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A NOVEL POLYMER-SURFACTANT COMPLEX MIXTURE TO IMPROVE DIESEL FUEL FLOW IN A ROTATING DISK APPARATUS

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Abstract

This paper introduces a novel complex system to decrease the polymer degradation using polyisobutylene (PIB) and sodium lauryl ether sulfate (SLES). These materials are tested individually and as a complex mixture in a rotating disk apparatus (RDA) at various concentrations and rotational speeds (rpm). From the experimental results, it can be observed that the drag reduction for the complex mixture of cationic polymer with anionic surfactant has a better performance than the reduction of individual polymer or surfactant, respectively. This can be as a result of the important role played by complex mixtures that are highly dependent on alkyl chain in the surfactant. The maximum %DR observed in laminar flow was 38.42% for complex mixture at 1000rpm, while the %DR of polyisobutylene and sodium lauryl ether sulfate at the same condition were 27.36% and 28.42%, respectively.

1. Introduction

Transportation of liquid in pipelines consumes a high percentage of energy which associated with the amount of energy required to pump the fluid to the desired destination. These energy losses can be increased due to friction resistance, which induced by the pipe wall and fluid viscosity. It is worth mentioning that most of the frictional drag in pipelines are caused by eddies. Thus, this is because their formation retards the movement of fluid particles, which invariably leads to drag. Eddies are of constant occurrence in pipelines flowing under a high degree of turbulence which caused by increase in the Reynolds number (*Re*). Different types of polymers, which called *drag reducing agents*, have been widely used in pipelines to reduce the high degree of turbulence and to improve the fluid movement. This phenomenon, called *turbulent drag reduction* (*DR*), not only has been effectively employed in several engineering areas such as irrigation systems, firefighting, and transportation of crude oil but also has drawn a lot of attentions to the scientific community (Kim et al. [12]). Many reports have shown that polymer can be used to reduce drag even at the smallest quantity usually in ppms (Kulicke et al. [13], and Rose and Foster [22]). On this note, many efforts have been made to study the working principle of these materials (Lumley [15, 16], Tu et al. [25] and Virk [27]). Despite all these efforts, there is yet to be any reasonable conclusions about the main reasons while these materials reduce drag. Another important point to note here is that, these polymers break down after a period, referred to as a mechanical or thermal degradation, which occurs because of the high shear stress systems associated with turbulence at which they are exposed (Pereira et al. [20]). When this takes place, the working efficiency of these materials is reduced (Vanapalli et al. [26]).

In the like manner, another group of materials which have the ability to reduce drag and have as well been widely investigated are the surfactants. These surfactants have an advantage over the polymers, which can withstand such degradation. In addition, they are able to realign or reassemble and self-repair after mechanical degradation through the formation of micelles, this has been well reported by (Hellsten [8]).

As a result of these attributes, they have been individually studied using pipelines or channels (Gasljevic et al. [6], Lu et al. [14] and Qi et al. [21]) and in combined form with polymers, referred to as complexes (Ioannou et al. [9], Matras et al. [17], Mya et al. [18, 19] and Suksamranchit et al. [24]). In contrast, the DR performance of complex mixtures of dilute polymer and surfactant solutions using rotating disk apparatus has been studied previously by several researchers (Abdulbari et al. [2], Akindoyo et al. [3], Bari et al. [4] and Kim et al. [12]). Several parameters, such as charge density, surfactant structure and ionic strength affect the binding of surfactant to the polymer, which can lead to the formation of characteristic micro- and macrostructure. In complex mixtures with polymers, surfactant can modify the properties of these polymers after mechanical degradation and improve their drag reduction effectiveness. All previous works on complex mixture in pipelines, conduits, channels and rotating disk apparatus show that the drag reduction performance of complex mixture is better than individual polymer or surfactant. This can be as a result of the critical role played by the complex mixtures which are greatly dependent upon the alkyl chain in the surfactant. Matras et al. [17] proposed a mechanism for surfactant-polymer drag reduction and concluded that an interaction between polymer and surfactant causes an aggregation, which is responsible for drag reduction.

In this study, an enclosed rotating disk apparatus (RDA) was used to study the drag reduction performance of diesel fuel using cationic polymer (polyisobutylene) and anionic surfactant (sodium lauryl ether Sulphate) individually and in a novel combined form. In addition, the influences of different variables on %DR such as complex concentration and rotational disk speed were also studied.

2. Methodology

2.1. Experimental materials

Materials utilized in this work were all supplied by Sigma-Aldrich, Malaysia and used without further purification. They are polyisobutylene (Mw = 4,700,000g/mol) and sodium lauryl ether sulfate (Mw = 288.38g/mol). The main fluid used in the present investigation is diesel fuel, which purchased from shell.

2.2. Complex preparation

Complex mixture was prepared by measuring the required weight of both polymer and surfactant; these were as well dissolved in about 4.5L of diesel fuel using hot plate stirrer. Mild agitation was applied to reduce mechanical degradation induced by stirring. Five different concentrations of polymer (50, 100, 150, 200 and 300ppm) and surfactant (200, 400, 600, 800 and 1000ppm) were used to prepare twenty-five samples of the complex with different concentrations.

2.3. Rotating disk apparatus

The rotating disk apparatus employed in this work consists of a simple disk, made of aluminum with a diameter of 14cm and a thickness of 0.6cm. The fluid container consists of a stainless steel cylinder with dimensions of

180mm diameter × 110mm height, and a removable 20mm thick stainless steel lid to seal the solution. The distance between the disk surface and fluid container lid is 10mm, and it is constant for all disks types (see Figure 1). XINJE company has manufactured the electric servomotor (MS-80STE-M02430B-20P7), by which the rotational speed of the disk can be controlled from zero up to a maximum of 3000rpm. The used volume of solution necessary to fill the entire container is about 4.5L. A high accurate torque sensor (LONGLV-WTQ1050D, Range: 3Nm, Output: 1.397mv/V) was used to calculate the loaded torque on the disk. The torque values are thereby transforming to readable form in the computer display system with an InduSoft Web Studio v7.1 software.

Samples and the reference were examined at the rotating disk apparatus to measure torque with different rotational speed ranges from 1000 to 3000rpm, in each solvent and in a dilute polymer solution at a temperature of 27°C ±0.05°C. The %DR was calculated by:

$$\%DR = \frac{T_s - T_a}{T_s} \times 100, \tag{1}$$

where T_s and T_a are the torques required for the diesel fuel solvent without additives and with additives, respectively. Note that:

$$NRe = \frac{\rho \omega r^2}{\mu} \tag{2}$$

is based on the rotational speed of RDA, in which ρ is the fluid density, μ is the fluid viscosity and r is the radius of the disk. The critical Reynolds number value is 3×10^5 (Kim et al. [11] and Sohn et al. [23]). Depending on this value, the minimum rotational disk velocity at which the flow becomes turbulent is 1948.7rpm.

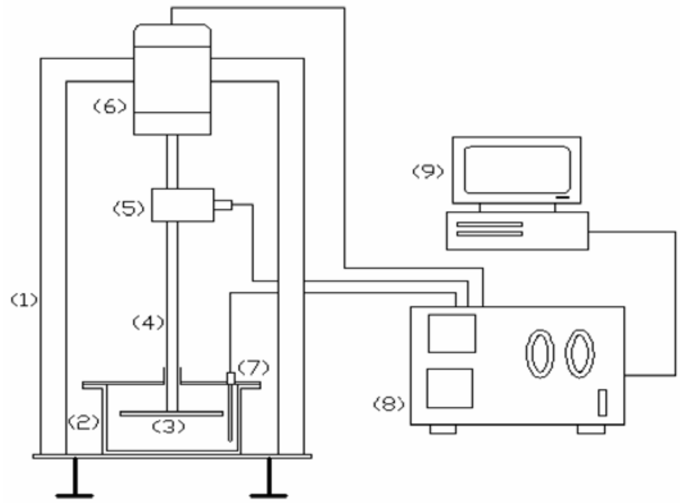

Figure 1. Schematic diagram of the rotating disk apparatus for drag reduction measurement: (1) outside frame, (2) fluid container, (3) rotating disk, (4) disk holding shift, (5) torque sensor, (6) electric motor, (7) thermocouple, (8) controller interface, and (9) PC.

2.4. Experimental procedure

In this research, polymer-surfactant mixture samples were prepared in different concentrations by using 4.5L of diesel fuel. The samples were left for 24 hours until dissolved exactly, and tested using a constructed rotating disk apparatus. The experimental procedure starts by filling the fluid container with pure diesel and fixing the smooth aluminum disk and then measuring the torque values for all rotational disk speed ranges (1000-3000rpm). The same procedure was repeated with different complex solutions, which prepare by various concentrations and the torque values were measured to calculate the %DR using equation (1). Four variables are tested in this work, which are:

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

(2) Surfactant concentration (200, 400, 600, 800 and 1000ppm).

(3) Complex concentration.

(4) Rotational disk velocity (1000-3000rpm).

3. Results and Discussions

3.1. Drag reduction with polymer additives

The results of drag reduction percent as a function of rotational disk speed for various polyisobutylene concentrations using flat disk are shown in Figure 2. Generally, it is interesting to notice that all the maximum drag reduction points are spotted in the laminar flow region $(Re < 1948)$. As shown, %DR increased with increasing polymer concentration until reaching critical concentration, similar results are shown by other workers (Kim et al. [10, 11] and Sohn et al. [23]). The effect of polymer concentration on %DR 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, i.e., reduction of *NRe* and an increase in the frictional drag. In addition, it is clearly observed that the %DR decreased with increasing of Reynolds number. The maximum %DR of (27.368%) is obtained at 150ppm polyisobutylene.

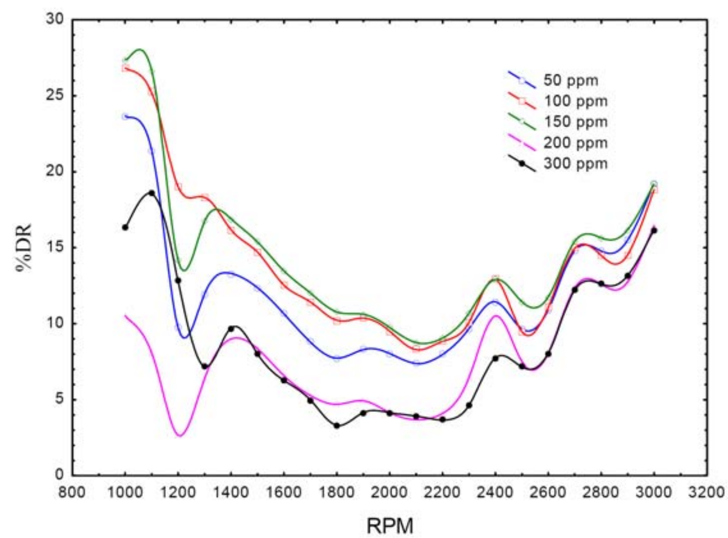

Figure 2. The effects of polyisobutylene concentrations on drag reduction performance for different rotational disk speeds.

3.2. Drag reduction with surfactant

Figure 3 depicts the study of drag reduction percentage (%DR) as a function of rotational speed at different concentrations of sodium lauryl ether sulfate (SLES) using smooth disk. It can be observed clearly that the drag reduction decreases with increasing the rotational speed due to increase of Reynolds number, which leads to a high degree of turbulence. This high degree of turbulence generates extra numbers of small eddies on the smooth surface, which absorbs the main flow energy to complete their shapes (Abdulbari et al. [1]). As for the polymer additives (Figure 2), the drag reduction increased with increasing surfactant concentration, because their mechanism of working can be based on the increase in percentage drag reduction molecules, which is favored by the increase in their respective concentrations. The maximum drag reduction percentage noticed for sodium lauryl ether sulfate (SLES) using smooth disk was 29.5% at 1100rpm and 1000ppm.

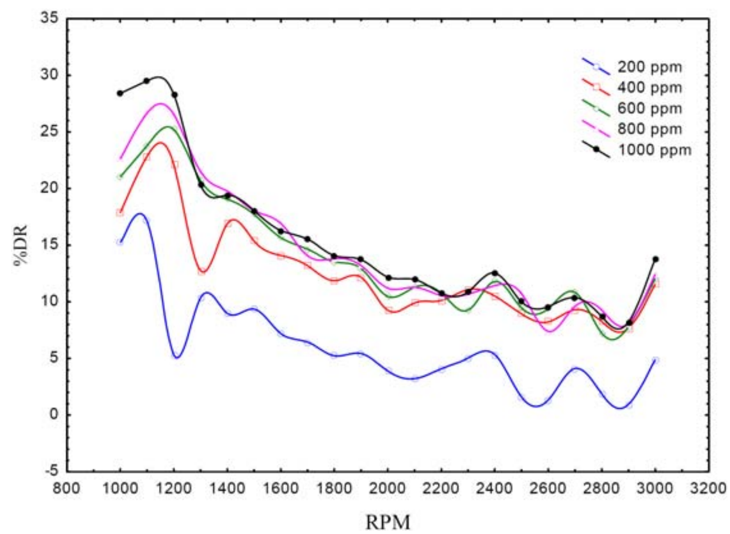

Figure 3. The effects of sodium lauryl ether sulfate concentrations on drag reduction performance for different rotational disk speeds.

3.3. Drag reduction with complex mixture

The series of Figures 4-8 show the results of drag reduction percentage (%DR) with various rotational disk velocities (RPM) at different concentrations of PIB and SLES complex mixture. All these figures show the almost same behavior of drag reduction with different values. At first, the %DR decreases with increasing the rotational speed due to the mechanical degradation of polyisobutylene. Then the formation of surfactant micelles increases the polymer degradation resistance, thus improves the drag reduction efficiency. In addition, the %DR increases with complex mixture concentration until the critical concentration, which is 150ppm of polyisobutylene with 200, 400, 600, 800 and 1000ppm of surfactant, respectively. These concentrations %DR start to decline due to the increase in the complex solution viscosity leading to a decrease in the turbulent strength, i.e., reduction of *NRe* and an increase in the frictional drag (Kim et al. [10]). The %DR is calculated at 1000rpm with a concentration of 150ppm and the five concentrations of SLES, which continue to be stable up to 3000rpm. Stability exhibited by the polymer and surfactant complex is due to the formation of micelles resulting in a higher reduction of barriers and hamper the mechanical deformation of the polymer-surfactant chain. The maximum %DR achieved using the complex mixture as drag reducing agent was 38.42% at a PIB concentration of 150ppm and SLES concentration of 1000ppm at a rotational speed of 1000rpm. However, in the same condition, the %DR of 150ppm of PIB with 200, 400, 600 and 800ppm of SLES were 28.94, 30.52, 34.21 and 34.73%, respectively.

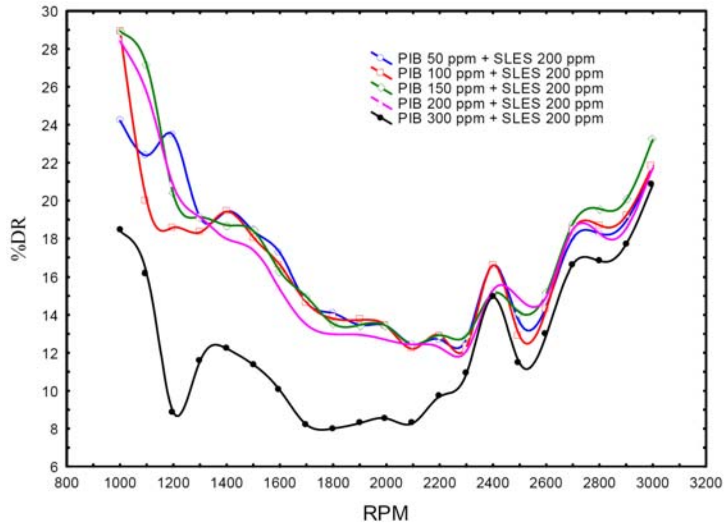

Figure 4. Complex mixture concentrations (five PIB concentrations + 200ppm SLES) effect on drag reduction performance with different rotational disk speeds.

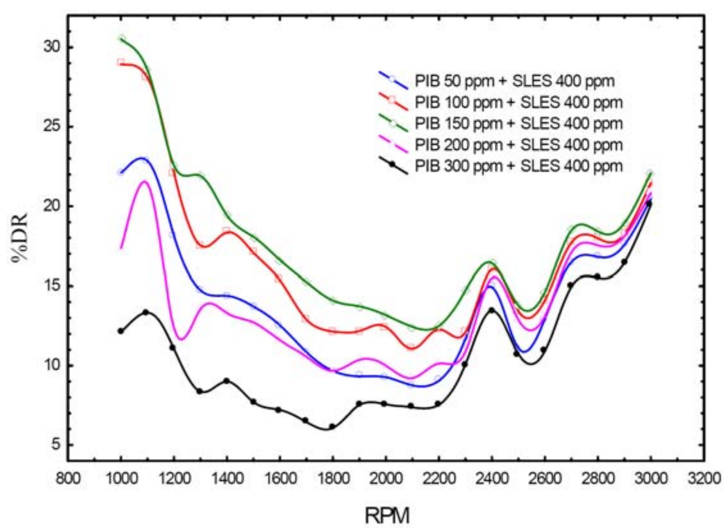

Figure 5. Complex mixture concentrations (five PIB concentrations + 400ppm SLES) effect on drag reduction performance with different rotational disk speeds.

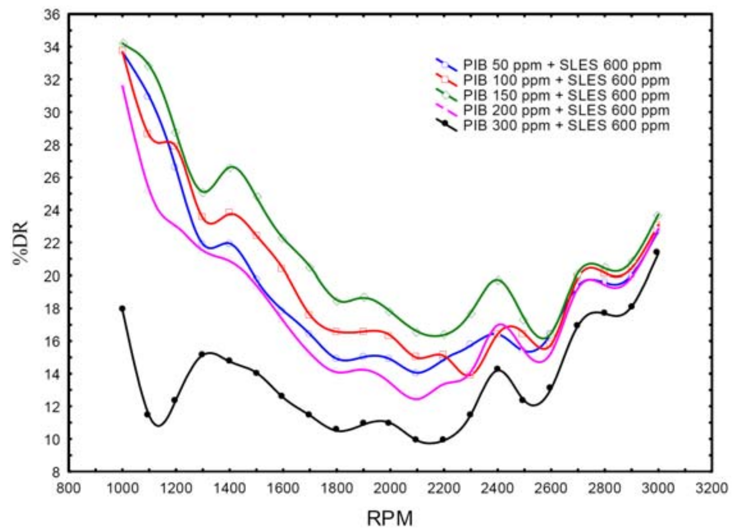

Figure 6. Complex mixture concentrations (five PIB concentrations + 600ppm SLES) effect on drag reduction performance with different rotational disk speeds.

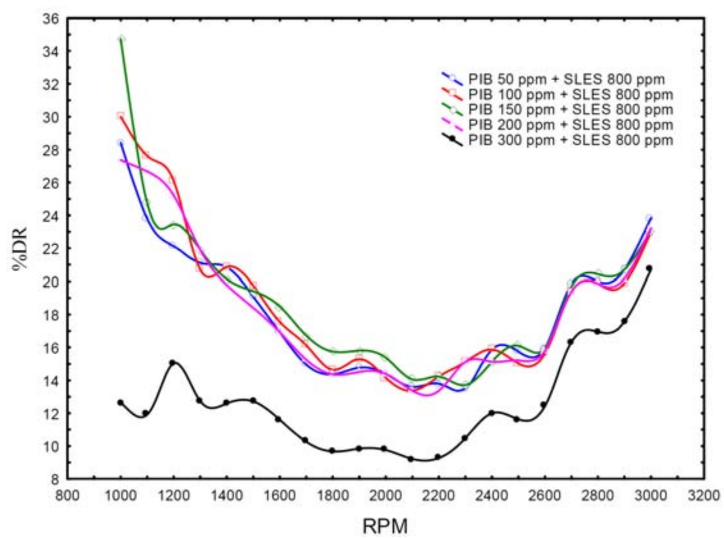

Figure 7. Complex mixture concentrations (five PIB concentrations + 800ppm SLES) effect on drag reduction performance with different rotational disk speeds.

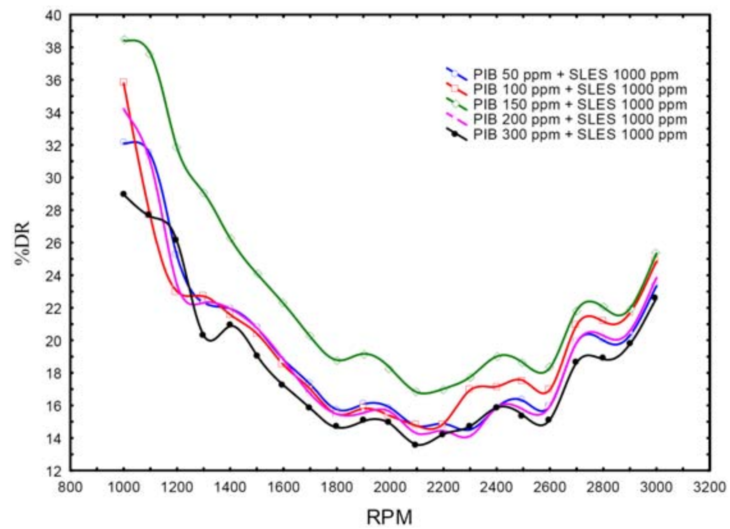

Figure 8. Complex mixture concentrations (five PIB concentrations + 1000ppm SLES) effect on drag reduction performance with different rotational disk speeds.

3.4. Comparison between individual additives and their complex mixture

The comparison of the torque values and the drag reduction efficiency for individual additives and their complex mixture using smooth disk is shown in Figures 9 and 10, respectively. From Figure 9, it can be noticed that the torque values of all three solutions (PIB, SLES, complex mixture) are less than its value for pure diesel, however, the complex mixture shows the minimum torque values. All these solutions show a good ability to reduce frictional drag forces in smooth and structured disks. This comparison exhibits a higher %DR of a complex mixture than their references. Similar observations have been observed in the study by Akindoyo et al. [3], Bari and Faraj [5], and Hall and Joseph [7]. This higher performance induced by the interaction between surfactant and polymer chain, in which that polymer film is formed around surfactant micelles forming aggregate structure. This structure has a drastic effect on the solution rheology. The maximum %DR observed was 38.42% for complex mixture at 1000rpm, while the %DR of polyisobutylene and sodium lauryl ether sulfate at the same condition were 27.36% and 28.42%, respectively.

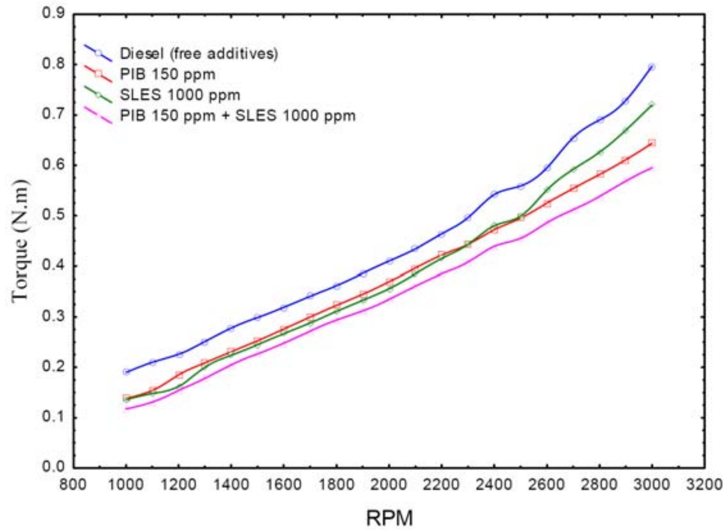

Figure 9. A comparison of torque values for polymer or surfactant and their complex with different concentrations using smooth disk.

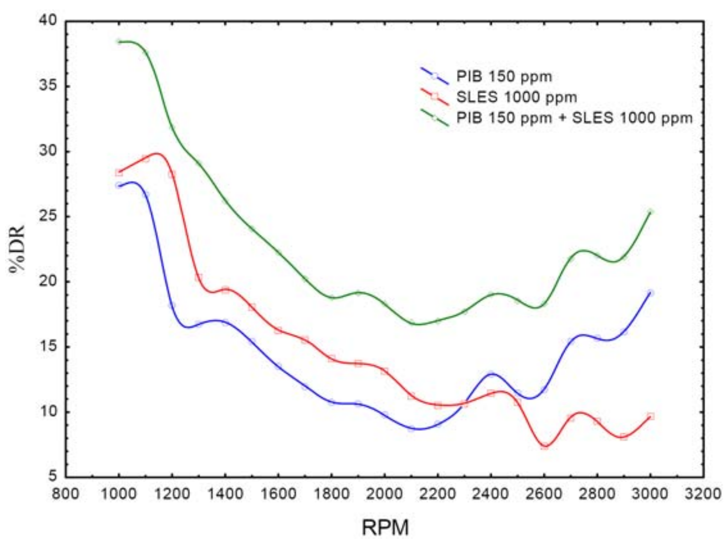

Figure 10. A comparison of drag reduction performance for polymer or surfactant and their complex with different concentrations using smooth disk.

4. Conclusion

In conclusion, the effect of several parameters such as additive concentration, additive types, and rotational disk speed on drag reduction efficacy of diesel fuel was investigated using a high precise rotating disk apparatus. Two types of additives, one is a cationic polymer (polyisobutylene), and the other one is anionic surfactant (sodium lauryl ether sulfate), were employed to prepare a complex mixture of (PIB-SLES). All these solutions were found to behave as real drag reducing agents. The DR efficacy induced by the complex mixture is found to be obvious higher than that of individual polymer and surfactant. In addition, it was noticed that the drag reduction performance increased with increasing additive concentration in all cases, and decreased with increasing rotational disk velocity.

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