

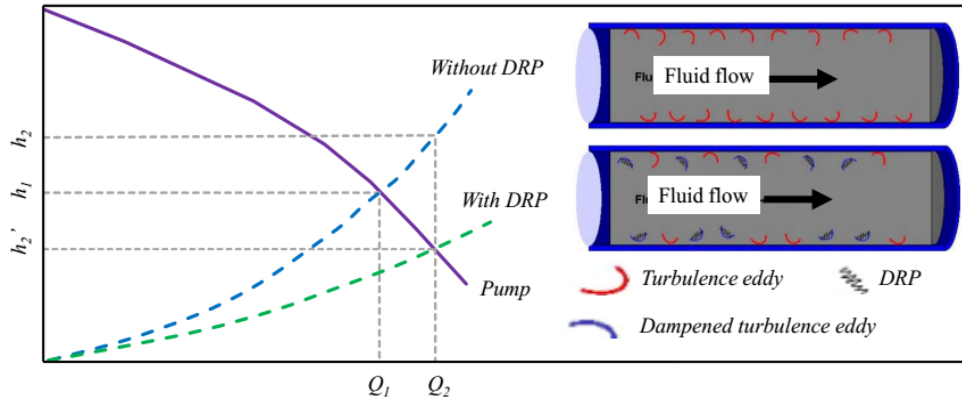
# Drag-Reducing Polymers as Energy-Saving Agents in Horizontal Two-Phase Oil-Water Dispersed Flow

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**ABSTRACT:** In this era of scarce and expensive energy, it has become imperative to devise means of reducing energy consumption, particularly in petroleum industries where huge amounts of energy are usually consumed. It is within this context that attempts have been made to reduce the energy consumption during pump-driven fluid transportation by the addition of drag-reducing polymers (DRPs), which mitigate the adverse frictional drag caused by the pipe wall. Hence, this study focused on quantifying the energy savings by the DRPs in dispersed oil-water flow at different Reynolds numbers using twelve DRPs, which possess different combinations of properties such as molecular weight, charge density, and ionic type. The results revealed substantial savings in energy in all cases with the highest saving of about 60.4%. Molecular weight posed a positive and most dominant impact among the three polymer properties investigated. The charge density slightly increased the energy savings at low values while the reverse was the case at high values. Cationic polymers produced slightly better performances than their anionic counterparts of comparable molecular weights and charge densities. Specifically, the energy saving at oil fractions of 0.1 and 0.3 increased from 6.9 to 60.4% and 5 to 51.9%, respectively, indicating the negative impact of the oil fraction. Overall, the use of DRPs has proved to be an efficient and sustainable means of saving substantial amounts of energy required to overcome the frictional drag in pipe flow.

**Keywords:** Drag-reducing polymer; energy-saving agents; head loss; oil-water flow.

## البوليمرات المخفضة للسحب كعوامل لتوفير الطاقة في تدفق النفط والماء ثنائي الطور الأفقي المتشتت

عبدالكريم أبو بكر, محمد إشراتي, طلال الوهبي, عبد العزيز الهاشمي, يحيى الوهبي, عادل العجمي

**الملخص:** في هذا العصر الذي يعاني من ندرة وارتفاع تكلفة الطاقة، أصبح من الضروري ابتكار وسائل لتقليل استهلاك الطاقة، خاصة في الصناعات البترولية التي تستهلك كميات هائلة من الطاقة عادةً. في هذا السياق، تم إجراء محاولات لتقليل استهلاك الطاقة أثناء نقل السوائل بواسطة المضخات من خلال إضافة البوليمرات المخفضة للسحب (DRPs)، والتي تقلل من السحب الاحتكاكي الضار الناجم عن جدار الأنبوب. لذلك، ركزت هذه الدراسة على قياس توفير الطاقة بواسطة البوليمرات المخفضة للسحب في تدفق النفط والماء المتشتت عند أرقام رينولدز المختلفة باستخدام اثني عشر بوليمراً، تمتلك تركيبات مختلفة من الخصائص مثل الوزن الجزيئي، كثافة الشحنة، والنوع الأيوني. وكشفت النتائج عن توفير كبير في الطاقة في جميع الحالات مع أعلى نسبة توفير بلغت حوالي 60.4%. وكان للوزن الجزيئي تأثير إيجابي وأكثر هيمنة بين الخصائص الثلاثة للبوليمر التي تم التحقيق فيها. وزادت كثافة الشحنة من توفير الطاقة عند القيم المنخفضة بينما كان العكس هو الصحيح عند القيم العالية. وأظهرت البوليمرات الكاتيونية أداءً أفضل قليلاً من نظيراتها الأنيونية ذات الأوزان الجزيئية وكثافات الشحنة المماثلة. على وجه التحديد، زاد توفير الطاقة عند كسور النفط بنسبة 0.1 و 0.3 من 6.9% إلى 60.4% ومن 5% إلى 51.9% على التوالي، مما يشير إلى التأثير السلبي لجزء النفط. بشكل عام، أثبت استخدام البوليمرات المخفضة للسحب كوسيلة فعالة ومستدامة لتوفير كميات كبيرة من الطاقة المطلوبة للتغلب على السحب الاحتكاكي في تدفق الأنابيب.

**الكلمات المفتاحية:** البوليمرات المخفضة للسحب؛ عوامل توفير الطاقة؛ فقدان الرأس؛ تدفق النفط والماء.

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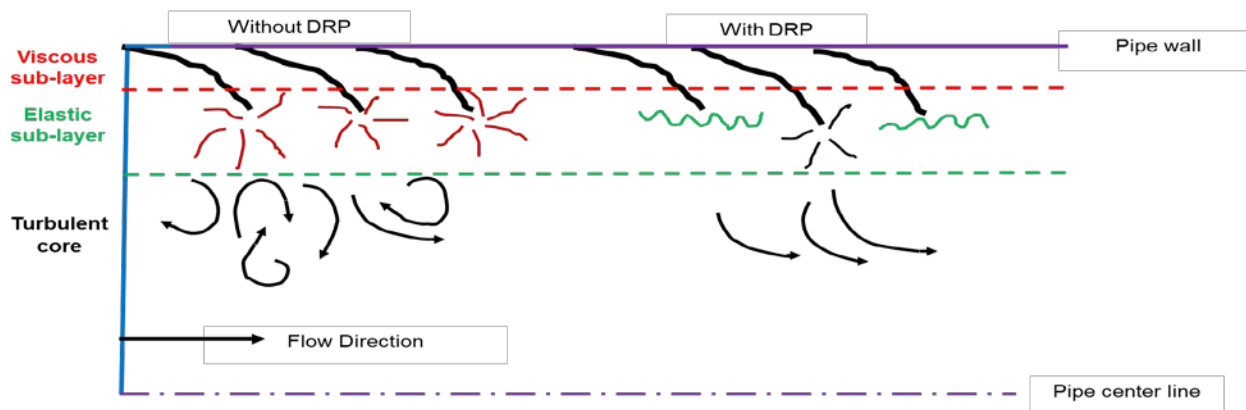


## 1. INTRODUCTION

Drag reduction has been defined as the decrease in pressure loss at a constant flow rate in turbulent pipe, tube or channel flow caused by the addition of small amounts of additives to the carrier fluid. Just a year before the formal discovery of the drag reduction phenomenon by Toms in 1948, Mysels had discovered that the addition of aluminium soap to gasoline lowered the resistance of the fluid to turbulent flow in a pipe. The additives causing drag reduction can be divided into five categories: polymers, surfactants, fibres, micro-bubbles, and compliant coating. However, among all the drag-reducing agents (DRAs), the use of polymers as drag reducers in turbulent single and multiphase flows has been most employed at the industrial level. This is because the polymer additives are the most effective DRAs, even at low concentrations as minute amounts of long-chain polymer molecules dissolved in water or in organic solvents have a tremendous ability to dramatically reduce the frictional drag of turbulent flow of the polymer solution through pipes and channels. In pipe flows for example, drag reduction of up to 80 % can be achieved by adding just a few parts per million (ppm) of polymer (Gimba and Edomwonyi-Otu, 2020; Akbari *et al.*, 2020; Zhang, 2020; Ayegba *et al.*, 2021). The potential benefits

of polymeric drag reduction, from practical and fundamental fluid dynamics points of view, is the reason there has been an explosion of research work in many countries on this subject during the last five decades. As stated earlier, this remarkably fascinating knowledge was first discovered by Toms in 1948 when he was conducting experiments to study the degradation of polymers in pumps. Meanwhile, it is important to note that although drag-reducing polymers have directly contributed to the reduction of pressure drops in single-phase flows, multiphase flows in pipes are a much more complex process compared to single-phase flows due to phase interaction and redistribution within the cross-sectional area of the pipeline. The overall pressure loss in pipelines in a multiphase flow regime depends on fluid properties and flow conditions (Burlutskiy, 2012; Al-Dawery *et al.*, 2022; Alsarkhi and Salah, 2023).

Drag-reducing polymers are long-chain, ultra-high molecular weight (typically ranging from 1 to 15 million Da) polymers which can be soluble in water or oil phase. With the higher molecular weight polymers giving better drag reduction performance, only a few parts-per-million concentrations of the polymers in the working fluid is enough to suppress the formation of turbulent bursts in the buffer (or elastic) sub-layer and in turn suppress the formation and propagation of turbulent eddies (Figure 1).



**Figure 1.** The effect of drag-reducing polymer in the near-wall region of a pipeline (Nelson and Hennion, 2003)

The bursts are caused by the large difference in fluid velocity between the laminar (or viscous) sub-layer and the turbulent core. The suppression of the turbulent eddies allows the hydraulic energy provided by the pumps to be more directed towards moving the fluid down the pipeline rather than being used for a chaotic and random motion (Nelson and Hennion, 2003). In other words, the suppression of turbulent eddies will inevitably translate into a reduction in head losses and the saving of a significant amount of energy consumption by the pumps during fluid transportation (Mahmood *et al.*, 2022; Alsurakji *et al.*, 2023). Meanwhile, the method of injecting a polymer into the fluid flow has a significant influence on the performance of the polymer. The two well-known methods are homogeneous and heterogeneous methods. The former involves the direct

mixing of the polymer with the fluid for several hours before the solution is pumped through a pipe. The latter involves the injection of initially prepared polymer solution into the fluid flow after the pump (Smith and Tiederman, 1991). In short, it can be found that, in most cases, the polymers perform better when they are injected through a heterogeneous method than through a homogeneous method (Vlachogiannis *et al.*, 2003, Baik *et al.*, 2005, Wyatt *et al.*, 2011).

Several studies have been carried out using numerical approaches to come up with a model that accurately elucidates polymer drag reduction mechanism without achieving a consensus (Thais *et al.*, 2013; Asidin *et al.*, 2019, Serafini *et al.*, 2022; Utomo *et al.*, 2021; Zhang, 2020). In recent times, the use of natural or bio-based polymers in place of the well-established synthetic

counterparts has been prioritized. In comparison, natural, eco-friendly polymers are less effective than synthetic ones chiefly because of the high presence of impurities that need to be removed to enhance their performances (Prasad *et al.*, 2020; Rajappan, 2020; Al-Dawery *et al.*, 2022).

The energy and cost-benefit analyses that have been reported in the literature are few and mostly directed towards only single-phase flows using a particular type of drag-reducing polymer without taking into consideration the influence of the unique characteristic features of different polymers. For instance, Cuenca *et al.* (2008) developed an energy-saving model for oil pipelines that used drag-reducing additives. This was achieved in two ways - using power reduction at a constant oil flow rate and using the increase in fuel flow rate at constant power. They found out that a 42.6% reduction in energy or a 43% increase in flow rate could be achieved using an oil flow rate of 320 m<sup>3</sup>/h with a polymer concentration of 20 ppm. Matras and Kopiczak (2018) studied the possibility of using drag-reducing polymers and surfactants to reduce the cost of transport energy in water systems. Without stating specific values, they discovered that a significant increase in the flow rate without the necessity of increasing the power demand or a reduction in the power demand while maintaining a constant flow rate could be achieved by the co-addition of polymer and surfactant to water solvent. Akbari *et al.* (2020) investigated the increase in the flow capacity of single-phase water flow in microtubes by drag-reducing polymers. Using the best concentrations of all the polymers used, they achieved about a 36% increase in the flow capacity at 20 ppm concentration. Alsurakji *et al.* (2023) carried out experimental insights into energy savings and future directions of drag-reducing polymers in single-phase water and oil flows, two-phase air-water and air-oil flows, and three-phase air-oil-water flow. They used two pipes of different diameters and material types and evaluated two polymers (water-soluble and oil-soluble). They discovered that although the soluble polymer was more promising, there was a reduction in head loss, an increase in energy savings, and an increase in throughput irrespective of the type of flow or variations in liquid and airflow rates. Al-Sarkhi *et al.* (2024) optimized water jet pump efficiency via drag-reducing polymers. They achieved this by introducing drag-reducing polymers into the suction flow of the water jet pump using a specific configuration. The results show a significant reduction in drag within the water jet pump, raising its efficiency in some cases from 13.8% to 26.7%.

From the aforementioned, most of the studies concentrated on single-phase flows and none of the studies considered the polymer properties. In addition, energy analysis of polymers in oil-water flow is lacking. To bridge these gaps, this study was intended to focus on analyzing the energy benefits of adding drag-reducing polymers to two-phase oil-water flow in a dispersed regime. Secondly, detailed comparisons of the performances of the different polymers were made with a

view to understanding the relative contribution of each polymer property to energy saving. To achieve this, the performances in terms of energy savings of twelve polymers with different combinations of molecular weight, ionic type, and charge density, were investigated as a function of Reynolds number and as a function of oil fraction. This will undoubtedly help industries in selecting the right combinations of polymer properties that can guarantee high energy savings in their fluid transportation systems.

## 2. MATERIALS AND METHOD

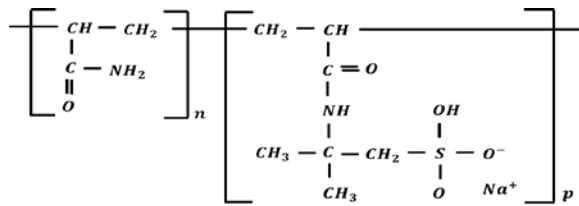
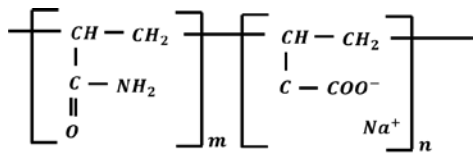
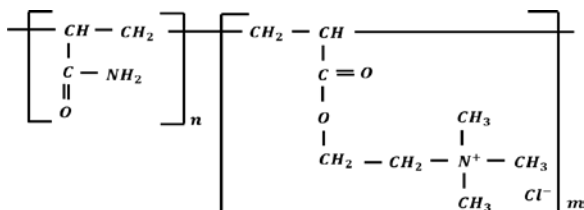
The materials used for this study were working fluids (tap water and hydraulic fluid based on mineral oil, which is commercially known as Shell Tellus S2 V 15) as well as twelve (12) drag-reducing polymers shown in Table 1. The tap water has a density of 997 kg/m<sup>3</sup>, a viscosity of about 1 cP, and a surface tension of 71.4 mN/m while the oil has a density of 872 kg/m<sup>3</sup>, a viscosity of 24 cP, and a surface tension of 29.5 mN/m.

The polymers consisting of eight (8) anionic types and four (4) cationic types were produced by SNF Floerger Company, headquartered in France. Each of these polymers has different combinations of ionic type, molecular weight, and charge density. For easy identification of the values of their properties, the commercial names of these polymers (AN105SH, AN113SH, AN125SH, AN125, AN125VLM, AN934BPM, FLOPAMM3430S, FLOPAMM3630, FO4190, FO4190SH, FO4190VHM, and FO4550SH), were replaced in this work with nomenclatures (A-12-5, A-12-13, A-12-25, A-6-25, A-2.5-25, A-6-30, A-12-30, A-20-30, A-5-10, A-7-10, A-12.5-10, and A-5.5-45), respectively.

The letters in the nomenclature names denote the ionic types (A for anionic and C for cationic), the first numbers denote the molecular weights, and the last numbers denote the charge densities. As presented in Figures 2, 3, and 4, all the polymers were produced using a copolymerization process with acrylamide as the base monomer. Polymer master solutions with concentrations of 1000 ppm were prepared by dissolving the polymer granules in tap water and allowed to homogenize for 24 hours. The detailed experimental procedure for the preparation of the master solution of the polymers has been previously published (Eshrati *et al.* 2015). The polymer master solution was injected into the oil-water flow at the test section with the help of a Masterflex I/P<sup>®</sup> tubing pump, manufactured by Barnant Company Division, Cole-Parmer Instrument Company, at different flow rates and at a distance of 1.5 m from the entrance of the test section so that the desired polymer concentration of 30 ppm could be achieved. This pump was considered the most suitable for shear-sensitive fluids like polymers and blood to avoid mechanical degradation of the polymer during injection into the flow line since it operates peristaltically (Klespitz and Kovács, 2014).

**Table 1.** Drag-reducing polymers and their properties.

S/No.	Polymer Commercial Name	Polymer Nomenclature	Ionic Type	Average MW (x 10 <sup>6</sup> Da.)	Charge Density (%)
1	AN105SH	A-12-5	Anionic	12	5
2	AN113SH	A-12-13		12	13
3	AN125SH	A-12-25		12	25
4	AN125	A-6-25		6	25
5	AN125VLM	A-2.5-25		2.5	25
6	AN934BPM	A-6-30		6	30
7	FLOPAMM3430S	A-12-30		12	30
8	FLOPAMM3630	A-20-30	20	30	
9	FO4190	C-5-10	Cationic	5	10
10	FO4190SH	C-7-10		7	10
11	FO4190VHM	C-12.5-10		12.5	10
12	FO4550SH	C-5.5-45		5.5	45

**Figure 2.** Anionic polymers (copolymer of acrylamide and 2-acrylamide-2-methylpropane sodium sulfonate) with a charge density of 5 – 25%.**Figure 3.** Anionic polymers copolymer of acrylamide and sodium acrylate) with a charge density of 30%.**Figure 4.** Cationic polymers (copolymer of acrylamide and trimethylammonium ethyl acrylate chloride) with charge density of 10 and 45%.

The pilot-scale flow facility used for this study is made up of 0.0306-m ID acrylic pipe and it is schematically shown in Figure 5. Again, the detailed experimental procedure for the operation of the flow loop has been previously published (Abubakar *et al.*, 2015; Eshрати *et al.*, 2015). Meanwhile, as stated in our previous study (Eshрати *et al.*, 2022), the experimental uncertainty of the pressure drop measurements was as high as  $\pm 8\%$  for the range of investigated velocities after considering the accuracy of the differential pressure transmitter which was 0.0375% full scale according to the manufacturer.

From the measured pressure drops, the head losses before ( $h_L$ ) and ( $h_{L-DRP}$ ) After the addition DRP was calculated using the following expressions:

$$h_L = \frac{\Delta P}{\rho_m g} \quad (1)$$

$$h_{L-DRP} = \frac{\Delta P_{DRP}}{\rho_m g} \quad (2)$$

Similarly, the energy consumption by the pump per unit of time before ( $\dot{E}$ ) and after ( $\dot{E}_{DRP}$ ) The addition of the DRP can also be expressed as:

$$\dot{E} = \dot{m}_T g h_L = \rho_m \dot{Q}_T g h_L \quad (3)$$

$$\dot{E}_{DRP} = \rho_m \dot{Q}_T g h_{L-DRP} \quad (4)$$

Therefore, the percentage saving in energy per unit of time (i.e., the pumping power saving),  $\dot{E}_S$  (%), is obtained from the combination of Equations (3) and (4) to give:

$$\dot{E}_S (\%) = \left(1 - \frac{h_{L-DRP}}{h_L}\right) \times 100 \quad (5)$$

$\Delta P$  is the pressure drop without DRP,  $\Delta P_{DRP}$  is the pressure drop with DRP,  $\rho_m$  is the oil-water mixture density,  $g$  is the acceleration to gravity,  $\dot{m}_T$  is the mass flow rate of the oil-water mixture, and  $\dot{Q}_T$  is the volumetric flow rate of the oil-water mixture.

The mixture Reynolds number ( $Re$ ) is expressed as follows:

$$Re = \frac{\rho_m u_m D}{\mu_m} \quad (6)$$

Both the  $\rho_m$  and  $\mu_m$  are functions of oil fraction ( $\alpha_o$ ) expressed as:

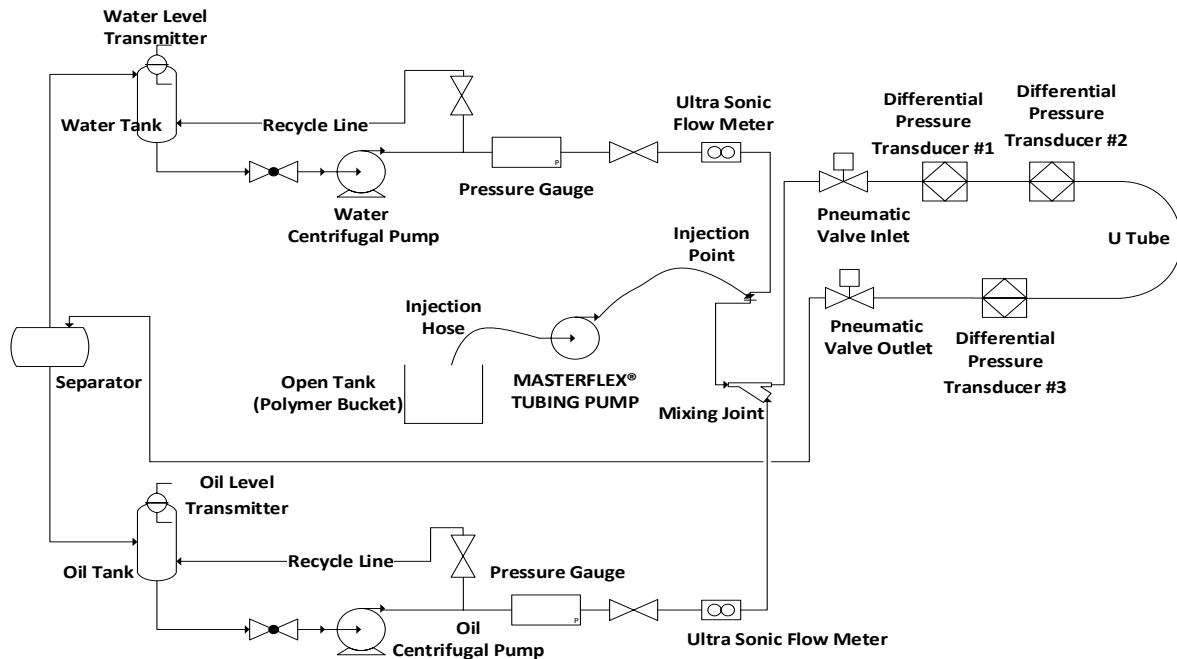
$$\rho_m = \alpha_o \rho_o + (1 - \alpha_o) \rho_w \quad (7)$$

$$\mu_m = \alpha_o \mu_o + (1 - \alpha_o) \mu_w \quad (8)$$

Finally, the mixture velocity ( $u_m$ ) was determined as the summation of the superficial velocities ( $u_o$  and  $u_w$ ), which were themselves determined from the following expressions.

$$u_o = \dot{Q}_o / A \text{ and } u_w = \dot{Q}_w / A \quad (9)$$

$\dot{Q}_o$  and  $\dot{Q}_w$  are oil and water volumetric flow rates respectively.



**Figure 5.** Schematic of two-phase oil-water flow loop.

### 3. RESULTS AND DISCUSSION

Figures 6 and 7 present the savings in energy consumption by different polymers when they were injected into a dispersed oil-water flow containing 0.1 and 0.3 oil fractions respectively. While both figures show similar trends with respect to Reynolds numbers, it is clear that the savings at 0.1 oil fraction were higher than those of 0.3 oil fraction. This is expected due to the fact that the polymers are only soluble in water and therefore the higher the oil fraction in the flow the lower the performance of the polymers in terms of their drag-reducing abilities. Another general observation in the two figures is that the Reynolds number positively affected the savings in energy consumption. The higher the mixture Reynolds number, the higher the savings in energy. This trend is clearly shown in Figures 8 and 9 and it follows the trend of drag reduction with respect to Reynolds number. An increase in Reynolds number increases the level of flow turbulence, which favours intense mixing of the polymer molecules with flowing fluids thereby increasing the drag reduction. In fact, there is a threshold of Reynolds number below which drag reduction does not occur. This observation is in agreement with previous studies (White and Mungal, 2008, Karami and Mowla, 2012). In terms of individual polymers, it is observed that molecular weight is the most dominant factor that influences the saving in energy consumption.

Precisely, molecular weight is the most overwhelming dominant factor that positively enhances the saving in energy consumption. This can be appreciated when comparing the performance of anionic A-6-30 polymer

with that of anionic A-20-30 polymer on one hand and the performance of cationic C-5-10 polymer with that of cationic A-12.5-10 on the other hand. This is not also surprising as an increase in the molecular weight of the polymers increases drag reduction. This is because of the entanglement of polymer chains, which are favoured by high molecular weight. For low molecular-weight polymers, the susceptibility of the polymers to undergo degradation further reduces their chain lengths thereby shortening the entanglement, unlike their high molecular-weight counterparts that can still produce enough entanglement even after the shortening of the polymer chains due to degradation. The charge density seemed to have positively enhanced the saving in energy consumption up to a certain value before it became counter-productive to the energy saving. of that can be attributed to ionic type and charge density. For instance, there was a slight increase in the energy saving of the anionic polymers (Figures 6 and 7) from a charge density of 5% to 13% before it began to decrease at a higher charge density. Abubakar *et al.* (2014), who observed a similar trend in their study suggested that there was a critical value of the charge density after which the polymer chains could not long retain enough degree of flexibility. Instead, more rigid conformation of the polymer chains became dominant after this critical value resulting in the inability of the polymers to form desirable intermolecular interactions that could favour drag reduction. Finally, with respect to charge type, cationic polymers seemed to have performed better than their anionic counterparts of comparable molecular weights and charge densities. It is possible that the anionic polymers, which show lower

performances are characterized by smaller hydrodynamic sizes than their cationic counterparts. Meanwhile, the increase in energy savings with respect to Reynolds number as clearly depicted in Figures 8 and 9 was more pronounced at low Reynolds numbers than at high Reynolds numbers. As the Reynolds number increased, the magnitude of the savings in energy consumption progressively decreased until the marginal savings became insignificant at much higher Reynolds numbers. There is even a tendency to record a decrease in the savings in energy consumption after attaining the maximum performance of the polymers. This observation can be attributed to the possibility of the interaction between polymer chains and the flowing fluids, caused by high Reynolds numbers that bring about drag reduction, being overwhelmed by the polymer degradation thereby resulting in to decrease in the performance of the polymers. This trend is similar to the drag reduction trend

with respect to polymer concentration as reported severally in the literature though different reasons were adduced for it (Abubakar *et al.*, 2015). Overall, A-20-30 and C-12.5-10 jointly gave the highest energy saving of about 60% at the highest mixture velocity of 1.5 m/s (corresponding to mixture Reynolds number of 13,694) when the oil fraction was 0.1. It is difficult to make a direct comparison of the performances of these polymers with those reported in the literature because of the difference in the type of flow, the polymers used, and flow conditions. For instance, Cuenca *et al.* (2008) achieved a maximum of 42.6% in energy saving in single-phase diesel flow with polymer of 20 ppm concentration at Reynolds number of 60,000 to 160,000. Similarly, Akbari *et al.* (2020) achieved 36% energy savings in the single-phase water flow of a different polymer of 20 ppm concentration using different flow conditions.

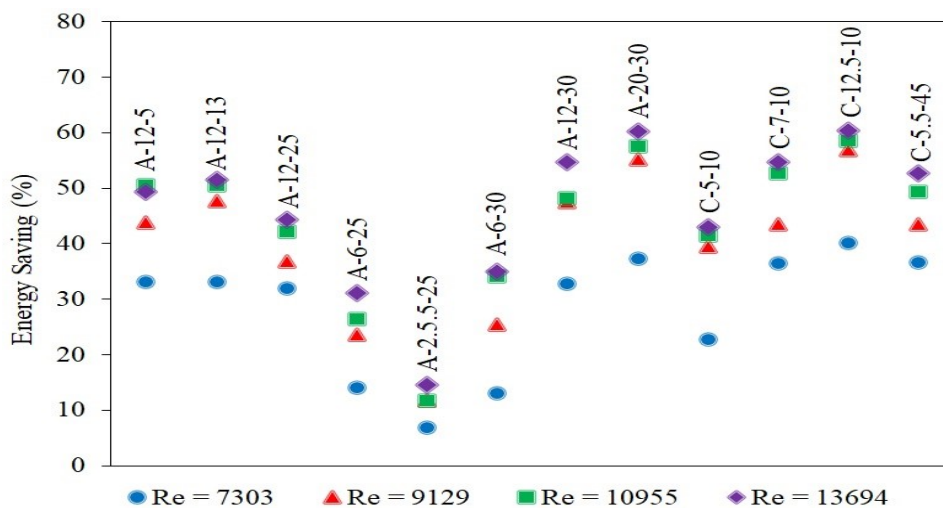


Figure 6. Percentage saving in energy consumption in dispersed oil-water flow by different polymers at 0.1 oil fraction

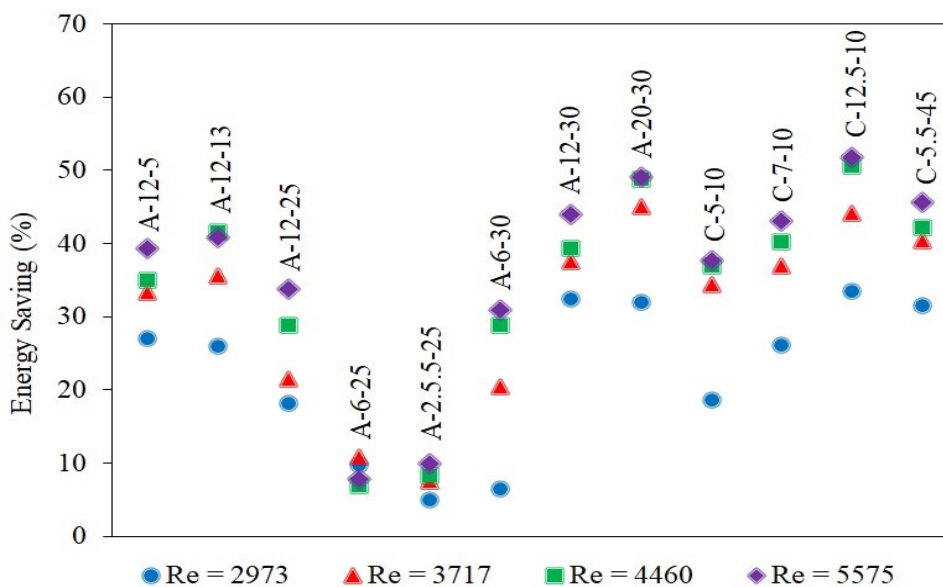
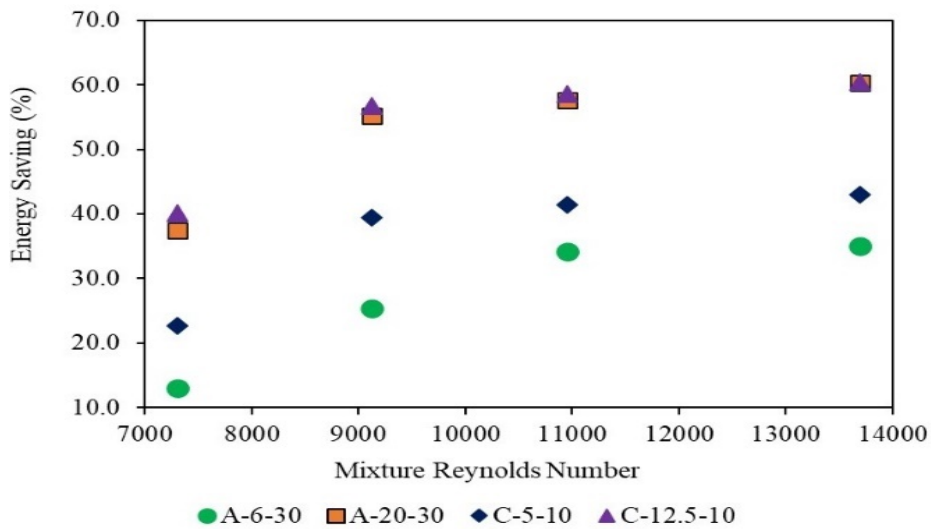
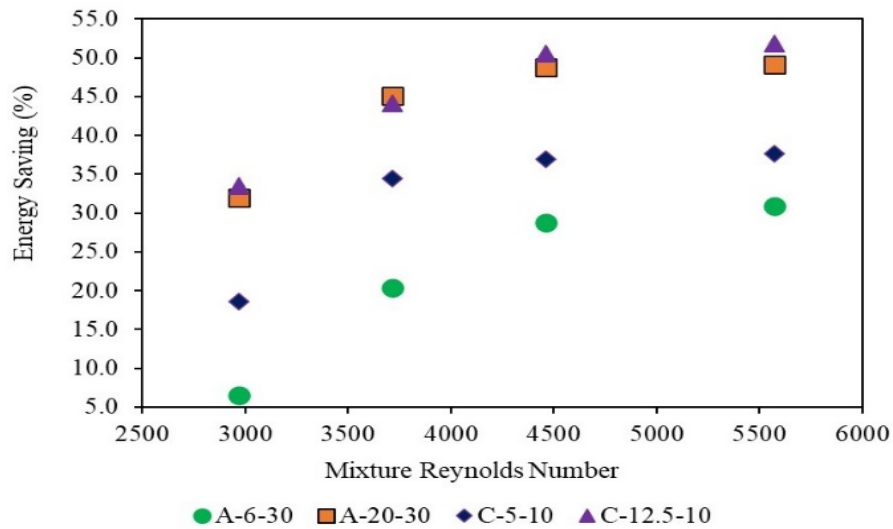


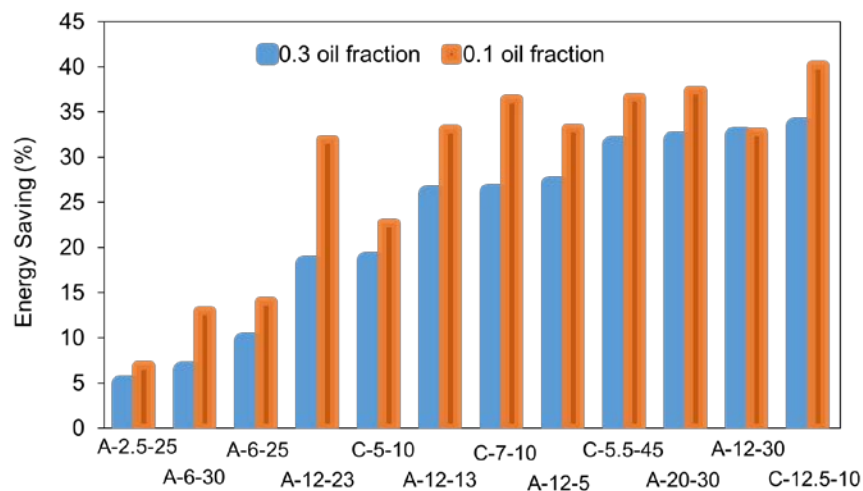
Figure 7. Percentage saving in energy consumption in dispersed oil-water flow by different polymers at 0.3 oil fraction



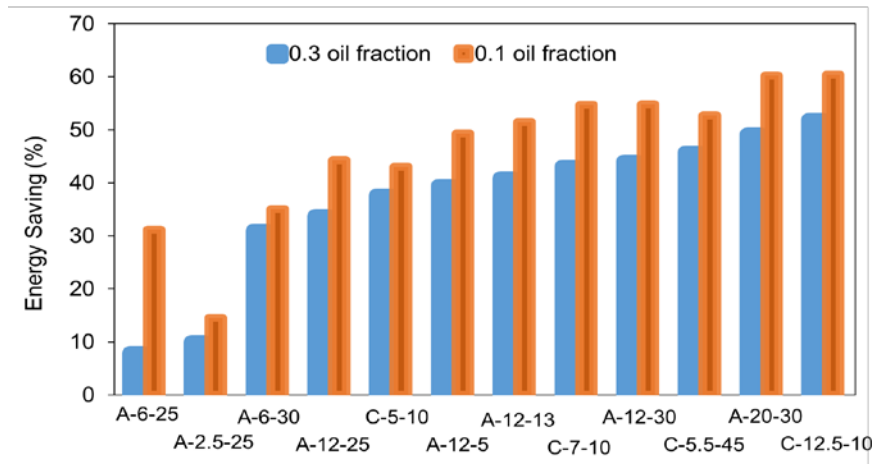
**Figure 8.** Influence of molecular weight on saving in energy consumption in dispersed oil-water flow at 0.1 oil fraction



**Figure 9.** Influence of molecular weight on saving in energy consumption in dispersed oil-water flow at 0.3 oil fraction



**Figure 10.** Energy saving as a function of oil fraction at a mixture velocity of 1.5 m/s



**Figure 11.** Energy saving as a function of oil fraction at a mixture velocity of 1.5 m/s

#### 4. CONCLUSION

Based on the results of the experimental work, it can be concluded that there was an increase in the energy saving by all the tested polymers with an increase in the Reynolds number cumulating to about a maximum of 60% in energy saving at the highest Reynolds numbers. While it was found that the energy savings increased with an increase in the molecular weight, they initially increased with an increase in the charge density before they began to decrease at higher charge density. It was also observed that the energy savings by the cationic polymers were higher than those of anionic counterparts of comparable molecular weights. Finally, the energy savings at an oil fraction of 0.1 were higher than those recorded at an oil fraction of 0.3.

#### CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in this work.

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