system. The mixture was being stirred at a minimum speed for about 4 h by slow magnetic stirrer to reduce shear effect from the blades and then left to stand for 12 h for proper hydration of the polymer particles [22]. The solution was then ready for dilution to obtain the required concentrations.

2.2. Experimental setup

The flow system shown in Figure 1 is used for obtaining the experimental data for all polymer concentrations. It is made up of the handling, regulating and testing sections. The handling section contain two separate tanks of capacity 200 L for the oil and freshwater respectively, and a 220-liters gravity separator. The regulating section comprises of two (2) centrifugal pumps (Jet 102M/N.31227) for circulating the oil and the water, an ultra-flux portable flow meter (LZM-20J) with precision of $\pm 2\%$ for measuring flow rates and flow control valves.

The testing section is made up of two parallel 1.2-cm internal diameter (ID) conduits made from unplasticized polyvinyl chloride (uPVC) which are coupled together by flanges for easy separation. There is also a Pyrex manometer (U-tube) with mercury as the measuring fluid for pressure drop determination, as well as a new Era Peristaltic Pump

(Model: NE-9000) with precision of $\pm 2\%$ for injecting polymer into the testing section.

The flow loop was designed in such a way that the freshwater in the water tank is pumped at a measured flow rate from the bottom outlet while oil in the oil tank is similarly pumped from the top. Both fluids met at the Y-junction measured at an angle of 30° to ensure minimum mixing of the fluids at the inlet of the test section. The pressure ports (0.5 m apart) was positioned 3 m from away from the inlet of the testing section in order to guarantee fully developed flow before taking pressure drop measurements. The mixture is then allowed to flow back to the separator, where both mixtures are separated by gravity. The water which is denser than the oil is allowed to drain to the sink from the bottom of the separator, while the oil is recycled to the oil tank. The centrifugal pump rated at 0.75 kW, 220–240 V was used to ensure steady circulation of the test fluids around the flow loop. The flow meters of each fluid were calibrated before the start of the experiments with obtained R^2 values greater than 0.98.

Table 1 shows some of the properties of the freshwater and oil used in this investigation. All samples were used as obtained without further purification.

2.3. Experimental procedure

2.3.1. Molecular weight (MW) measurement

0.05 g/dl polymer solution was prepared from each component of guar gum and xanthan gum. Each sample was then diluted with the aid of Ostwald viscometer (VS 135) at ambient condition to get different solute-water ratio ranging from 0.01 - 0.05 g/dl and the various viscosities estimated. The intrinsic viscidities were then evaluated by taking reduced viscosity at various solute-water ratio and extending to $c = 0$. Thus, by substituting the intrinsic viscosity into Mark-Houwink's Eq. (1), the MW was then estimated.

$$[\mu] = KM^a \quad (1)$$

Where $[\mu]$ is the intrinsic viscosity, M is the average MW, K and a are constants for a specific solvent, temperature and polymer system.

At 25 °C, for guar gum, $K = 3.800 \times 10^{-4}$ dl/g and $a = 0.732$ [23] while for xanthan gum, $K = 2.790 \times 10^{-7}$ dl/g and $a = 1.2754$.

2.3.2. Pressure drop (ΔP) measurement

The effect of polymer concentrations on freshwater were first investigated. The results from the segment were to provide answer to the

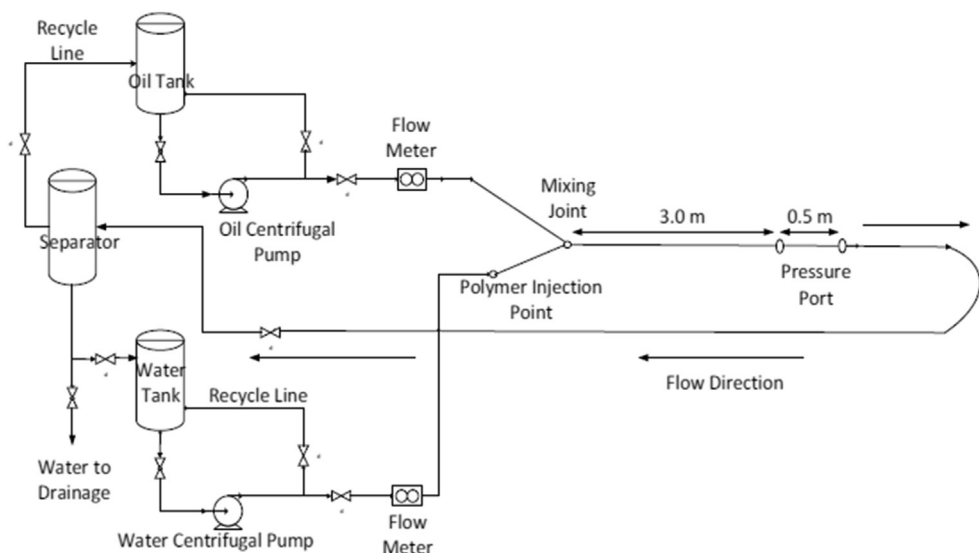


Figure 1. Schematic diagram of the experimental flow rig.

Table 1. Physical property of the test fluids at 25 °C.

Property	Water	Oil
Viscosity (cP)	1	3.5
Density (kg/m ³)	998	832

question: At what concentration should the test be carried out in oil-water flows? Polymer concentration was varied from 50 to 250 ppm in freshwater flow. Testing was performed at water flow rates ranging from 10 to 35 l/min. The operation began by pumping water from its storage tank to the testing section at a measured flow rate. Within a minimum of 5 min when the flow is stable, the pressure drop was measured. Subsequently, the different polymer concentrations were added and the pressure drop values also measured [24]. Same approach was followed for the studied water velocities (superficial and in-situ). The experiments were repeated at least three times and the average value recorded with error/deviations less than 4%.

In order to study how oil affects the performance of the natural polymeric substances, oil-water flow experiment was performed at variable mixture velocity (Um) and input oil fraction (αo) of 0.25, 0.5 and 0.75. The experiments were done at time intervals of 50 min to avert temperature rise of the oil-phase by the shearing effect of the centrifugal pump. In each of the test conducted (i.e. for each Um and a fixed αo), the oil was initially pumped to the regulating section, where it was metered. Subsequently, the water was similarly pumped and metered before mixing with the oil at the Y-junction (Figure 1). The mixture was then transferred to the testing section. After attaining stability within a minimum of five minutes, the pressure drop was measured. The master polymer solution was then infused to the water flow line before the Y-junction and the pressure drop was also measured [25]. This was done for each polymer solution separately.

The same experimental procedure was repeated for different ratios of oil and water flow rates. Reproducibility of the experimental data was checked by performing the experiment in triplicate and the average was recorded to be less than 5%. Drag reductions by drag reducing polymers (DRPs) were calculated from Eq. (2) using the experimental pressures while Reynolds numbers were calculated from Eq. (3).

$$\%DR = \frac{(\Delta P_o - \Delta P)}{\Delta P_o} \times 100 \tag{2}$$

Where ΔPo is the pressure drop without DRP and ΔP is the pressure drop with DRP [26].

$$Re = \rho VD / \mu \tag{3}$$

Where ρ is fluid density, D is pipeline diameter, V is mean flow velocity and μ is the viscosity [27].

3. Results and discussion

3.1. Molecular weight measurement

Figure 2 show the plot of reduced viscosity against different concentrations of polymers tested. By extrapolation, the intrinsic viscosity of guar gum and xanthan gum were calculated to be 9.33 and 22.38 g/dl respectively. It is very obvious that the intrinsic viscosity of XG is high compared to that of GG. This might be due to the rigidity of the polymer molecules as well as the presence of coulomb forces in the aqueous solution of xanthan gum [28].

By substituting for intrinsic viscosity into Eq. (1), the MW of guar gum and xanthan gum was calculated to be 994,040 g/mol and 1,575,700 g/mol respectively. The calculated molecular weights are close to reported values of 954,000 and 1,675,310 g/mol for GG and XG respectively [29, 30]. The variation in the molecular weight values of the gums reported by Mahmoud [29] and Martin [30] might be due to the difference in species or purification level of samples used.

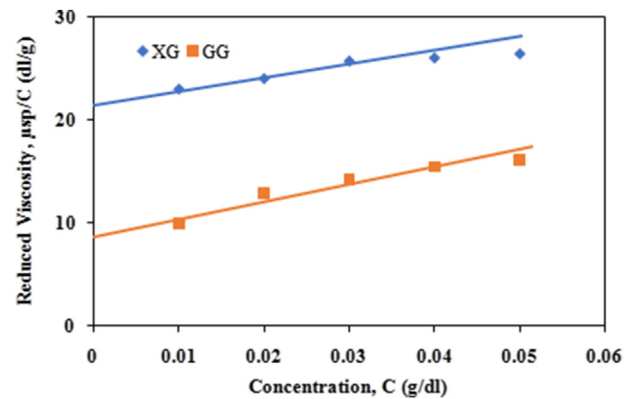


Figure 2. Reduced viscosity against polymer at ambient temperature.

3.2. Effect of polymer concentrations on DR

The effect of polymer concentrations in freshwater was investigated at different water velocities expressed in terms of Reynolds number and the results presented in Figures 3 and 4. It can be observed that DR increased with increasing polymer concentration before reaching a plateau at polymer concentration of 150 ppm. This is because as the polymer concentration was increased, there was more polymer molecules interacting with eddies inside the main flow system. This caused an apparent increase in the viscosity of the fluid and hence increases in the observed DR [28]. Also, from Figures 3 and 4, it was revealed that XG performed better in terms of reducing frictional drag in comparison to guar gum.

Specifically, at Reynolds number of 59000, maximum drag reduction values of 39 % and 44 % were attained when 200 ppm of guar gum and xanthan gum solutions were added respectively. The high value of drag reduction with xanthan gum might be due to its high molecular weight (1,575,695 g/mol) compared to that of the guar gum which was 994,035 g/mol [31]. Further increase of polymer concentration beyond this value did not cause appreciable increase in the drag reductions. This is because an optimum additive-liquid balanced concentration was reached beyond which no effect was observed [21, 32]. It is believed that the turbulence spots become saturated with the polymer and further increase in polymer concentration will not yield significant drag reduction [32]. At this saturation point, the polymer was unable to stretch further, thereby leading to no change or in most cases, slightly drops in drag reduction.

These results also revealed that the optimum performances of the polymer solutions studied is dependent on the extent of turbulence. By increasing the flow inside the pipes, the extent of turbulence will also

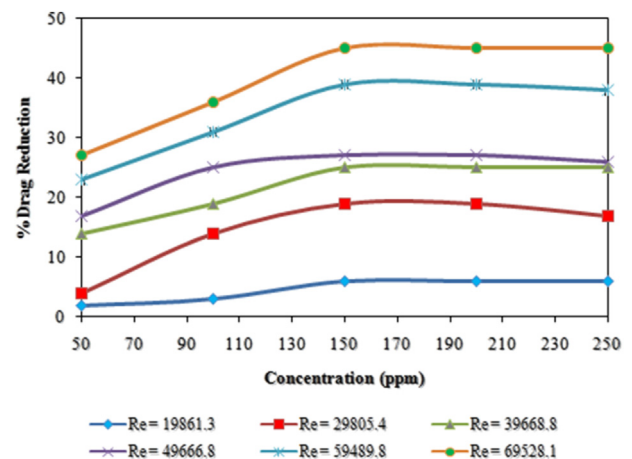


Figure 3. Drag reductions in single water flow by guar gum at different polymer concentrations and Reynolds numbers through 1.2-cm internal diameter pipe.

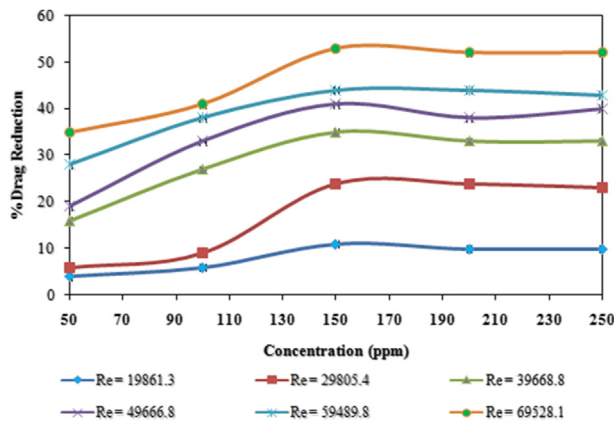


Figure 4. Drag reductions in single water flow by xanthan gum at different polymer concentrations and Reynolds numbers through 1.2-cm internal diameter pipe.

increase thus providing more favourable environment for the polymer solutions to perform. Generally, based on the experiments carried out, all concentrations reduced drag in the range of Re investigated. Most of the experimental results agree well with the previous works published by many researchers such as Ram et al. [20], Reddy and Singh [33] and Kulmatova [1]. Based on the observed drag reductions, polymer concentration of 200 ppm was selected for both polymers in the multiphase oil-water flow investigation to ensure that maximum drag reductions were achieved.

3.3. Effect of input oil volume fraction on DR

Based on the observations in the preceding section, the performance of the polymers in freshwater flow is identical. Therefore, polymer concentration of 200 ppm was chosen to study the effect of oil on the performance of natural polymers in freshwater flow and the results shown in Figures 5 and 6. From both figures, it can be observed that guar gum was much more sensitive to the presence of oil than xanthan gum. For instance, at 0.5 input oil fraction and mixture velocity of 4.67 m/s, the DR by guar gum dropped from 39 % to 19 %. That of xanthan gum decreased from 44 % to 32 %.

Generally, the experimental results proved that the addition of oil reduced the performance of the polymers in freshwater flow. This is anticipated as water soluble polymers were used in this investigation. Hence, increasing the input oil fraction inhibits the interaction of the polymer molecules with the water phase [26, 34, 35]. In other words, the oil inhibited the elongation of the polymer chain under turbulences and

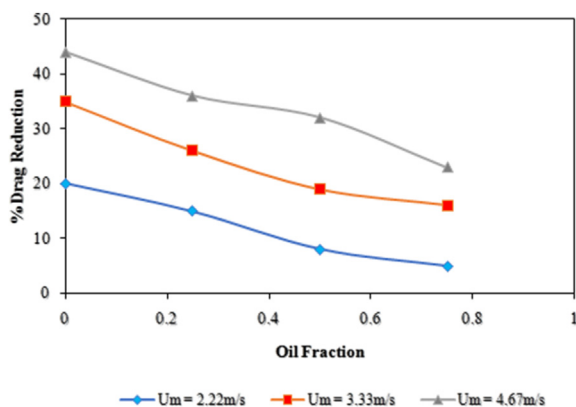


Figure 5. Effect of input oil fraction on oil-water drag reduction at different mixture velocities by 200 ppm xanthan gum at different mixture velocities through 1.2-cm internal diameter pipe.

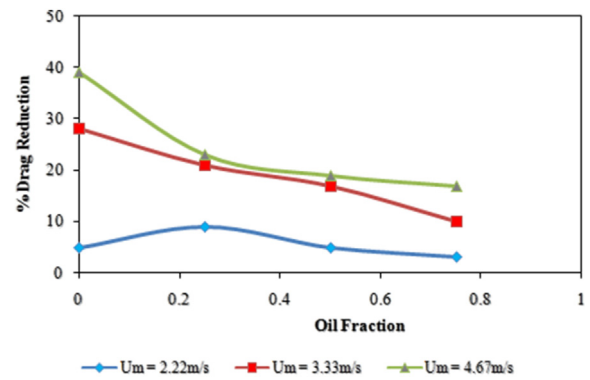


Figure 6. Effect of input oil fraction on oil-water drag reduction at different mixture velocities by 200 ppm guar gum at different mixture velocities through 1.2-cm internal diameter pipe.

therefore decreased the DR. The general observations so far showed that the xanthan gum performed better than the guar gum. This might also be due to difference in molecular weight as observed in the single-phase water flow [31, 36]. It is known that the higher the molecular weight of a polymer, the more polymer entanglements and aggregates are formed and these have been indicated to enhance drag reduction [37, 38].

4. Conclusion

This work centered on investigating the effect of oil on the performance of natural polymers in freshwater flow and the results summarized as follows:

Xanthan gum (XG) performed better than guar gum (GG) in freshwater. The DRs of GG and XG at 200 ppm in freshwater were 39 % and 44 % respectively. Natural polymers performed better as drag reducer in freshwater than in mixture with oil. However, more types of natural polymers need to be used to validate this observation.

XG performed better with the presence of oil than GG. The DRs of GG and XG at 200 ppm and 0.5 input volume oil fractions were 19 % and 32 % respectively. This shows that the addition of oil to fresh water flow reduced the interaction of the natural polymers with the fresh water.

The exploitation of the enormous opportunities for research within this dynamic field of expertise cannot be over emphasized. However, there are still many areas of uncertainties to be addressed. Therefore, from applied point of view, the following should be recommended for future research:

The effects of salinity and temperature have not been adequately investigated in oil-water flows. Hence, more works are needed in this area to address the performance of DRPs.

Further investigation on drag reduction should be carried out in vertical or near-vertical oil-water flows.

For industrial purposes, correlation models for pipe diameter scale-up are needed.

Consent of publication

All listed Authors have consented to the publication of this manuscript in Heliyon Journal.

Declarations

Author contribution statement

Lawrence C. Edomwonyi-Otu: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Dosumu I. Abdulwahid: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Nurudeen Yusuf: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported by the Petroleum Technology Development Fund (PTDF) Nigeria scholarship program for local postgraduate studies, and the Multiphase Flow and Separation Systems Research Group of the Ahmadu Bello University Zaria, Nigeria.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The Authors wish to appreciate the support of the Technical Team, and members of Multiphase Flows and Separation Systems Research Group of the Department of Chemical Engineering Ahmadu Bello University Zaria, Nigeria.

References

- [1] D. Kulmattova, Turbulent Drag Reduction by Additives, University of Amsterdam, 2013.
- [2] A.M. Hameed, R.S. Hamied, Z.Y. Shnain, Drag-reducing agent for aqueous liquid flowing in turbulent mode through pipelines, *Al-Khwarizmi Eng. J.* 10 (2) (2014) 15–22.
- [3] T. Al-Wahaibi, M. Smith, P. Angeli, Effect of drag-reducing polymers on horizontal oil–water flows, *J. Petrol. Sci. Eng.* 57 (3–4) (Jun. 2007) 334–346.
- [4] M. Al-Yaari, A. Soleimani, B. Abu-Sharkh, U. Al-Mubaiyedh, A. Al-Sarkhi, Effect of drag reducing polymers on oil–water flow in a horizontal pipe, *Int. J. Multiphas. Flow* 35 (6) (Jun. 2009) 516–524.
- [5] D. Mowla, A. Naderi, Experimental study of drag reduction by a polymeric additive in slug two-phase flow of crude oil and air in horizontal pipes, *Chem. Eng. Sci.* 61 (5) (Mar. 2006) 1549–1554.
- [6] L.C. Edomwonyi-Otu, M. Chinaud, P. Angeli, Effect of drag reducing polymer on horizontal liquid-liquid flows, *Exp. Therm. Fluid Sci.* 64 (2015) 164–174.
- [7] M.N. Abdallah, L.C. Edomwonyi-Otu, N. Yusuf, A. Baba, Aloe vera mucilage as drag reducing agent in oil-water flows, *Arid Zo. J. Eng. Technol. Environ.* 15 (2) (2019) 248–258.
- [8] B.A. Tom, Some observations on the flow of linear polymer solutions through straight tubes at large Reynolds numbers, in: *First International Congress on Rheology*, 2, 1948, pp. 135–141.
- [9] L.C. Edomwonyi-Otu, *Drag Reduction in Oil-Water Flows*, University College, London, UK, 2015.
- [10] J.L. Lumley, Drag reduction by additives, *Annu. Rev. Fluid Mech.* 1 (1969) 367.
- [11] R.C. Little, R.J. Hansen, D.L. Hunston, O. Kim, R.L. Patterson, R.Y. Ting, The drag reduction phenomenon, observed characteristics, improved agents, and proposed mechanisms, *Ind. Eng. Chem. Fundam.* 14 (1975) 283–296.
- [12] P.S. Virk, Drag reduction fundamentals, *AIChE J.* 21 (4) (1975) 625–656.
- [13] N.S. Berman, Drag reduction by polymers, *Annu. Rev. Fluid Mech.* 10 (1978) 47–64.
- [14] V.E. Terrapon, Y. Dubief, P. Moin, E.S.G. Shaqfeh, S.K. Lele, Simulated polymer stretch in a turbulent flow using Bronian dynamics, *J. Fluid Mech.* 504 (2004) 61–71.
- [15] Y. Dubief, C.M. White, V.E. Terrapon, E.S.G. Shaqfeh, P. Moin, S.K. Lele, On the coherent drag-reducing and turbulence-enhancing behaviour of polymers in wall flows, *J. Fluid Mech.* 514 (Sep. 2004) 271–280.
- [16] Y. Dubief, V.E. Terrapon, C.M. White, E.S.G. Shaqfeh, P. Moin, S.K. Lele, New answers on the interaction between polymers and vortices in turbulent flows, *Flow, Turbul. Combust.* 74 (2005) 311–329.
- [17] C.D. Dimitropoulos, Y. Dubief, E.S.G. Shaqfeh, P. Moin, Direct numerical simulation of polymer-induced drag reduction in turbulent boundary layer flow of inhomogeneous polymer solutions, *J. Fluid Mech.* 566 (2006) 153–162.
- [18] J.M.J. Den Toonder, M.A. Hulsen, G.D.C. Kuiken, F.T.M. Nieuwstadt, Drag reduction by polymer additives in a turbulent pipe flow: numerical and laboratory experiments, *J. Fluid Mech.* 337 (Apr. 1997) 193–231.
- [19] M.M. Gimba, A. Edomwonyi-Otu, Lawrence C. Abubakar, Y. Nurudeen, “Synergistic effect of natural and synthetic polymers as drag reducing agents in single phase water flow, *Niger. J. Mater. Sci. Eng.* 7 (2017) 16–22.
- [20] P.S. Ram, S. Pal, S. Krishnamoorthy, P. Adhikary, A.S. Ali, High-technology materials based on modified polysaccharides, *J. Pure Appl. Chem.* 81 (2009) 525–547.
- [21] H.A. Abdulbari, S. Nuraffini Bt Kamarulizam, M.Y. R. A. Gupta, Introducing slag powder as drag reduction agent in pipeline: an experimental approach, *Sci. Res. Essays* 7 (18) (2012) 1768–1776.
- [22] A. Dosumu, I. Abdulwahid, Edomwonyi-Otu, Lawrence C. Abubakar, Y. Nurudeen, Effectiveness of natural gums as drag reducing agent in oil-water flows, *Niger. J. Mater. Sci. Eng.* 8 (2018) 44–50.
- [23] K.N. Venugopal, M. Abhilash, Study of hydration kinetics and rheological behaviour of guar gum, *Int. J. Pharmaceutical Sci. Res.* 1 (2010) 28–30.
- [24] A.I. Dosumu, L.C. Edomwonyi-Otu, A. Abubakar, N. Yusuf, Drag reduction performance of natural gums in oil-water flow through pipes of different diameters, *Niger. Res. J. Eng. Environ. Sci.* 4 (1) (2019) 17–26.
- [25] L.C. Edomwonyi-Otu, A.H. Barral, P. Angeli, Influence of drag reducing agents on interfacial wave characteristics in horizontal oil-water flows, in: *The 16th International Conference on Multiphase Production Technology*, 2013, pp. 353–362.
- [26] M. Robert, J. Vancko, Effects of A Drag Reducing Agent on Pressure Drop and Flow Regime Transitions in Multiphase Horizontal Low Pressure Pipelines, *Water*, 1997, pp. 35–40.
- [27] H.F. Fadhl, Silica powder as drag reducing agent in gas-oil flowing in pipeline system, in: *First Scientific Conference on Modern Technologies in Oil & Gas Refinery*, 2011, pp. 1–14, 1.
- [28] H.A. Abdulbari, A. Shabirin, H.N. Abdurrahman, Bio-polymers for improving liquid flow in pipelines-A review and future work opportunities, *J. Ind. Eng. Chem.* 20 (4) (Jul. 2014) 1157–1170.
- [29] N.M. Mahmoud, *Physico-chemical Study of Guar Gum*, University of Khartoum, Khartoum, 2000.
- [30] A.M. Martin, Mark-houwink parameters for aqueous-soluble polymers and biopolymers at various temperatures, *J. Polym. Biopolym. Phys. Chem.* 2 (2) (2014) 37–43.
- [31] L.C. Edomwonyi-Otu, Distortion of velocity profiles of water flow with heavy molecular weight polymers, *Transf. Phenom. Fluid Heat Flows VII J. Defect Diffus. Forum* 392 (2019) 228–238.
- [32] K. Hoyer, A. Gyr, A. Tsinober, On the mechanism of drag reduction in dilute polymer solutions, *Appl. Sci. Res.* 55 (4) (1996) 289–295.
- [33] G.V. Reddy, R.P. Singh, Drag reduction effectiveness and shear stability of polymer-polymer and polymer-fibre mixtures in recirculatory turbulent flow of water, *Rheol. Acta* 24 (1985) 296–311.
- [34] M.M. Gimba, L.C. Edomwonyi-Otu, Drag reduction with polymer mixtures in oil-water flows: effect of synergy, *J. Turkish Chem. Soc. B Chem. Eng.* 3 (1) (2020) 1–8.
- [35] I.A. Dosumu, L.C. Edomwonyi-Otu, N. Yusuf, A. Abubakar, Guar gum as flow improver in single-phase water and liquid – liquid flows, *Arabian J. Sci. Eng.* 45 (2020) 1–7.
- [36] A. Al-Sarkhi, Drag reduction with polymers in gas-liquid/liquid-liquid flows in pipes: a literature review, *J. Nat. Gas Sci. Eng.* 2 (1) (Mar. 2010) 41–48.
- [37] C.S. Makanza, J.P. Dunne, *Current Account Dynamics and Monetary Policy Transmission in South Africa*, July, 2015, pp. 1–37.
- [38] L.C. Edomwonyi-Otu, P. Angeli, Effects of polymer addition on pressure drop and interfacial waves in horizontal oil-water flows, *Pet. Technol. Dev. J.* 2 (July) (2014) 5–18.