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Performance Analysis of Drag Reducing Agents in Crude Oil Pipeline

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Abstract

The problem of frictional pressure drop in crude oil pipelines leads to significant energy losses and increased pumping cost during transportation. Drag reducing agents (DRAs) offer a proven solution to mitigate these losses. This study experimentally investigates the drag reduction performance of bio-derived cashew nut shell liquid (CNSL) and commercial polyacrylamide (PAM) as DRAs in crude oil flow through horizontal pipes of three diameter (0.0127, 0.0254, and 0.0381 m). Pressure drop measurements were conducted in a closed loop system under controlled flow conditions, with CNSL concentrations of 10-60ppm. Drag reduction percentage (DR%) was calculated under constant flow rate, using additive-free crude oil as baseline. Results showed non-uniform performance across Reynolds number regimes: CNSL achieved a maximum DR% of 92.3% at 10 ppm in the transitional-turbulent regime (Re ≈ 2622), approaching or exceeding Virk's asymptote (~84%), while PAM reached 89.9% at the same concentration. At higher Re (≈7312), low-concentration CNSL caused drag augmentation (~91.3%), recovering to 62.6–67.8% at 35–60 ppm; PAM maintained stable positive DR% (51.3%). Peak efficiency occurred at the intermediate diameter (0.0254 m), attributed to optimal turbulence intensity for additive turbulence interaction and eddy suppression via phenolic structure. These findings indicate that CNSL a biodegradable phenolic-rich bio-additive (CNSL) can deliver drag reduction levels approaching near-theoretical maximum in crude oil pipelines at concentrations far below those required for conventional synthetic polymers.

Keywords: Drag reduction; cashew nut shell liquid; polyacrylamide; crude oil pipeline; flow enhancement

1. Introduction

Crude oil remains a cornerstone of global energy supply, with its transportation over long distances primarily relying on pipeline networks that vary in diameter, inclination, and operating conditions (Edomwonyi-Otu, 2015; Souas & Meddour, 2022). Frictional pressure drop in turbulent flow constitutes the primary source of energy loss during pipeline transport, necessitating multiple booster pump stations to maintain throughput (Souas & Meddour, 2022). In single-phase crude oil transport, the primary source of energy dissipation is wall friction caused by turbulent eddies near the pipe wall. To compensate for these losses, multiple booster stations are installed along the pipeline route, leading to higher capital and operating expenses. (Gu *et al*., 2020; Jalal *et al*., 2021; Subkh *et al*., 2022).

Since the discovery of the Toms phenomenon in 1948 addition of minute quantities of certain high-molecular-weight additives can dramatically reduce turbulent friction losses, a finding that has since driven extensive research into drag-reducing agents (DRAs) (Toms, 1948; Virk, 1975). Synthetic polymeric DRAs, such as polyacrylamide (PAM), polyisobutylene (PIB), polyethylene oxide (PEO), and polymethyl methacrylate (PMMA), have been widely applied in crude oil systems, achieving drag reduction (DR) up to 80% by suppressing near-wall turbulent eddies through viscoelastic damping (Abdulbari, 2012; Han *et al*., 2017; Khadom & Abdul-Hadi, 2014; Sanchez & Zakin, 1994; Rashed *et al*., 2016; Zakin *et al*., 1979). Despite their effectiveness, synthetic polymers suffer from several critical limitations, including high cost, limited availability, poor shear stability, and irreversible mechanical degradation under high-shear turbulent conditions (Abdulbari *et al*., 2010, 2018; Fakhruddin *et al*., 2018; Mahmood *et al*., 2021; Tamano *et al*., 2015; Zhang *et al*., 2016). These drawbacks restrict their long-term commercial viability and raise environmental concerns due to poor biodegradability and persistence in ecosystems. Therefore, there is need for research investigations for alternative drag reduction agents.

Recent reserch has explored bio-derived and natural additives that offer renewability, low toxicity, biodegradability, and cost-effectiveness (Gu *et al*., 2020; Joseph & Ajienka, 2010; Marina, 2012; Sheng *et al*., 2017; Kotenko *et al*., 2019). Natural mucilages, such as okra mucilage, have shown promising drag reduction in aqueous systems, with a maximum DR % of 71% reported at 1000 ppm in turbulent water flow through galvanized iron pipes (Abdul Bari *et al*., 2010; Ahmad *et al*., 2009;). However, most natural polymers are water-soluble, limiting their direct applicability in oil-based systems like crude oil pipelines (Chauhan *et al*., 2002; Mishra & Pal, 2008). Oil-soluble or amphiphilic bio-based alternatives remain underexplored, particularly for single-phase crude oil transport.

Cashew Nut Shell Liquid (CNSL), a phenolic-rich by-product of cashew nut processing, emerges as a promising oil-compatible bio-derived alternative. CNSL is abundant, inexpensive, renewable, and biodegradable, with surface-active alkyl phenols (anacardic acid, cardanol, and cardol) that interact with turbulent structures (Eke *et al*., 2019). While CNSL has been investigated as a pour point depressant, flow improver, and corrosion inhibitor in crude oil systems, its application as a drag-reducing agent in turbulent single-phase crude oil pipelines has received limited attention. This research gap is significant, as existing studies on bio-based DRAs in oil systems are limited. Also, there is limited information on the comparative evaluations of CNSL against established synthetic polymers like PAM under controlled pipelines.

Although PAM and CNSL have individually been reported as flow improvers and CNSL as a corrosion inhibitor, comparative experimental studies focusing on the effect of additive concentration and pipe diameter on drag reduction parameters remain limited. Therefore, this study addresses this gap by experimentally investigating the drag reduction performance of bio-derived CNSL and commercial PAM in single phase crude oil flow through horizontal pipes of varying diameters. The study aims to evaluate the influence of additive concentration on drag reduction percentage (DR%) and Reynolds number and to assess pipe diameter influence on additive efficiency.

2. Materials and Methods

2.1 Materials

2.1.1 Drag Reducing Agents

Two drag reducing agents were investigated: a commercial polyacrylamide (PAM) and Cashew Nut Shell Liquid (CNSL)

Cashew Nut Shell Liquid (CNSL) was obtained from cashew nut shells derived from the cashew tree (*Anacardium occidentale L.*), a widely cultivated tropical plant of significant economic importance in many developing countries. The cashew nut shell contains a viscous, dark reddish-brown liquid of high technological relevance due to its phenolic composition. CNSL is primarily composed of alkyl phenols, including anacardic acid, cardanol, cardol, and 2-methyl cardol, whose functional groups (phenolic hydroxyl, carboxylic acid, alkyl unsaturation, and aromatic ring) make the liquid suitable for chemical and flow-modification applications (Lubi & Thachil, 2000).

CNSL was extracted using a standardized solvent extraction method in accordance to Eke *et al*., (2019). Cashew nuts were sourced from local suppliers and washed thoroughly with deionized water to remove surface contaminants. Then the nuts were air-dried at ambient temperature, after which they were manually split to separate the kernels from the shells. Thereafter, the shells were retained and mechanically shredded to increase surface area and enhance solvent penetration.

Approximately 700 g of the prepared shell material was loaded into a Soxhlet extractor, and acetone was used as the extraction solvent. The extraction was conducted continuously for 6 h to ensure maximum recovery of the liquid from the shell matrix. Following extraction, the acetone- CNSL solution was concentrated using a rotary evaporator under reduced pressure of 250 mbar at a bath temperature of approximately 38 °C to remove the solvent. The final product was a thick, dark brown viscous liquid, representing purified CNSL, free from residual solvent.

The resultant CNSL was characterized using Fourier Transform Infrared (FTIR) spectroscopy analysis to ascertain the various functional groups using Agilent Technologies in the wavelength range of 650–4000 cm^{-1} and used as a bio-based drag reducing agent in the present work. The physicochemical properties of CNSL include a dynamic viscosity of 71.4 mPa·s, with kinematic viscosity decreasing from 37.565 cSt at 60 °C to 29.673 cSt at 100 °C, indicating improved flowability at elevated temperatures. CNSL exhibited a density of 1.08 g/mL, specific gravity of 1.0118, and an API gravity of 8.35°, classifying it as a heavy liquid relative to crude oil. Additional properties include a pH of 5.03, acid value of 2.805 gKOH/g, iodine value of 126.9, and surface tension of 423.64 m^2/g.

Polyacrylamide (PAM) is a versatile family of synthetic polymers used worldwide and high infinitely soluble in water. It is white dry solid form with molecular weight of 3 X 10^6. Polyacrylamide was used in concentration of (10ppm).

CNSL additive was introduced into the crude oil at various concentrations (10, 35, 60 ppm) as reported in the experimental dataset.

2.2 Crude oil

Crude oil obtained from Egbaoma field in the Niger-Delta region was used in the present work was classified as a light crude oil. The physical properties of the crude oil as received were a specific gravity of 0.773, a density of 0.80 g/mL, a kinematic viscosity of 1.33 cSt, a dynamic viscosity of 0.5 mPa·s, and an API gravity of 52°. The kinematic viscosity was determined according to ASTM D445, while the specific gravity was measured following ASTM D1217-81. Crude oil used in the experiments was characterized at ambient temperature.

2.3 Flow Loop Description

The experimental setup is represented in Figure 1. As shown in the figure, it consists of a closed-loop horizontal pipeline system equipped with a crude oil reservoir, centrifugal pump, flow meter, and differential pressure gauges. The test section is a straight pipe of length of 0.5334 m, and different pipe internal diameters of 0.0127 m, 0.0254 m, and 0.0381 m. The crude oil was circulated at controlled flow rates, and pressure drops were recorded before and after additive injection.

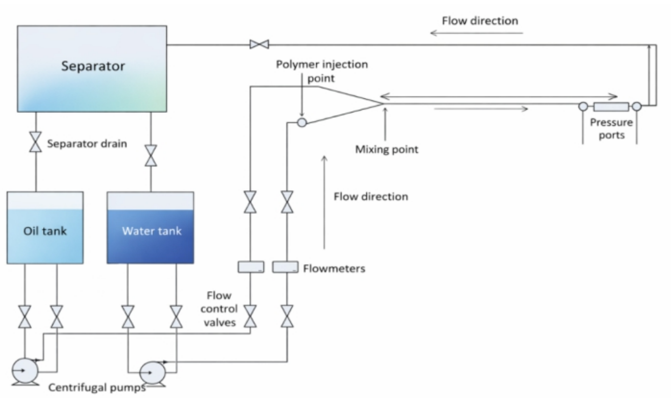

Figure 1: Schematic diagram of flow circulation loop

2.4 Experimental Procedure

Baseline measurements were obtained using untreated crude oil. Subsequently, CNSL and PAM were added separately at increasing concentrations. For each test condition, steady-state pressure drop and flow rate were recorded. These measurements were used to calculate Reynolds number, drag reduction percentage, flow increase percentage, and friction factor.

2.5 Governing Equations

In this work, Equations 1-4 are used to predict the flow Reynolds number (Re), percentage of, percentage of the drag reduction (%DR), and Darcy friction factor, respectively (Darby *et al,* 2006). The liquid flow system verification is achieved by comparing the friction factor of the additive-free crude oil flow data, and the asymptotes suggested by Blasius (1913), Virk (1975), and Zakin *et al.* (1979) for maximum drag reduction performance. The data utilised in this comparison was collected from the experimental rig. The flow behaviour of any liquid represented by the Reynolds number (Re) can be divided into two major regions:

(a) Turbulent region (Re > 3,000), where the friction factor (f) follows the correlation equation suggested by (Moody, 1944):

$$f = 0.0791\, Re^{-0.25} \quad (1)$$

(b) Maximum drag reduction asymptote region proposed by (Virk, 1975):

$$f = 0.59\, Re^{-0.58} \quad (2)$$

Fanning friction factor was calculated by Darcy friction factor

$$f = \frac{2d\Delta P}{L\rho v^2} \quad (3)$$

Reynolds number using the standard equation for pipeline flow

$$Re = \frac{\rho v d}{\mu} \quad (4)$$

Drag reduction percentage

$$DR(\%) = \frac{\Delta P_b - \Delta P_a}{\Delta P_b} \times 100 \quad (5)$$

where ΔP_b and ΔP_a are the pressure drops before and after additive injection, respectively.

3. Results and Discussion

3.1 FTIR Analysis of Cashew Nut Shell Liquid (CNSL)

Fourier Transform Infrared (FTIR) spectroscopy was used to identify the functional groups present in Cashew Nut Shell Liquid (CNSL). The FTIR spectrum of CNSL is presented in Table 1. Distinct absorption bands characteristic of alkyl phenolic compounds, including anacardic acid, cardanol, and cardol, were observed.

Table 1: Functional groups of cashew nut shell liquid (CNSL) identified from FTIR spectrum

Groups / Compounds	Wave number (cm^{-1})
O–H stretching (phenols)	3377.0
=C–H stretching (aromatics / alkenes)	3009.8
C–H stretching (alkanes, –CH_2– / –CH_3)	2924.1, 2853.3
C=O stretching (carboxylic acids)	1701
C=C stretching (aromatics / alkenes)	1600.9
C–H bending (alkanes)	1449
C–O stretching (phenols, ethers, esters)	1157.3, 1249.4
C–H out-of-plane bending (aromatics / alkenes)	911, 877, 777
–$(CH_2)_n$– rocking (long alkyl chains)	72.6, 708.2

A broad absorption band centered at approximately 3377.0 cm^{-1} corresponds to O–H stretching vibrations of phenolic hydroxyl groups, indicating hydrogen bonding (Kyei *et al.,* 2019). Strong absorption bands at around 2924.1 and 2853.3 cm^{-1} are attributed to asymmetric and symmetric stretching vibrations of aliphatic –CH_2– and –CH_3 groups, confirming the presence of long hydrocarbon side chains and supporting oil compatibility (Achi & Myina, 2011). A weak band near 3009.8 cm^{-1} is associated with =C–H stretching of unsaturated alkyl and aromatic groups.

A medium band at 1701 cm^{-1} is attributed to carboxylic C=O stretching from anacardic acid, supporting surface activity (Ike *et al.,* 2021). Bands at 1638–1600 cm^{-1} reflect aromatic and alkene C=C stretching, indicating thermal stability (Balgude & Sabnis, 2014; Ecochard *et al.,* 2019). Medium bands in the 1265–1157 cm^{-1} range correspond to phenolic C–O stretching, promoting viscoelastic damping in turbulent flow (Lubi & Thachil, 2000). Overall, the FTIR spectrum confirms that CNSL contains phenolic, aliphatic, and unsaturated functional groups that contribute to its moderate viscosity, thermal stability, and solubility in crude oil, supporting its suitability as a bio-based additive for drag reduction in pipeline flow systems (Pandian *et al.,* 2021).

3.2 Effect of Additive Concentration on Drag Reduction

The additive free crude oil showed Newtonian behaviour, as evidenced by the close agreement between the experimentally determined Fanning friction factors and the Blasius correlation ($f \approx 0.0791\, Re^{-0.25}$), with deviations of less than 1% across all pipe diameters. Similar findings have been widely reported for untreated crude oils under turbulent conditions (Al-Wahaibi *et al.,* 2014; Souas & Meddour, 2022), confirming both the reliability of the experimental setup and the suitability of the friction-factor-based approach for subsequent drag reduction analysis.

Figure 2 illustrates the variation in DR% with CNSL concentration across Reynolds numbers. In the transitional regime (Re ≈ 2042), DR% was moderate and non-monotonic: 21.6% at 10 ppm, 14.7% at 35 ppm, and 28.1% at 60 ppm. This limited effectiveness reflects underdeveloped turbulent structures, restricting viscoelastic interactions.

In the transitional-turbulent regime (Re ≈ 2622), CNSL exhibited peak efficiency: 92.3% DR at 10 ppm (exceeding Virk's MDR asymptote of ≈84%), 75.2% at 35 ppm, and 84.5% at 60 ppm. These values exceeded literature reports where 40-55% for polymers at 20-250 ppm (Karami & Mowla, 2012; Zabihi *et al.,* 2019), indicating strong CNSL-crude oil interaction and optimal eddy suppression via phenolic damping. This highlights CNSL's potential for high drag reduction at low doses in moderate turbulence.

In the turbulent regime (Re ≈ 7312), concentration sensitivity was evident in -91.3% DR resulting in drag augmentation (i.e., a substantial increase in frictional pressure drop relative to the additive-free baseline) at 10 ppm, which is indicative of ineffective interaction with turbulent eddies and enhanced energy dissipation, positive drag was recovered at higher concentrations, reaching 62.6% at 35 ppm and 67.8% at 60 ppm, below MDR (≈90%). This behavior indicates that intense

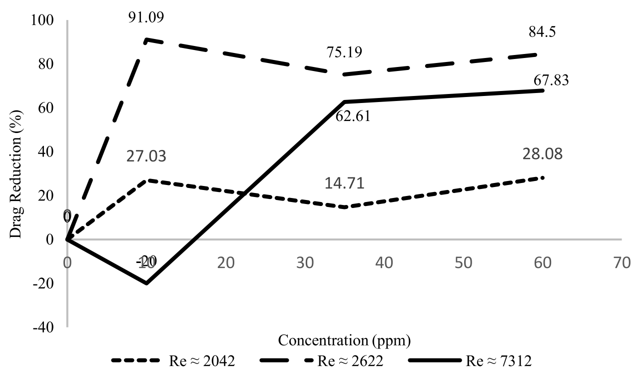

Figure 2: Variation of drag reduction percentage with additive concentration at different Reynolds numbers.

turbulence and shear stresses at high Reynolds numbers can overwhelm the viscoelastic damping capacity of CNSL at low doses, highlighting shear-induced limitations in its performance under such conditions.

PAM at 10 ppm showed stable performance: 32.4% (Re ≈ 2042), 89.9% (Re ≈ 2622), and 51.3% (Re ≈ 7312), without augmentation. This robustness stems from superior shear stability and chain extensibility, aligning with literature (40–60% DR in high Re).

Both additives peaked in transitional-turbulent flow, where turbulence enables but does not dominate damping. CNSL matches or exceeds PAM at low doses, offering sustainable benefits, but its narrower Re window requires optimized dosing for pipelines.

3.3 Effect of Pipe Diameter on Drag Reduction

Figure 3 shows how pipe diameter influences drag reduction performance for both the bio-derived CNSL additive and commercial polyacrylamide (PAM) in crude oil flow. Reynolds number (Re) increases with diameter under fixed flow conditions in this setup, reflecting diameter-dependent changes in Reynolds number and flow regime. In the smallest pipe (0.0127 m, Re ≈ 2042), drag reduction was moderate CNSL achieved 21.6% at 10 ppm, 14.7% at 35 ppm, and 28.1% at 60 ppm; PAM reached 32.4% at 10 ppm. These values fall well below Virk's maximum drag reduction asymptote (≈82%), as the weakly developed turbulence limits effective interactions between the additives and turbulent eddies. Performance peaked in the intermediate pipe (0.0254 m, Re ≈ 2622), CNSL delivered 92.3% drag reduction at 10 ppm, 75.2% at 35 ppm, and 84.5% at 60 ppm; PAM achieved 89.9% at 10 ppm. These results approach or exceed the MDR asymptote (≈84%) for this regime, indicating an optimal turbulence level that promotes additive chain extension and efficient suppression of near-wall eddies.

In the largest pipe (0.0381 m, Re ≈ 7312), effectiveness declined, CNSL showed drag augmentation −91.3% at 10 ppm and partial recovery to 62.6–67.8% at 35–60 ppm; PAM maintained 51.3%, both below the MDR asymptote (≈90%). The intensified shear stresses in this fully turbulent regime overwhelm the damping ability of the additives, especially at low CNSL doses.

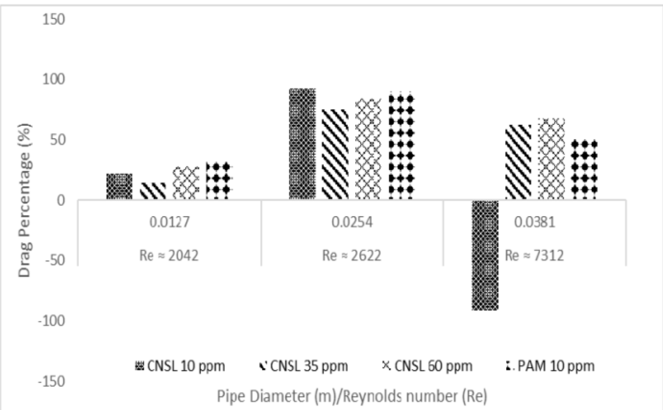

Figure 3: Variation of drag reduction percentage (DR%) with pipe diameter for CNSL bio-derived additive at 10, 35, and 60 ppm, and commercial PAM at 10 ppm.

4. Conclusions

This study demonstrates that both bio-derived Cashew Nut Shell Liquid (CNSL) and commercial Polyacrylamide (PAM) are effective drag-reducing agents in crude oil pipeline flow, with performance dependent on additive concentration and pipe diameter. CNSL, as a sustainable alternative, achieved significant drag reduction in the transitional-to-turbulent regime at low concentrations, performing comparably to or exceeding PAM under moderate flow conditions. PAM exhibited more consistent drag reduction across flow regimes, particularly avoiding drag increase at higher Reynolds numbers. Pipe diameter was found to influence performance, with peak results observed at intermediate diameters, likely due to optimal turbulence intensity for additive turbulence interactions, and reduced stability in larger diameters where shear effects dominate. These results are consistent with established polymer drag reduction behavior and with observations from natural mucilage systems, which indicate diameter-dependent turbulence scaling. Therefore, CNSL represents a promising environmentally friendly drag-reducing agent with strong low-dose potential, supporting energy-efficient crude oil transportation when dosage and operating conditions are appropriately optimized. Further investigations into long-term stability and industrial-scale application are recommended to enable broader practical implementation.

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