INVESTIGATING THE EFFECT OF INSOLUBLE ADDITIVES TYPE ON THE DRAG REDUCTION PERFORMANCE IN A CRUDE OIL TURBULENT FLOW SYSTEM

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Highlight

Enhancing the flow of crude oil transported at turbulent flow mode using different types of insoluble rigid additives to replace traditional soluble viscoelastic additives

Abstract

In the present work, the effect of three insoluble additives densities on reducing the drag of crude oil was investigated. The objective of the present work is to evaluate the effect of the insoluble additive's densities on their drag reduction efficiency in hydrocarbon flow medium. Three powders with different densities are chosen, namely carbon powder, glass powder, and copper powder, with a density of 1710 kg/m^3, 2550 kg/m^3, and 8950 kg/m^3, respectively. The turbulence flow environment was created in a custom-made rotating disc apparatus with a maximum rotation speed of 300 rpm. To evaluate the effect of the powder density, the particle's size was chosen to be 100 µm. All the solutions were tested at the exact operating conditions with a rotation speed ranging between 200 to 2200 rpm. The experimental results showed a clear effect of the powder density on the drag reduction performance. The glass powders showed the highest drag reduction effect, while the copper and carbon powders were lower. The effect of the degree of turbulence on the drag reduction performance of the powders was clear, where the interaction between the powders and the turbulence structures (eddies) governed the turbulence-suppression efficiency of the additives.

Keywords

drag reduction; turbulence; insoluble additives; crude oil; powders.

Introduction

The introduction of minute quantities of soluble additives (polymers, surfactants, or their complexes) to the main turbulent flow systems was proven to have a noticeable impact on reducing the pumping power dissipation [1–3]. Such an approach has attracted the attention of enormous researchers worldwide since the first discovery by Tom et al. in the late forties of the past century [4]. Soluble additive viscoelastic properties are believed to be the main reason behind the flow enhancement (drag reduction) effect in turbulent flow systems, where several mechanisms were proposed to explain this phenomenon [5–8]. Large numbers of researchers investigated polymeric drag-reducing agents (DRAs) with different operating conditions and flow mediums due to their high molecular weights that provide new viscoelastic properties to the turbulent flow systems. The presence of such high molecular weight polymers will enable "turbulence suppression" by preventing the eddies from completing their shapes or by mobilizing the laminar sub-layer on the pipe's wall, which reduces the friction with the pipe wall [9].

On the other hand, applying polymeric drag-reducing agents had several drawbacks that limited its use in several essential industries like crude oil transportation [10–12]. Polymers additive's resistance to mechanical degradation is considered a significant drawback where long-chained polymeric molecules tend to degrade when exposed to high-shearing areas in elbows, valves, and pumps.

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Such degradation is irreversible and can lead to a permanent loss in the polymer's drag reduction ability. Usually, the only way to sustain the drag reduction performance after degradation is by re-injecting fresh polymeric additives to the mainstream, increasing the operating costs. Another drawback is the impact of the long-chained polymeric additives on the properties of the transported liquid itself. Any dramatic changes in the apparent physical properties are irreversible (due to the solubility of the polymeric additives in the flowing media), and that will change its market value [13].

Surface Active Agents (surfactants) are another type of DRAs used to overcome some of the polymeric DRA's drawbacks. Surfactants are polar molecules with low molecular weight compared to polymers [14–16]. These short polar molecules migrate to the interface of two immiscible liquids when they get into direct contact and reduce the interfacial tension. In single-phase flow systems, the surfactant molecules will start aggregating and forming what is called "micelles" that act as one entity to interact with the turbulence structures (eddies) and reduce the drag in pipelines. The micelle's resistance to high-shear forces is low, and they usually break when exposed to high-shearing zones during transportation. After breaking, the polar nature of the surfactant molecules will drive them to re-join to form micelles again (regain their shape), which means regaining their drag reduction abilities. Despite this important characteristic, the low molecular weight of the surfactant's molecules or even micelles, compared to polymeric DRAs, will produce limited drag reduction performance [17–19]. To match the long-chained polymers' high drag reduction performance, high concentrations of surfactant additives are needed, and that will affect the apparent physical properties of the transported liquids.

Several researchers have investigated insoluble DRAs to replace soluble additives in pipelines carrying liquids in turbulent flow mode. Different additives were introduced and tested, such as silica [20], agricultural wastes [21,22], pulps [23–25] and even some metals [26,27]. Insoluble additives were proven on many occasions to be effective flow enhancers and, what is more, important not affect the apparent physical properties of the transported liquids. Particle diameter, addition concentration, liquid flow rate, and pipe dimensions are the significant parameters usually investigated when testing any new soluble DRA. The effect of the additive's density on the drag reduction performance of insoluble additives was not critically investigated before. The additive's density effect will reflect the impact of one of the critical parameters in determining the suitability of the additives to act as a DRA, the additive density.

In the present work, three different commercial insoluble additives, namely glass powder, carbon powder, and copper powder, will be used as DRAs. The drag reduction test will be conducted using crude oil as the flowing media and rotating disk apparatus as a flow testing method to simulate the turbulent flow behavior in pipelines. The effect of the diameter and type of the particles will be investigated and compared to evaluate their impact on the flow enhancement.

Methods

Materials

Four commercial powders will be used in the present work: carbon powder, glass powder, and copper powder with a density of 1710 kg/m^3, 2550 kg/m^3, and 8950 kg/m^3, respectively. All the powders were prepared by crushing and grinding commercial glass bottles (for the glass powder), commercial charcoal (for the carbon powder), and commercial copper beads (for the copper powder) using an automated ball mill (RTSCH model PM 200). The required particles size to be investigated in the present work was 100 μm. The resulting powder was screened using an automated screen shaker to separate the particles within the desired size.

The addition concentrations for each type of powders were 100, 300, 500, 800, and 1100 weight parts per million (wppm). The concentration range was chosen to investigate the broadest possible additive concentration range and their effect on the drag reduction performance.

Crude oil was used as the testing medium. The crude oil properties are mentioned in Table 1. The purpose of using crude oil as the carrying medium was to evaluate the effect of insoluble additive's drag reduction performance in hydrocarbon medium transported in turbulent flow mode.

Table 1. Properties of crude oil.

Viscosity (cSt)	6.1
Density (kg/m^3)	846.0
API	41.1
Pour Point (^{o}F)	61.0

Rotating Disk Apparatus

A rotating disk apparatus (RDA) was designed and fabricated to simulate the turbulent flow in the pipelines. Figures 1 and 2 show the schematic diagram of the RDA and a photo of the apparatus, respectively. As shown in Figure 1, the RDA consists of a servo motor with a maximum rotation speed of 3000 rpm, mounted on an aluminum structure and connected to a torque sensor by a shaft. The torque sensor is connected directly to a disk made of aluminum with a diameter of 7 cm by a cylindrical shaft. The disk is located in the middle of a 6.5 L stainless steel container that will carry the tested solutions. The container is supported with a stainless-steel lid with one hole for the rotating disk shaft and another for the thermocouple used for the crude oil temperature measurement.

The servo motor, thermocouple, and torque sensor are connected to a SCADA system connected to a desktop computer for torque and temperature measurements and motor speed control.

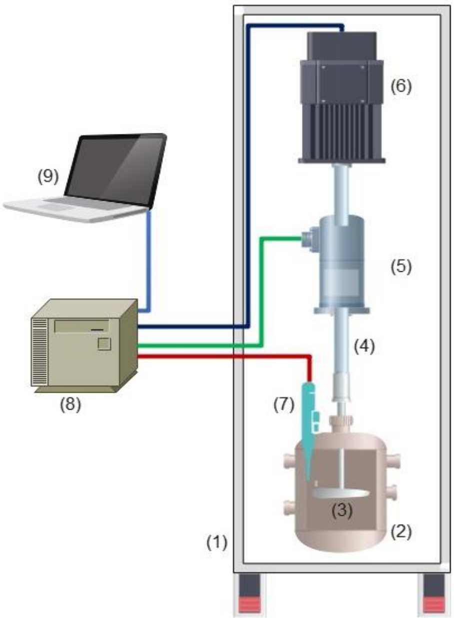


Figure 1. Schematic diagram of the rotating disk apparatus: (1) Outside frame, (2) Container, (3) Aluminum disk, (4) Connecting shift, (5) Torque sensor, (6) Servo motor, (7) Digital thermocouple, (8) Controlling system, and (9) PC with SCADA system.

Figure 2. A picture of the RDA system in the lab.

Testing Procedures and Calculations

- Solutions Preparation

Each solution is prepared by mixing the desired weight of the powder in crude oil. The concentration is measured in weight parts per million (wppm) which is calculated as in equation (1):

(1)
$$wppm = \frac{w_s}{w_o}$$

where:
w_s is the weight of the solid powder (gm)
w_o is the weight of the crude oil (gm)

The solutions are adequately mixed using an overhead mixer before their introduction to the RDA container.

- Solutions Testing

After pouring the solutions into the testing tank, the tank will be firmly closed using the stainless-steel lid after placing the rotating disk exactly at the center of the tank. The servo motor will operate at different rotation speeds ranging from 200 to 2200 rpm. Choosing this range is to avoid heating the tested solutions that can change the crude oil viscosity. The solution temperature was monitored at each test and was kept within. The torque readings were taken for 20 seconds (1 reading/ second). Each rotation speed test was repeated at least three times to compare and minimize the experiment readings error below 0.7%. The Reynold Number (Re) was determined using the rotational speed as in equation (2):

(2)
$$Re = \frac{\rho \omega r^2}{\mu}$$

where:
ρ is the fluid density (kg/m^3),
ω is the angular velocity,
r is the disk radius (m),
μ is the viscosity of the solution (Pa·s).

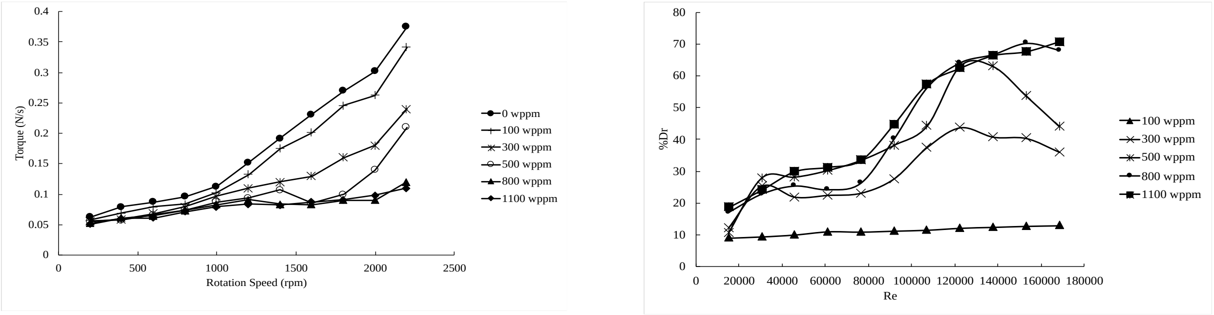
The drag reduction percentage was determined using the formula as in equation 3:

(3)
$$\% DR = \frac{To - Ts}{To} x100$$

where:
T_o is the torque reading of pure crude oil (N/m)
T_s is the torque reading of the solutions (N/m)

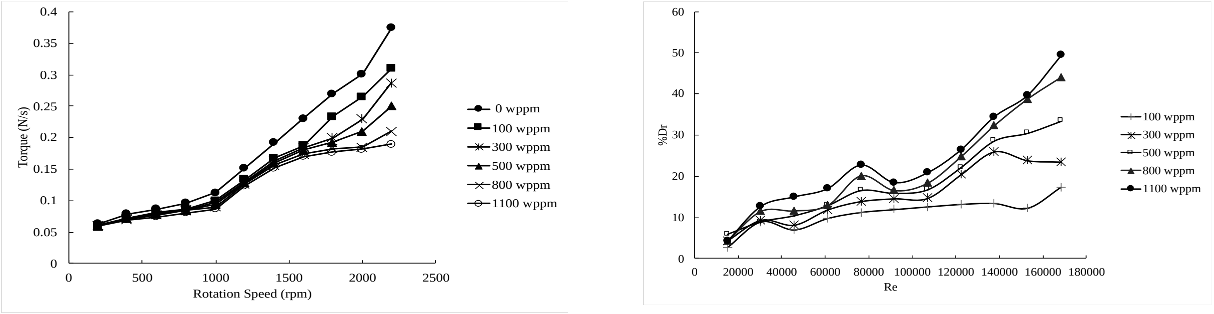
Results and discussion

Figure 3 shows the torque readings of the glass powder-water solution tested at different rotation speeds ranging between 200 to 2100 and at different powder addition concentrations ranging between 100 to 1100 wppm. Figure 3 (a) demonstrates the effect of the degree of turbulence on the drag reduction performance of the proposed insoluble additives (glass powder). Two significant responses to the degree of turbulence increment can be observed where the differences between the pure crude oil torque values and the investigated solutions from 200 to almost 1000 rpm were very low. On the other hand, increasing the degree of turbulence (increasing the rotation speed beyond 1000 rpm) started to show more segregated lines with a distinguished drag reduction effect where the torque values of all the solutions were lower than that of the pure crude oil. The lowest torque values were observed with the 800 and 1100 wppm solutions with very close drag reduction performance for both. The reduction in the torque values means reducing the solution's resistance to high shear forces applied by the RDA, which means a flow enhancement effect. Increasing the degree of turbulence means increasing the interaction area between the suspended solids and the flow medium, which means increasing the turbulence spectrum under the influence of the turbulence suppression effect. Figure 3 (b) shows the drag reduction performance of the glass powder solutions. Interestingly, the 100 wppm solution performance was the lowest compared with the other solutions with an almost constant %Dr of almost 10%. Increasing the concentration of the additive increased the %Dr with clear responses to the increase of the degree of turbulence represented by the Reynolds number (Re). For the 300 wppm and 500 wppm, the %Dr increased with the increase in the Re until reaching the maximum drag reduction point at Re = 122543. Further increase in the degree of turbulence resulted in a decline in the drag reduction performance, and that was expected since the relationship between the degree of turbulence the %Dr is not always linear, and it depends on the interaction between the additives and the turbulence structures formed during the flow (eddies). The decline in the %Dr curve means that the degree of turbulence has overcome the effect of the interfering additives (within the investigated concentrations), resulting in reducing their effect. Increasing the addition concentrations to 800 and 1100 wppm resulted in achieving the maximum %Dr point (70.6%) at the maximum Re investigated (168497), and that confirms the fact that the maximum performance is directly related to the additive's concentration. Increasing the additive concentration means increasing the number of additive particles interacting with the turbulence structures (eddies) responsible for power losses. The degree of interaction is governed by the number of particles and the degree of turbulence simultaneously, suggesting that the maximum %Dr point is the optimum degree of turbulence where the additives act as turbulence suppressors. Figure 4 shows the experimental results using the copper powder solutions at the same operating conditions as the glass powder solutions. It is interesting to see how the solution behavior (Figure 4 a) changed when the powder density from 2500 kg/m^3 to 8950 kg/m^3 where the lines started separating at much higher rotation speeds. In other words, the powder with higher density needed a higher degree of turbulence to be able to fully function as a drag-reducing agent with a distinguished effect of additives concentration. Increasing the powder density means increasing the additive's total weight, increasing the shear forces needed to create a suitable turbulence environment with optimum solid-liquid interaction. Figure 4 b shows that the maximum %Dr point was not reached within the investigated rotation speed range due to the high-density powder used.



(a) (b)

Figure 3. (a) effect of glass powder concentration on the torque values at different rotation speeds, (b) effect of Reynolds number on the %Dr at different powder concentrations.



(a) (b)

Figure 4. (a) effect of copper powder concentration on the torque values at different rotation speeds, (b) effect of Reynolds number on the %Dr at different powder concentrations.

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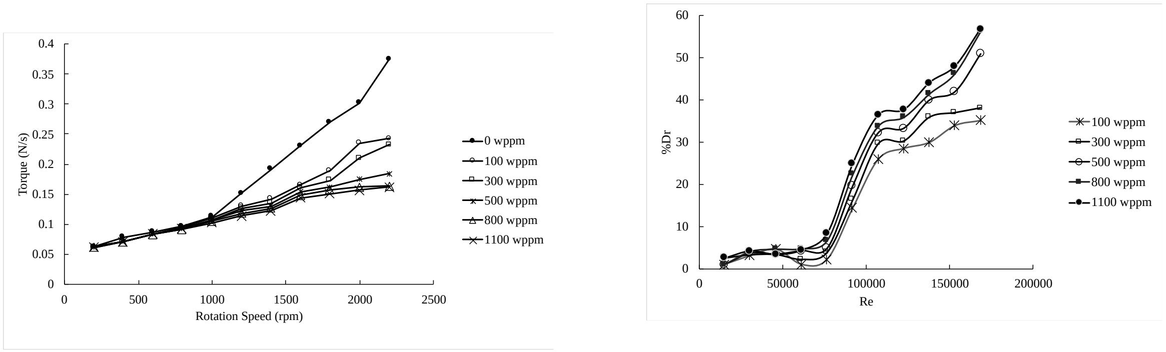


(a) (b)

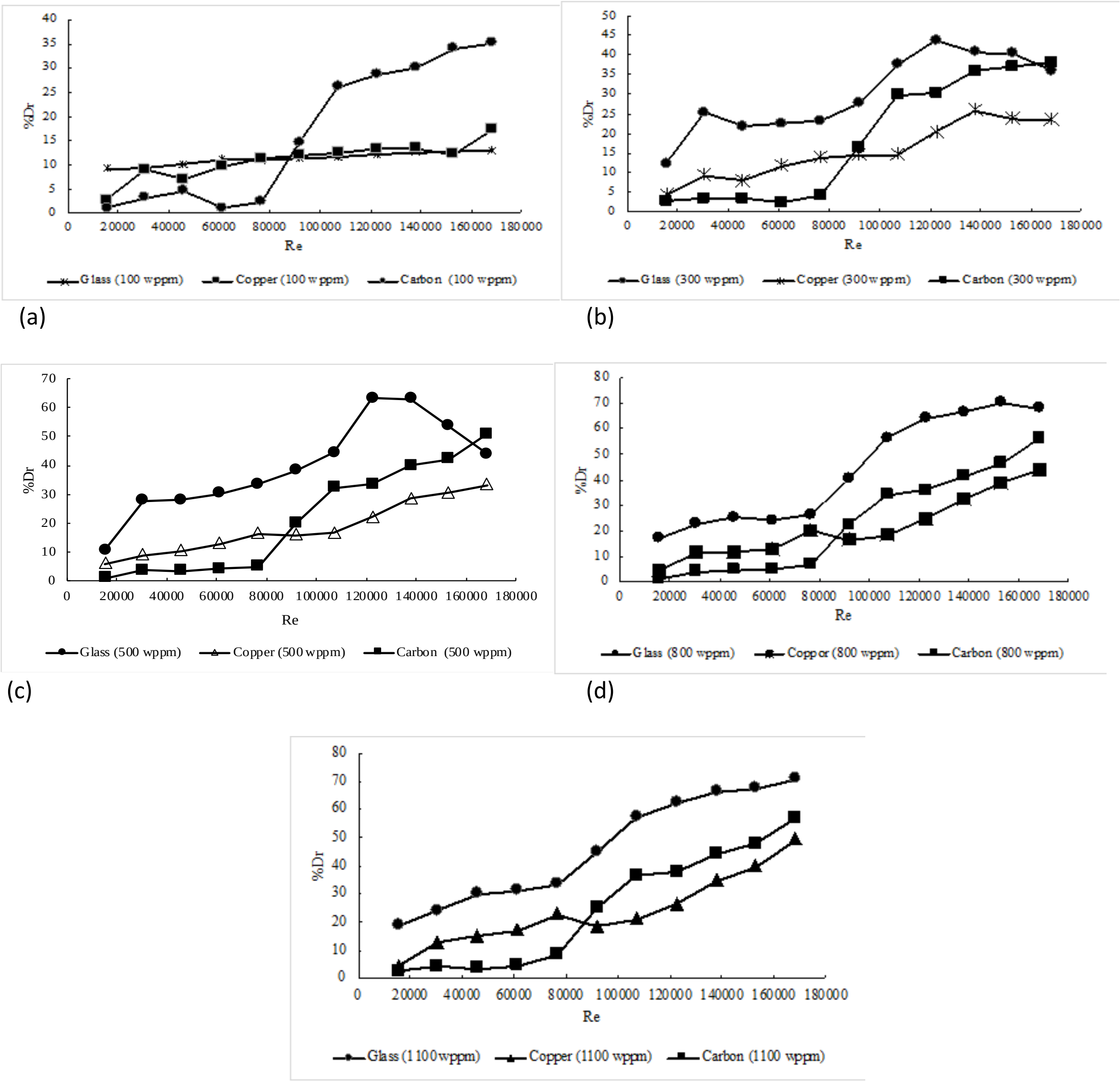
Figure 5. (a) effect of carbon powder concentration on the torque values at different rotation speeds, (b) effect of Reynolds number on the %Dr at different powder concentrations

Figure 5 shows the drag reduction performance of the carbon powder with a density of 1710 kg/m^3. It is interesting to see how reducing the density of the powder affects its overall drag reduction performance where a clear drag reduction onset point was spotted at Re = 76589 while that was not observed with other powders. Even though the maximum %DR was less than the other powders, the optimum performance was distinguishable with a unified degree of turbulence that led to a clear drag reduction onset point.

The effect of the degree of turbulence on the drag reduction performance of soluble and insoluble additives was extensively investigated by large numbers of researchers [28–31]. The investigated suspended solid solutions responses to Reynolds number increment are in many cases identical to the reported behaviors of different types of additives at different flow mediums where a drag reduction onset point is detected where the additives start to interact with the turbulence flow structures effectively. Further increase in the degree of turbulence (Re) will enable observing the effects of the investigated parameters such as the additive's concentrations, additives molecular weight, soluble additive types, and conduits dimensions. In the case of suspended solids, the same phenomena apply since the suggested controlling mechanism emphasizes the additives-liquid interaction, which was observed in the present work. The effect of Re (degree of turbulence) on the %Dr observed in the present work was also observed by Suzuki et al., (2006) [18] who used trimethylolethane (TME) clathrate–hydrate slurry in water. Their experimental results show that the drag reduction onset point started when the Reynolds number was almost 10,000.0 and was more distinguishable at the higher Re range. This behavior was also observed by Akindoyo & Abdulbari [32], who investigated carbon nanotubes powder as drag reducing agent with water flowing in turbulent flow mode in pipelines. The results showed that at low additive’s concentrations, the relationship between the additives drag reduction performance and degree of turbulence is not always linear where a decline in the %Dr was observed after reaching the maximum %Dr when the Re exceeds 140,000 (Figures 3 b and 4 b). To explain such behavior, it is important to bring another factor into this discussion: the additive's concentration. Generally, it is believed that increasing the additives concentrations (soluble and insoluble additives) will increase the %Dr within certain limitations. In other words, increasing the additive's concentrations will enable the suppression of a broader spectrum of turbulence at the investigated degree of turbulence reaching the maximum %Dr point where the interaction of the specific additive is almost optimum. Further increment in the degree of turbulence will result in unbalancing the mentioned optimum point by introducing extra shear forces that will overcome the effect of additives presence in the turbulent flow medium, resulting in reducing the %Dr [33]. Such a phenomenon was observed by Kazi et.al. [23] and Gharehkhani et.al. [25] when they investigated different grades of pulp and Kenaf fibers as drag-reducing agents. Their experimental results showed that the relationship between the fiber concertation, size, nature, and the degree of turbulence controls the drag reduction performance, and the effect of the addition concentrations of these fibers is directly related to the turbulent flow medium. The complex relationship between the solid additive's concentrations and the degree of turbulence was also highlighted by Akindoyo and Abdulbari [32] when testing carbon nanotubes as drag-reducing agents in pipelines. Their experimental findings confirmed the nonlinear relation between the additive’s concentration and the drag reduction performance at lower concentration ranges while the maximum %Dr was achieved at the highest nanoparticles concentration.

Figure 6 shows the effect of the powder density on the %Dr for all the investigated solutions at the diameter and concentration of the same particles. The glass powder with the density of 2550 kg/m^3 showed the best and most stable drag reduction performance when compared with the other two powders that have a lower density (carbon powder, 1710 kg/m^3) and the powder with the higher density (copper powder, 8950 kg/m^3). The only case where the cast iron showed higher drag reduction performance was at the lowest concentration (100 wppm). This is expected since the generated degree of turbulence with the presence of minute quantities of the powder (100 wppm) will dominate with maximum turbulence-powder interaction. This will reach the optimum drag reduction flow environment at low concentrations with the less dense investigated powder (Figure 6 a).

Increasing the concentrations of the investigated powders resulted in a very interesting behavior where the carbon and copper powders exchanged domination when the Re increased. The copper powder drag reduction performance was higher at low Re ranging between 15317 to 91907. On the other hand, the carbon powder drag reduction performance was higher at higher Re values. Such behavior demonstrates the relationship between the particle's concentrations, density, and degree of turbulence. Increasing the Re means increasing the degree of turbulence, which includes increasing the number of eddies and their swirl-motion intensities. The interaction of these eddies with the powders will suppress the overall degree of turbulence due to the new apparent physical properties introduced to the main flow by introducing the additives. At the low Re range, the degree of turbulence allows the interaction of high-density copper powders, which will result in suppressing more weak turbulence structures than the carbon powder due to the high-density differences. Increasing the Re will increase the turbulence intensity that might create clusters of accumulated copper powders due to the centrifugal force while the carbon powder will continue to suspend effectively in the solution with stable drag reduction performance.



(a)

(b)

(c)

(d)

(e)

Figure 6. Comparing the drag reduction performance of the three insoluble additives at different concentrations: (a) 100 wppm, (b) 300 wppm, (c) 500 wppm, (d) 800 wppm and (e) 1100 wppm.

Impact

The present work addresses an important fundamental and commercial problem which is the stability of soluble drag-reducing agents on the overall drag reduction process. The work proved that the insoluble additives have a significant potential to replace known and commercially applied soluble additives, like polymers, with excellent flow enhancement efficiency. Adopting such an approach will eliminate the mechanical stability drawback associated with soluble additives and will introduce low-cost and effective insoluble drag-reducing agents that have no direct impact on the transported liquid's apparent physical properties, high resistance to shear forces, and are reusable. These additives can be effectively used in pipelines carrying crude oils or refinery products at turbulent flow mode.

Conclusions

The present work investigates the effect of three different insoluble additives, namely, carbon powder, glass powder, and copper powder, on the drag reduction performance using rotating disk apparatuses and crude oil as the flowing medium. The work aimed to examine the effect of the powder density on the overall drag reduction efficiency, and that was achieved by eliminating the effect of particles size where all the investigated powders were 100 µm. The experimental results showed that the glass powder with the density of 2550 kg/m^3 showed the highest and most stable drag reduction performance among the other two powders (copper, 8950 kg/m^3, and carbon 1710 kg/m^3). It is believed that the interaction between three dominating factors controlling the drag reduction performance is essential in identifying the powder with the optimum drag reduction efficiency. The high-density copper %Dr was higher than that of the carbon at a certain degree of turbulence (low Re), while the carbon powder showed a higher %Dr at high Re. This exchange of drag reduction performance domination is believed to be due to the exchange of the degree of interaction between the suspended solid particles and the turbulence structures and the effect of the particle's density on both. The relationship between the particles densities and their drag reduction performance was not linear (within the investigated conditions) where this kind of complex interaction between several factors acting at the same system is interesting needs to be examined further with a wider range of powders and the inclusion of the particles size as one of the influencing factors to generalize the understanding of this phenomenon

Conflict of interest

There are no conflicts to declare

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