# Next-Generation Flow Improvers for Waxy Crude Oil: Unveiling the Performance of Hybrid Additives through CFD and Rheology

Zarana Patel[1,*], Jinal Patel[2], Prabha Modi[3], Salman Hadi Dahwal[4], and Ashish Nagar[5]

[*1]R&D, TWC Rajsha chemicals, Lamdapura, Vadodara, Gujarat, India
[2]Faculty of Science, Sigma University, Vadodara, Gujarat, India
[3]Department of Applied Science and Humanities, Parul University, Vadodara, Gujarat, India
[4]Department of Petroleum Engineering, Faculty of Petroleum and Minerals, Shabwah University, Atqe, Yemen
[5]Department of Petroleum Technology, Parul University, Vadodara-391760, Gujarat, India
*Corresponding Author
z1987zarana@yahoo.com

**Abstract:** Crude oil continues to be a major obstacle to effective pipeline transportation due to its very high viscosity, inclination toward wax crystallisation, and multiphase flow behaviour. Each of these characteristics increases flow resistance, which raises energy costs and creates operating difficulties. Flue optimisation techniques, particularly the use of chemical agents, are often used to address these issues in order to lower energy losses and improve transportation efficiency. The present study investigated the flow behavior of untreated waxy crude oil (WC) and chemically modified samples containing conventional additives (CA-1 and CA-2) and new developed nanohybrid chemical additives (NHCA-1 and NHCA-2) using computational fluid dynamics97 simulations confined by ANSYS Fluent software. Various significant parameters such as velocity distribution, liquid fraction, pressure drop and shear stress were examined at both the inlet and outlet sections of pipeline The simulation results showed significant improvements in flow properties following chemical treatment. The untreated crude oil had the largest resistance to flow, with a pressure drop of $6.80 \times 10^2$ Pa and shear stress of 4741.98 Pa. In contrast, the sample treated with NHCA-1 showed the greatest improvement, dropping pressure drop by more than 90% and shear stress by around 95%. Furthermore, velocity profiles for the treated systems indicated a more uniform distribution and lower flow resistance than the untreated oil. Overall, the study demonstrates that the newly developed nanohybrid chemical additives outperform conventional additives in improving the flow properties of waxy crude oil. By effectively decreasing viscous drag and energy requirements, these additives present a promising approach for achieving more energy-efficient and economically viable pipeline transportation of crude oil.


J. Saxena et al. (eds.), *Proceedings of the International Conference on Sustainable Micro-Nano Materials & Innovative Technology (ICSUMMIT 2026)*, Atlantis Highlights in Engineering 44,
https://doi.org/10.2991/978-94-6239-727-9_22

**Keywords:** Flow assurance, Nano hybrid Polymer, CFD simulation, Rheology, ANSYS.

# 1 Introduction

Approximately one-third of the world's energy consumption comes from crude oil, which is still the primary energy source [1][2]. Therefore, an essential part of the global energy supply network is the effective transportation of crude oil via pipelines. However, paraffin wax, asphaltenes, and other heavy hydrocarbons with large molecular structures frequently impede the flow of crude oil, posing serious operational issues, particularly in offshore areas and low-temperature conditions [3][4]. The naturally high viscosity of untreated waxy crude oils combined with wax crystallisation and deposition can result in significant pressure losses, higher pumping power needs, and, in severe cases, total pipeline blockage [5][6].

Several flow assurance technologies have evolved throughout time to meet these transportation challenges[7]. Traditional methods include pipeline heating, mechanical cleaning via pigging, and chemical agent injection[8]. Chemical treatment has shown to be one of the most practical and cost-effective methods for increasing crude oil flow[9]. Commonly used additives, such as pour point depressants and flow improvers, work by lowering crude oil viscosity and changing the shape of wax crystals, thereby improving flow properties. However, their effectiveness may be reduced under complex operating conditions, especially in dynamic multiphase flow systems [10][11][12].

In recent years, research has focused on the development of novel hybrid chemical additives (NHCA). These formulations combine the functional capabilities of many chemical groups, such as polymers, surfactants, dispersants, and nanoparticles, into a unified system[13] [14]. The goal of these hybrid additives is to improve both rheological and hydrodynamic performance, resulting in lower drag and better control of wax deposition[15][13]. Although these materials have demonstrated significant potential, rigorous comparisons of untreated crude oil, conventional chemical additives, and advanced hybrid formulations under regulated flow conditions are still limited[16][17].

In this regard, computational fluid dynamics (CFD) has emerged as a significant analytical method for investigating fluid flow behaviour within pipelines [18]. CFD simulations allow for extensive evaluation of characteristics like as velocity distribution, liquid fraction, pressure drop, and shear stress, which provides a better understanding of flow mechanics and the efficacy of various chemical treatment strategies[19][14][20].

This study provides a comparative investigation of untreated waxy crude oil, conventional additives, and unique hybrids. CFD simulations were used in conjunction with experimental rheological data to assess their effects on flow velocity, pressure drop, and shear stress in pipeline conditions. The results of this study are expected to provide actionable insights for the petroleum sector in decreasing pumping costs, minimising energy losses, and assuring continuous crude oil transportation.

## 2. Materials and Methods

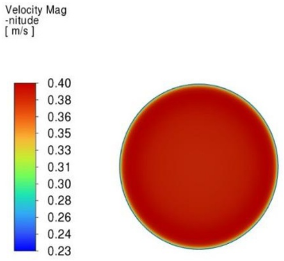
The crude oil sample used in this investigation was acquired from the Western Onshore field of Oil and Natural Gas Corporation (ONGC) and is referred to as WA. The physicochemical characteristics of crude oil were assessed using ASTM standard procedures. Conventional chemical additives (CA-1 and CA-2) and their corresponding nanohybrid formulations (NHCA-1 and NHCA-2), with carbon chain lengths of C20 and C22, were synthesised using a combination of monomers such as alkyl acrylate, stearyl methacrylate, and styrene, as well as modified nanosilica. Several analytical techniques were used to characterise the synthesised additions, including Fourier Transform Infrared Spectroscopy (FTIR), Proton Nuclear Magnetic Resonance ($^{1}$H NMR), and X-ray Diffraction. The performance of these additives was further evaluated through pour point measurements, rheological analysis, cold finger tests, and microscopic examinations, as reported in [17]. The methodology involves geometry creation, meshing and setting up model which is discussed in [20].

## 3. Results and Discussion

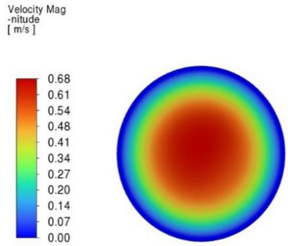
The examination of the synthesised formulations revealed that nanohybrid additives outperformed traditional chemical additives. The nanohybrid formulations reduced the crude oil's pour point by up to 15 °C at a concentration of 500 ppm, but the similar traditional additives achieved just a 6 °C reduction even at a greater dosage of 1000 ppm. Furthermore, when treated with 500 ppm of nanohybrid additions, the viscosity of the waxy crude oil dropped by nearly 90%, whereas traditional additives reduced the viscosity by only around 65% at 1,000 ppm. Cold finger tests revealed significant suppression of paraffin wax deposition, with nanohybrid additions providing up to 65% inhibition. These data indicate their potent efficacy as pour point depressants. Microscopic examination confirmed these findings, revealing greater dispersion and change of wax crystal structures in samples treated with nanohybrid formulations. Overall, both the synthetic chemical additions and their nanohybrid equivalents were efficient at lowering the pour point and viscosity of crude oil. However, nanohybrid additions routinely outperformed traditional chemical additives [16]. The CFD model was validated by comparing simulated results for untreated crude oil to experimental data collected from a laboratory-scale flow loop. Following validation, the CFD simulations and rheological evaluations of untreated waxy crude oil (WA) and chemically treated samples containing conventional additives (CA-1 and CA-2) and nanohybrid additives (NHCA-1 and NHCA-2) were thoroughly evaluated. The investigation focuses on key flow characteristics such as velocity distribution, liquid percentage, pressure drop, and shear stress to better understand how chemical treatments affect the flow behaviour of waxy crude oil[21].

### 3.1 Velocity Distribution

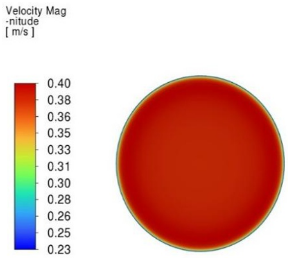
Figure 1 illustrates the velocity profile at the inlet and outlet of the pipeline for all oil samples. The untreated waxy crude oil (WC) had a distorted velocity profile, with notable boundary layer thickening and irregular velocity distribution over the pipe cross-section. The velocity in the core region was significantly lower than that reported in ideal Newtonian fluids, which is consistent with the non-Newtonian and shear-thinning behaviour frequently associated with waxy crude oils [22].



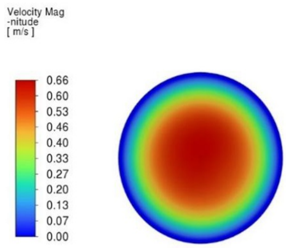

**WA (Inlet)**



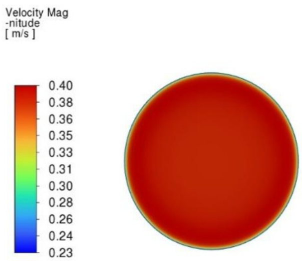

**WA (Outlet)**

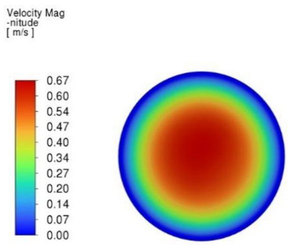



**WA + CA-1 (Inlet)**




**WA + CA-1 (Outlet)**



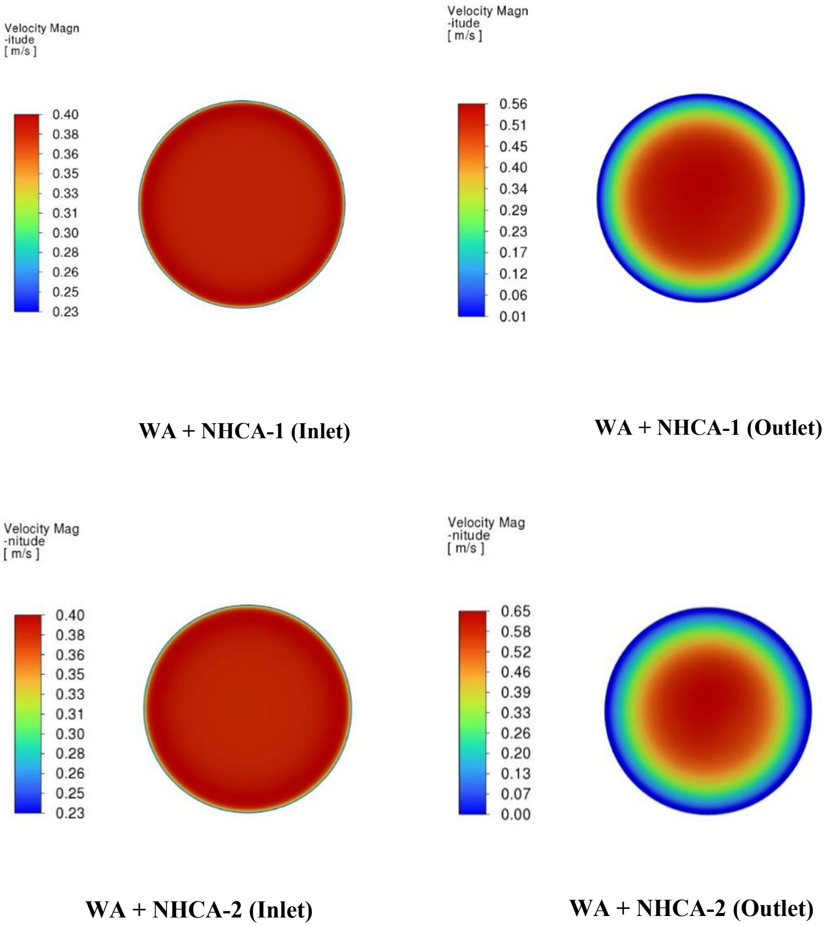



**Fig. 1.** Velocity profile of the oil sample at inlet and outlet

Chemical treatment resulted in improved velocity distribution for both conventional additives (CA-1 and CA-2) and nanohybrid additives (NHCA-1 and NHCA-2). The treated samples showed a more uniform flow pattern through the pipeline. Among them, NHCA-1 produced the highest velocity at the pipe core as well as the most symmetrical velocity profile, indicating improved momentum transmission across the pipe's cross section. This improvement is most likely due to the additive's ability to break the linked wax crystal network in crude oil, lowering internal structural resistance and allowing for smoother flow.

### 3.2 Temperature Influence on Velocity

Table 1 summarizes the inlet and outlet temperatures of crude oils during transport.

**Table 1.** Velocity at inlet and outlet of the pipeline

| Name of oil | Inlet temperature | Outlet temperature |
|---|---|---|
| WC | 333.15 | 315.15 |
| WC+CA-1 | 333.15 | 322.15 |
| WC+CA-2 | 333.15 | 321.15 |
| WC+NHCA-1 | 333.15 | 330.15 |
| WC+NHCA-2 | 333.15 | 331.15 |

The entrance temperature of untreated crude oil (WC) is 333.15 K, while the output temperature lowers to 315.15 K, representing an 18 K difference. This large temperature drop indicates the pipeline's high viscous and frictional losses. Waxy crude oil loses heat faster due to its high viscosity and poor flow, increasing the likelihood of wax deposition. With WC + CA-1 and WC + CA-2 (conventional additives), the output temperatures rise to 322.15 K and 321.15 K, respectively.

This lower temperature decrease (about 11-12 K) suggests that traditional additives reduce flow resistance and viscous heating losses by somewhat improving flow behaviour, allowing the crude to retain more heat as it passes down the pipeline. Outlet temperatures for WC + NHCA-1 and WC + NHCA-2 (nanohybrid additions) rise to 330.15 K and 331.15 K, respectively, with just a 2-3 K decline. This indicates nanohybrid additives' superior efficacy in lowering internal friction and increasing momentum transfer, which increases velocity and liquid fraction homogeneity while minimising thermal energy loss. The oil acts more like a Newtonian fluid, with greater laminar flow, so less energy is released as heat, and more heat is maintained down the pipeline.

## 3.3 Velocity Variation Along Pipeline Cross-Section

Figures 2 and 3 present velocity variations along the pipeline axis (longitudinal profile) and across the length of the pipeline and the pipe cross-section respectively.

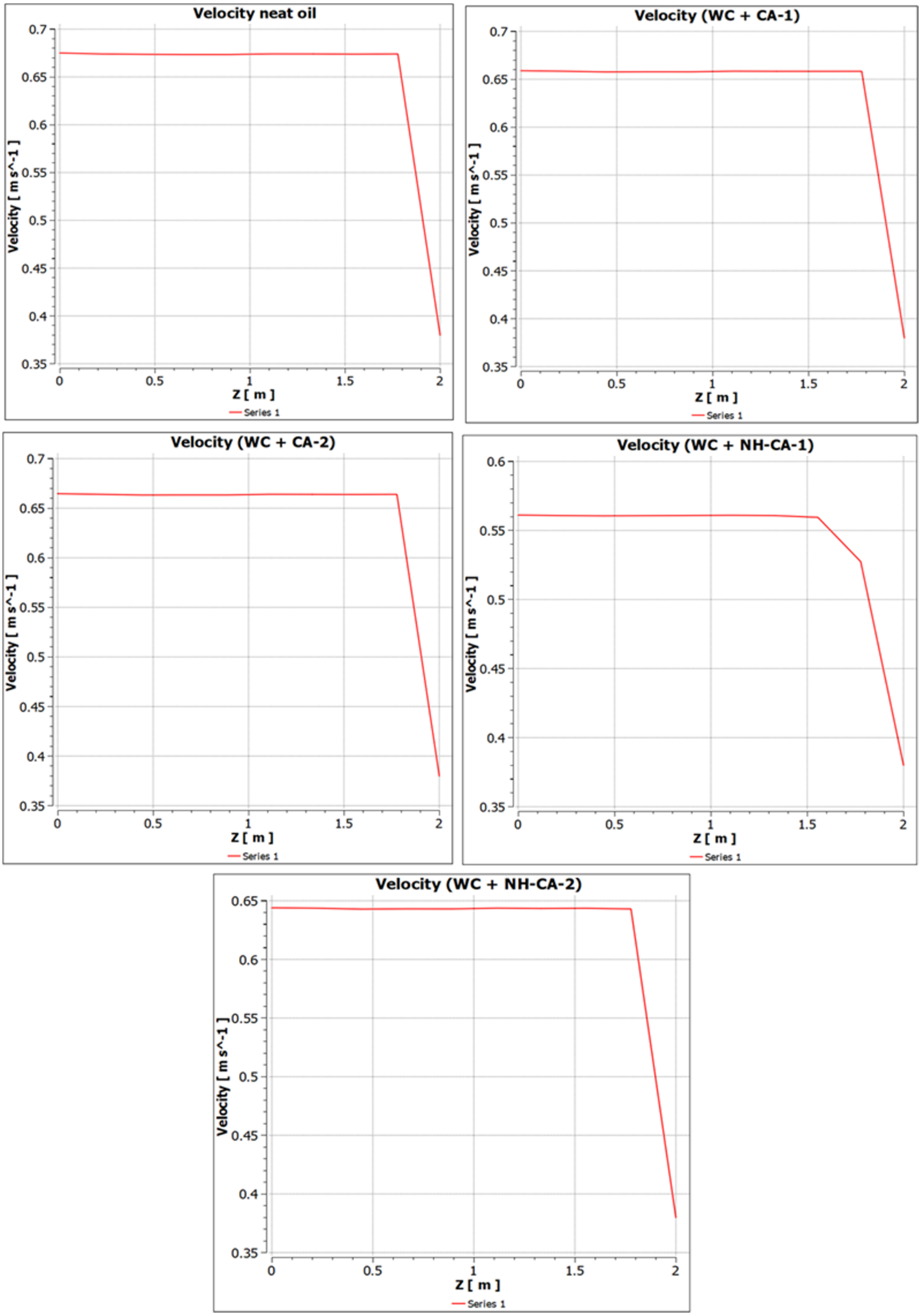



**Fig. 2.** Velocity profile of untreated and treated crude oil samples along the length of pipeline

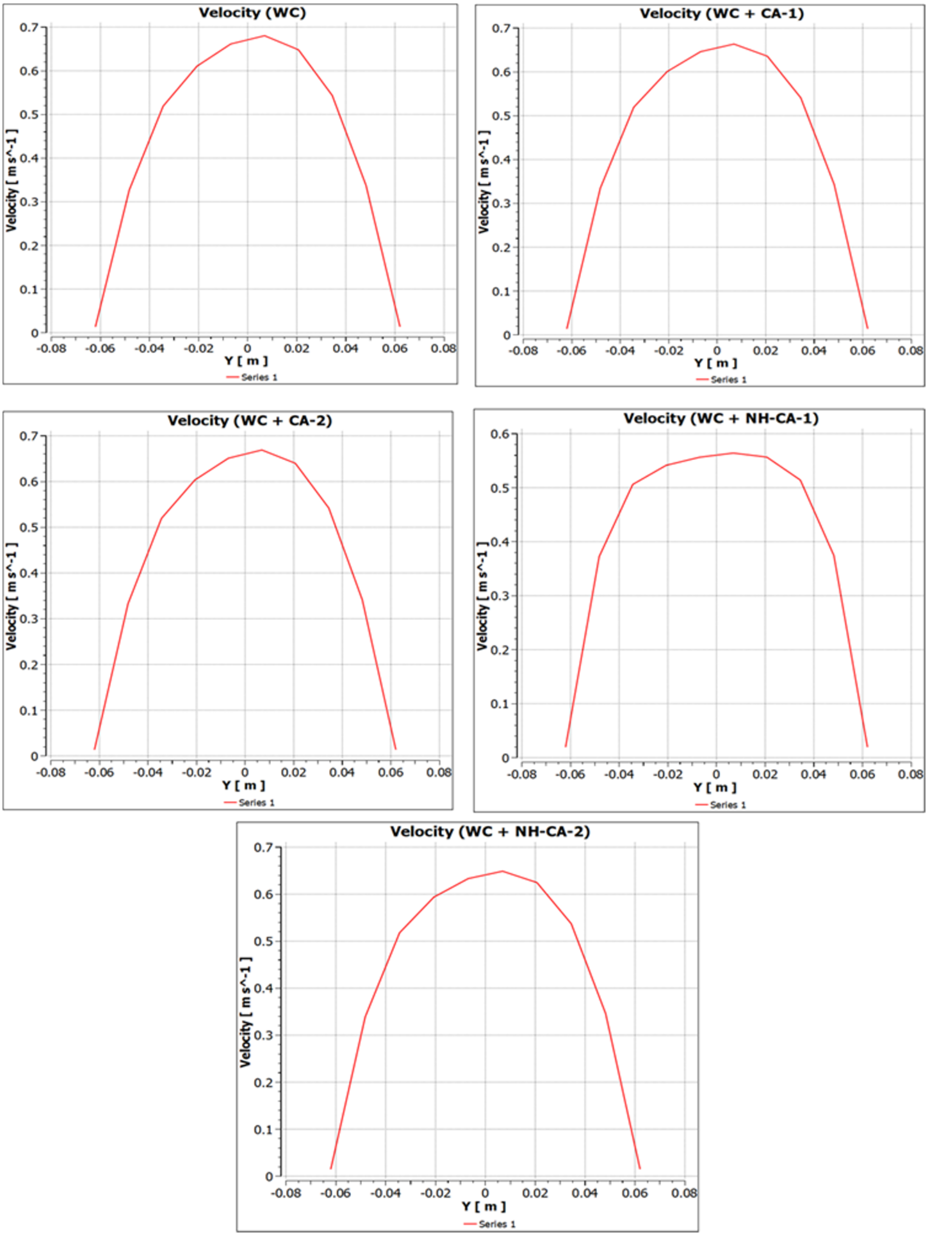



**Fig. 3.** Velocity profile of untreated and treated crude oil samples along the cross-section area of pipeline

The untreated crude oil (WC) showed high velocity gradients at the pipe wall, as well as localised stagnation regions, which are prevalent in wax-deposition-prone crude oils. Treatment with common chemical additives (CA-1 and CA-2) lowered the strength of the wall velocity gradient; nonetheless, considerable flow asymmetry and distortion persisted. In contrast, crude oil samples treated with nanohybrid chemical additives (NHCA), notably NHCA-1, demonstrated velocity profiles that were virtually parabolic in shape, closely mimicking the behaviour of Newtonian fluids. This suggests a significant improvement in flow properties, such as decreased drag and modified viscosity. The improved performance of nanohybrid additives can be due to their synergistic action, in which polymer components reduce viscosity and surfactant functions encourage wax crystal dispersion within the oil matrix [23].

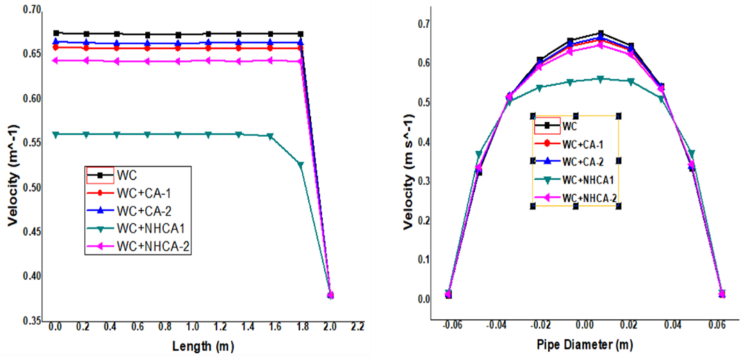
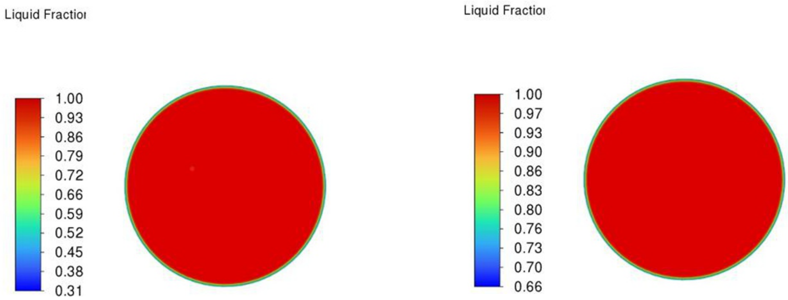



**Fig. 4.** Effect of different chemical additives on velocity of untreated and treated crude oil samples along the (a) length and (b) cross-section area of pipeline

## 3.4 Liquid Fraction Distribution

Figure 5 depicts the liquid fraction contours for untreated and treated crude oils. untreated waxy crude oil (WC) exhibited significant fluctuations in liquid holdup, including relatively immobile patches near the pipe walls and signs of multiphase stratification. Such behaviour is undesirable in long-distance pipelines because wax precipitation can exacerbate flow heterogeneity and encourage deposition on the pipe surface.




**WA** **WA + CA-1**

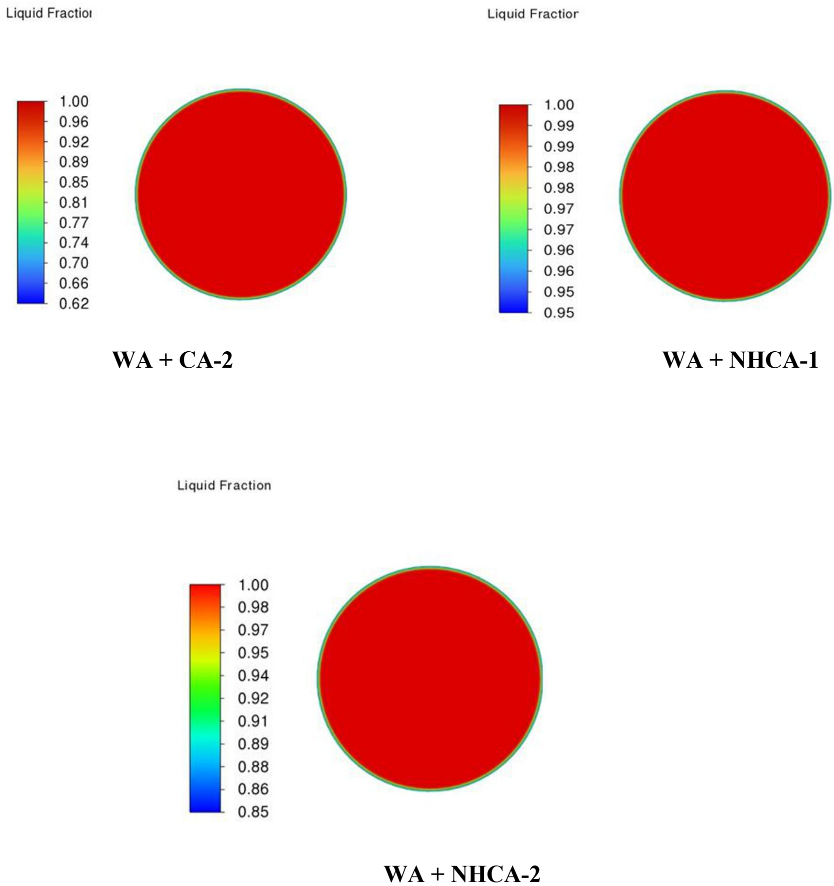



**Fig. 5.** Liquid fraction of untreated and treated crude oil samples

In comparison, the chemically treated crude oil samples demonstrated a more uniform liquid fraction distribution. The effects of the additives can be summarized as follows:

- **CA-1 and CA-2:** These conventional additives reduced the thickness of the stagnant wall layer and improved the overall homogeneity of the flow, although some minor irregularities remained.
- **NHCA-1 and NHCA-2:** The nanohybrid additives produced a nearly uniform phase distribution throughout the pipeline cross-section, effectively minimizing stagnant zones and supporting a more stable and continuous flow regime.

The enhanced uniformity of the liquid fraction plays an important role in limiting wax deposition and preventing slug formation, thereby improving the reliability and operational efficiency of crude oil pipeline transport.

## 3.5 Pressure drops

Table 2 and Figure 6 show a comparison of pressure drop results for untreated and chemically treated crude oil samples. The unprocessed waxy crude oil (WA) had the maximum pressure drop (6.80 × $10^2$ Pa), indicating severe resistance to flow in the pipeline. In contrast, the use of chemical additives resulted in a significant reduction in pressure losses. NHCA-1 had the most pronounced effect of all the studied formulations, lowering pressure drop by more than 90% when compared to the untreated sample. This significant drop demonstrates the efficacy of nanohybrid chemical additives in enhancing flow properties.

The remarkable reduction in pressure drop suggests that hybrid chemical formulations can significantly minimize hydraulic resistance in pipelines, thereby lowering pumping energy requirements and enhancing the overall efficiency of crude oil transportation.

**Table 2.** Pressure drops of untreated and treated oil

| Oil sample | Pressure drops (Pa) | Pressure reduction efficiency (%) |
|---|---|---|
| WA | 6800 | - |
| WA + CA-1 | 2990 | 56.03% |
| WA + CA-2 | 3750 | 44.85% |
| WA + NHCA-1 | 530 | 92.23% |
| WA + NHCA-2 | 1910 | 71.91% |

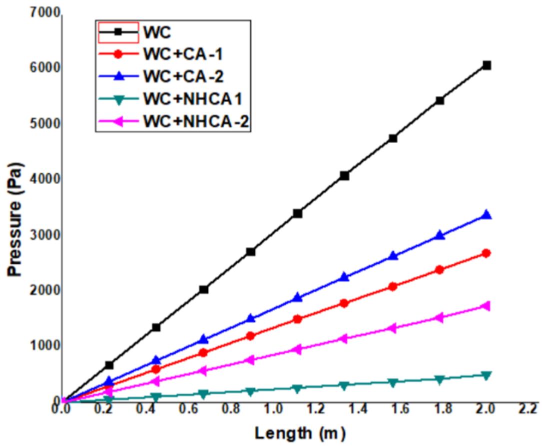



**Fig. 6.** Pressure drop across the length of the pipeline for treated crude oils

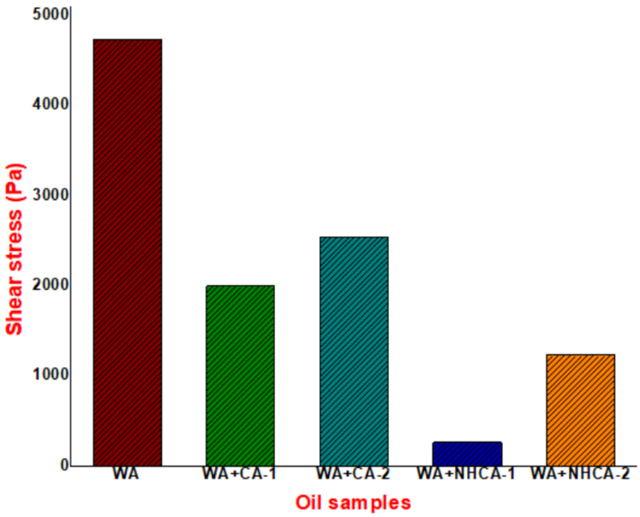
Lower pressure reductions correspond directly to lower pumping energy requirements, with significant industrial ramifications. Reduced flow resistance not only reduces operational expenses but also increases the life of pumping equipment. For example, in this study, the pressure drop dropped from 680 Pa for untreated WA to 53.4 Pa with NHCA-1 treatment, resulting in a nearly tenfold reduction in energy demand. Such benefits are consistent with field data, which have demonstrated that using chemical drag-reducing additives can reduce pumping costs by 30-70% [20]. This indicates how nanohybrid additives, such as NHCA-1, can give significant economic and operational benefits in large-scale pipeline transport of waxy crude oils.

### 3.5.1 Shear Stress

Table 3 and Figure 7 present the shear stress values.

**Table 3.** Shear stress of untreated and treated oil

| Oil sample | Shear stress Pa | Shear stress reduction efficiency % |
|---|---|---|
| WA | 4741.98 | - |
| WA + CA-1 | 2002.75 | 58 |
| WA + CA-2 | 2550.59 | 47 |
| WA + NHCA-1 | 266.91 | 95 |
| WA + NHCA-2 | 1232.69 | 74 |



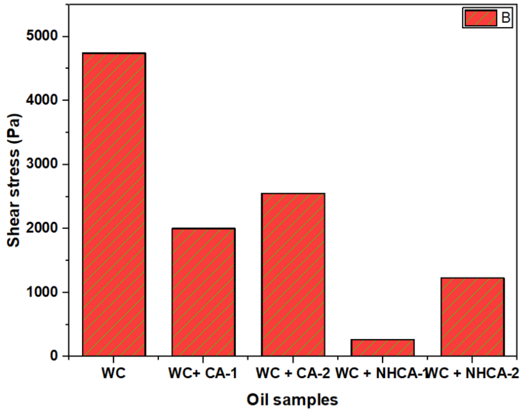



**Fig. 7.** Effect of chemical additives on shear stress of the untreated oil and treated crude oils

The untreated waxy crude oil (WC) had a very high shear stress of 4741.98 Pa, indicating severe resistance to flow within the pipeline. NHCA-1 again outperformed the other formulations, reducing shear stress by nearly 95%. The similar trends seen between shear stress and pressure drop support the efficacy of chemical treatments. Both measurements consistently show that nanohybrid additives, notably NHCA-1, significantly improve flow behaviour by reducing internal resistance, increasing momentum transfer, and allowing for smoother pipeline transit of waxy crude oil.

## 3.6 Discussion of Rheological Effects

The large reduction in shear stress observed with NHCA-1 suggests a significant adjustment of the crude oil's rheological properties, thereby moving WC's behaviour closer to that of a Newtonian fluid. Previous studies have demonstrated that polymer-surfactant hybrid additives can inhibit wax crystal interlocking while also dispersing asphaltene aggregates [21].

This process is highly supported by the findings of this study, which show that NHCA-1 not only reduces yield stress in waxy crude oil but also promotes a more laminar, uniform flow profile. This dual action—simultaneous rheological alteration and structural dispersion—explains the significant increases in velocity uniformity, pressure drop, and shear stress seen in the models.

## 3.7 Comparative Performance of Additives

NHCA-1 consistently performed better than the other additives, including CA-1, CA-2, and NHCA-2, across all assessed parameters, including velocity distribution, liquid fraction, pressure drop, and shear stress. Although traditional CA additives provided some improvements, they were insufficient to completely solve the problems caused by waxy crude oils. The NHCA formulations, particularly NHCA-1, on the other hand, showed a better synergistic effect by coupling significant rheological alteration with efficient drag reduction.

These findings show that NHCA-1 is an extremely attractive option for the industrial-scale pipeline transportation of crude oil, with the potential to reduce energy consumption while reducing flow assurance hazards such wax deposition and flow instabilities. Further validation of the numerical simulations revealed a divergence of less than 5%, confirming the CFD modelling framework's robustness and dependability

## 4. Conclusion

Using CFD simulations backed by rheological measurements, this study methodically examined the hydrodynamic and rheological behaviour of untreated waxy crude oil (WC) and chemically treated samples using conventional additives (CA-1, CA-2) and novel nanohybrid chemical additives (NHCA-1, NHCA-2). The following is a summary of the main findings.

- **Velocity profiles**: The flow of untreated crude oil was extremely uneven and showed clear boundary layer effects. Chemical additives, especially NHCA-1, increased momentum transfer by restoring near-parabolic velocity distributions.
- **Liquid fraction:** While NHCA-treated oils obtained very homogenous liquid fractions, minimising stationary zones and lowering the likelihood of wax deposition, WC displayed a heterogeneous phase distribution.
- **Pressure drop:** NHCA-1 reduced pressure losses by up to 92%, directly lowering pumping energy requirements and operational costs.
- **Shear stress:** Reductions in shear stress mirrored the pressure drop trends, with NHCA-1 achieving a 95% decrease, highlighting its superior ability to modify the rheology of waxy crude oils.
- **Overall performance:** The nanohybrid additives (NHCA) demonstrated a synergistic effect between rheological improvement and drag reduction, consistently outperforming conventional additives (CA) and offering a workable solution to flow assurance issues in crude oil pipelines.

In order to determine industrial viability, future steps should include pilot-scale field validation of NHCA performance, optimisation of additive dosages under various operational situations, and economic analyses contrasting additive costs with potential energy savings.

**Disclosure of Interest:** The authors have no competing interests to declare that are relevant to the content of this article.

## References

[1]Z. Sun, B. Yan, G. Jing, F. Zhang, H. Li, and X. Liu, “A review of nanoparticles and their composites as pour point depressant for waxy crude oil,” J. Dispers. Sci. Technol., 2023, doi: 10.1080/01932691.2023.2220783.

[2]D. Lord, “Crude oil properties overview,” Sandia Natl. Lab., 2014, [Online]. Available: https://www.osti.gov/servlets/purl/1242209

[3]W. Zhang, Q. Li, Y. Li, S. Dong, S. Peng, and G. Chen, “Viscosity Reduction and Mechanism of Aquathermolysis of Heavy Oil Co-Catalyzed by Bentonite and Transition Metal Complexes,” Catalysts, vol. 12, no. 11, 2022, doi: 10.3390/catal12111383.

[4]R. K. Ratnakar, S. Pandian, H. Mary, and H. Choksi, “Flow assurance methods for transporting heavy and waxy crude oils via pipelines without chemical additive intervention,” Pet. Res., vol. 10, no. 1, pp. 204–215, 2024, doi: 10.1016/j.ptlrs.2024.07.005.

[5]G. C. Savulescu, S. Simon, G. Sørland, and G. Øye, “Understanding the Effect of Asphaltenes and Wax Inhibitors on Wax Crystallization by Improved NMR Techniques,” Ind. Eng. Chem. Res., vol. 62, no. 44, pp. 18251–18262, 2023, doi: 10.1021/acs.iecr.3c02218.

[6]A. Harun, N. K. I. N. Ab Lah, H. Husin, and Z. Hassan, “An overview of wax crystallization, deposition mechanism and effect of temperature & shear,” ICIMSA 2016 - 2016 3rd Int. Conf. Ind. Eng. Manag. Sci. Appl., 2016, doi: 10.1109/ICIMSA.2016.7503992.

[7]M. C. K. De Oliveira, A. Teixeira, L. C. Vieira, R. M. De Carvalho, A. B. M. De Carvalho, and B. C. Do Couto, “Flow assurance study for waxy crude oils,” Energy and Fuels, vol. 26, no. 5, pp. 2688–2695, 2012, doi: 10.1021/ef201407j.

[8]J. R. Agarwal, S. Kumar, S. N. Shah, and A. Sircar, “Characterization and wax mass flux analysis of Bakrol field India crude oil,” Offshore Technol. Conf. Asia 2018, OTCA 2018, no. March, pp. 20–23, 2018, doi: 10.4043/28237-ms.

[9]M. R. Elkatory et al., “Mitigation and Remediation Technologies of Waxy Crude Oils’ Deposition within Transportation Pipelines: A Review,” Polymers (Basel)., vol. 14, no. 16, 2022, doi: 10.3390/polym14163231.

[10] R. Sharma, V. Mahto, and H. Vuthaluru, “Synthesis of PMMA/modified graphene oxide nanocomposite pour point depressant and its effect on the flow properties of Indian waxy crude oil,” Fuel, vol. 235, no. August 2018, pp. 1245–1259, 2019, doi: 10.1016/j.fuel.2018.08.125.

[11] Y. Wu, G. Ni, F. Yang, C. Li, and G. Dong, “Modified maleic anhydride co-polymers as pour-point depressants and their effects on waxy crude oil rheology,” Energy and Fuels, vol. 26, no. 2, pp. 995–1001, 2012, doi: 10.1021/ef201444b.

[12] S. Scherf and A. Boddien, “Next generation pour point depressants based on novel polymer modifications,” Proc. - SPE Annu. Tech. Conf. Exhib., vol. 0, pp. 1–11, 2017, doi: 10.2118/187386-ms.

[13] S. H. Dahwal, Z. Patel, and A. Nagar, “Application and evaluation of nanohybrid polymer as flow improver for Indian crude oil,” J. Dispers. Sci. Technol., vol. 0, no. 0, pp. 1–9, 2024, doi: 10.1080/01932691.2024.2417681.

[14] S. H. Dahwal, Z. Patel, and A. Nagar, “A nanohybrid polymer as a high-performance flow improver : experimental and CFD analysis for waxy crude oil transportation,” Geosystem Eng., vol. 00, no. 00, pp. 1–17, 2026, doi: 10.1080/12269328.2026.2627277.

[15] P. Lu et al., “Synthesis and Performance Evaluation of the Modified EVA Pour Point Depressants (PPDs) with Different Side Alkyl Chain Lengths,” ACS Omega, vol. 10, no. 38, pp. 44749–44762, 2025, doi: 10.1021/acsomega.5c08188.
[16] Z. Patel, J. Patel, and A. Nagar, “IPTC-24612-MS Synthesis and Performance Evaluation of a Novel Nano Hybrid Chemical Additive on Indian Crude oil,” 2024, doi: 10.2523/IPTC-24612-MS.
[17] J. Patel, Z. Patel, and A. Nagar, “Performance and Evaluation of Ionic Liquids as Viscosity Reducers on Indian Crude Oil,” Asian J. Chem., vol. 36, no. 7, pp. 1543–1548, 2024, doi: https://doi.org/10.14233/ajchem.2024.31584 Performance.
[18] J. O. Cabrera Escobar, G. Machado Sotomayor, D. Cajamarca Carrazco, M. M. Paredes Godoy, and R. Cabrera-Escobar, “CFD simulation of the surface pumping of heavy crude oil in eastern Ecuador,” Enfoque UTE, vol. 15, no. 3, pp. 35–40, 2024, doi: 10.29019/enfoqueute.1034.
[19] X. Liu, H. Jiang, Z. Lu, F. Meng, H. Zhao, and Y. Liu, CFD Analysis of Melting Process in Pipelines for Wax Removal by Hot Water. 2019. doi: 10.1115/APPC2019-7622.
[20] S. H. Dahwal, Z. Patel, and A. Nagar, “Modelling of wax deposition for waxy crude oil by ANSYS fluent,” vol. 3, pp. 1–14, 2025.
[21] E. Harkou et al., “Computational fluid dynamics (CFD) modelling as a power multiplier tool for the design improvement of gaseous and liquid fuels: current status, challenges and perspectives,” Fuel, vol. 404, p. 136401, 2026, doi: https://doi.org/10.1016/j.fuel.2025.136401.
[22] O. Benhacene and R. Boucetta, “Impact of Upward Turbulent Flow on Wax Deposition in Heavy Viscous Oil Pipelines: A Numerical Simulation,” Int. J. Heat Technol., vol. 41, no. 5, pp. 1282–1290, 2023, doi: 10.18280/ijht.410518.
[23] R. Sharma, B. Deka, V. Mahto, A. Barifcani, and H. Vuthaluru, “Experimental investigation into the development and evaluation of ionic liquid and its graphene oxide nanocomposite as novel pour point depressants for waxy crude oil,” J. Pet. Sci. Eng., vol. 208, no. October 2021, 2022, doi: 10.1016/j.petrol.2021.109691.