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Optimizing Viscosity Reduction of East Baghdad Heavy Crude Oil: A Comparative Study of Naphtha, Toluene, and Kerosene Diluents

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Abstract

Heavy crude oil transportation is severely limited by high viscosity, creating major operational and economic challenges. This study investigates viscosity reduction of Iraqi heavy crude oil from the East Baghdad field using dilution with light hydrocarbons. Three solvents—kerosene, toluene, and naphtha—were tested at concentrations of 5–20% v/v under controlled temperatures (21, 40, and 62 °C) and mixing times (30 and 60 min). Viscosity measurements were conducted using a capillary viscometer following ASTM D445. The results demonstrate that viscosity reduction is strongly influenced by solvent type, dosage, temperature, and mixing time. Naphtha emerged as the most effective diluent, achieving up to 60% reduction at 20% v/v, while toluene and kerosene showed lower but still significant effects. The combined influence of solvent choice and operating conditions highlights the importance of optimization for field application. These findings provide a practical, data-driven basis for improving pipeline transport efficiency and reducing operational costs in heavy crude handling, while also pointing to future work on cost–benefit evaluation and environmental considerations.

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1. Introduction

Heavy crude oil, a vital resource for economies like Iraq's, presents significant transportation challenges due to its high viscosity [1, 3]. This high viscosity impedes flow through pipelines, necessitating costly interventions such as heating or dilution with light hydrocarbons [5-7].

The extraction, production, and transportation of heavy crude oil faces several major challenges, most notably the problem of high viscosity, which directly affects all stages of dealing with this type of oil [5-7]. High viscosity makes extracting heavy oil more difficult using traditional techniques such as electric submersible pumps, which require the use of advanced techniques such as steam injection or chemicals [8-9]. These techniques increase production costs and consume large amounts of water and energy, leading to serious environmental problems such as polluting gas emissions. In the production stage, high viscosity leads to low efficiency, as production processes are less effective and produce low production rates. In addition, heavy oil contains a high percentage of impurities such as sulfur and heavy metals, which makes it require intensive processing and increases operational costs. In addition, the abrasives and chemicals found in heavy oil cause severe corrosion on equipment and piping, increasing maintenance and repair costs. At the transportation stage, the difficulty of pumping heavy oil through pipelines without diluting or heating it is one of the most prominent challenges, as this requires the consumption of large amounts of energy and the use of chemicals such as light hydrocarbons to reduce viscosity, which increases the complexity and costs of transportation. Heavy naphtha oil spills are considered more harmful to the environment because they are more difficult to clean up than light oil [10-12]. Therefore, the problem of high viscosity represents a major obstacle that requires huge technical and financial investments to develop effective and sustainable solutions to address it, whether in extraction, production or transportation technologies, with the need to focus on reducing negative environmental impacts.

Heavy crude oil is usually transported from production sites to refineries or ports, usually via pipelines known for their safety over long distances [13-14]. However, the high viscosity of heavy crude oil, due to undesirable components such as asphalt, heavy metals and sulfur, complicates its production, transportation and processing. As for relatively heavy crude oils, this method requires special facilities. The main problem with this type of oil that comes with high densities is its high viscosity, which ranges from a few thousand to millions of centipoises at reservoir temperature while 400 cP is the classical maximum viscosity desired for a pipeline. This type of oil is dense and thick due to the abundance of naphthene and paraffin in it. Unlike light oil, heavy crude oil contains a higher percentage of lubricating oils, grease, wax, motor oil, and residues such as residual fuel oil, coke, tar, and asphalt. In addition, heavy crude oil typically contains more aromatic compounds, and heteroatoms such as N, O, S, and metals [15-16]. The presence of heavy crude oil poses major challenges to the oil industry, leading to costly production losses and transportation difficulties. Despite these challenges, heavy crudes make up a significant portion of the world's recoverable oil reserves.

Using light hydrocarbon dilution technology to reduce the viscosity of heavy crude oil facilitates pipeline transportation by increasing pumping efficiency and reducing operational costs, such as reducing the need for heating and corrosion [17-20]. It can also improve oil processing and increase its quality. However, this technology faces challenges such as the high cost of added compounds and the necessary infrastructure, as well as environmental risks associated with leakage, pollution and emissions. There are also operational challenges such as achieving homogeneous mixing and the effects of added compounds on refining, as well as safety risks associated with flammability. Getting the most out of this technology requires a careful balance between benefits and risks.

Despite the increasing use of the dilution method to reduce the viscosity of heavy crude oil, there remains a significant lack of reported data, especially regarding the effect of different solvents on crude oil. Therefore, it is important to re-examine the use of materials such as naphtha, toluene, and kerosene in this context [21-22]. This study is important because it can help determine the most effective solvents in reducing the viscosity of heavy crude oil, leading to improved transportation efficiency and reduced operational costs. For example, the use of naphtha can provide a significant improvement in the viscosity of oil thanks to its high dilution capacity, in addition to its wide availability, which makes it an economical option [23]. Naphtha stands out as a valuable option in the oil sector because of its elevated API gravity and effectiveness in thinning dense oils. Nevertheless, when combined, it may impact the stability of the asphaltenes, leading to their clumping together and separating. This, in return, can obstruct the flow of gas in pipelines. Likewise, toluene is very effective in reducing oil viscosity and has an excellent ability to mix heavy oil easily, which contributes to a significant reduction in viscosity and improved performance of the pipes and equipment used. On the other hand, kerosene is characterized by its effectiveness in reducing viscosity with relatively lower environmental impacts, which reduces environmental risks associated with leakage and emissions and contributes to improving the efficiency of logistics operations. A better understanding of the impact of these different solvents can help reduce emissions from dilution processes, contributing to improved environmental performance of the oil industry [24]. In addition, analyzing the effect of different solvents can help in selecting solvents that provide the optimal balance between effectiveness and cost, which contributes to reducing operational expenses. Based on these studies, appropriate solvent concentrations can be determined, which contributes to achieving a significant reduction in viscosity, facilitates the pumping process, and increases energy efficiency [25-28].

While studies have examined diluents like naphtha and toluene for various crudes [23, 24, 28], there is a scarcity of systematic, comparative data for Iraqi heavy crudes, particularly from the East Baghdad field, under varying operational parameters (concentration, temperature, mixing time). This study directly addresses this gap by re-examining the use of materials such as naphtha, toluene, and kerosene in reducing the viscosity of heavy crude oil is a necessary step to develop more effective and efficient oil transportation technologies, which enhances sustainability and reduces negative impacts on the environment.

2. Experimental Procedure

Samples of crude oil from oil fields in Iraq were chosen for a scientific investigation. The feedstock in this study was East Baghdad crude oil, which was obtained from Baghdad's east oil fields. The analysis of these samples is summarized in Table 1. The East Baghdad crude, with an API gravity of 20 and a kinematic viscosity of 25 cSt at 40°C, is classified as heavy and presents significant flow challenges, primarily due to its asphaltene content (3.5 wt%).

Table 1. East Baghdad crude oil Properties

Property	**Value**
Specific gravity at 15.6/ 15.6 ºC	0.922
API at 15.6 ºC	20
Viscosity at 40 ºC, cSt	25
Asphaltene content, wt%	3.5
Sulfur content, wt%	4
Conradson carbon residue, wt%	9
Ash content	0.09
Vanadium, ppm	64
Nickle, ppm	28

High-quality naphtha, kerosene, and toluene with a purity of 99.9% were acquired from Merck GmbH, Germany. Hydrocarbon samples were created by combining heavy oil with a solvent of known concentration (5%, 10%, 15%, or 20% volume) in a closed beaker using a magnetic stirrer device and ultrasonic bath for thorough mixing. The viscosity of the samples was measured using a capillary viscometer (ASTM D445-97) [29]. It allows for viscosity measurements at different temperatures and atmospheric pressures. Figure 1 shows the Ostwald viscometer used in the current study for measuring the viscosity of oils.

A capillary viscometer is a device used to measure the viscosity of fluids based on the principle of capillary flow. This measure consists of a U-shaped glass tube with bubbles on both sides, one arm of which is narrower, forming the capillary section. To measure viscosity, the liquid to be measured is placed in a viscometer, and one of the bubbles is usually filled with this liquid. The device is then immersed in a temperature-controlled water bath to ensure a constant temperature, as viscosity measurements depend greatly on temperature. The fluid is drawn over an indicator line on the capillary and allowed to flow again under the influence of gravity while recording the time it takes to pass between two marked lines on the capillary. Viscosity is calculated using the flow time and density of the fluid, often by comparing it to a reference fluid such as water of known viscosity, density and flow time, through a known relationship. This method is particularly useful because of its simplicity and accuracy for low to medium-viscosity fluids and its compatibility with temperature-controlled environments. However, it is not suitable for highly viscous liquids, and manual measurement of flow time can lead to significant errors. This device finds applications in various industries, including the petroleum industry, where accurate viscosity measurements are crucial. Maintenance includes constant cleaning between measurements, regular calibration with reference fluids, and careful handling when cleaning to prevent breakage. Despite its limitations, capillary viscometry remains a reliable and widely used tool for determining viscosity in both research and industrial contexts.

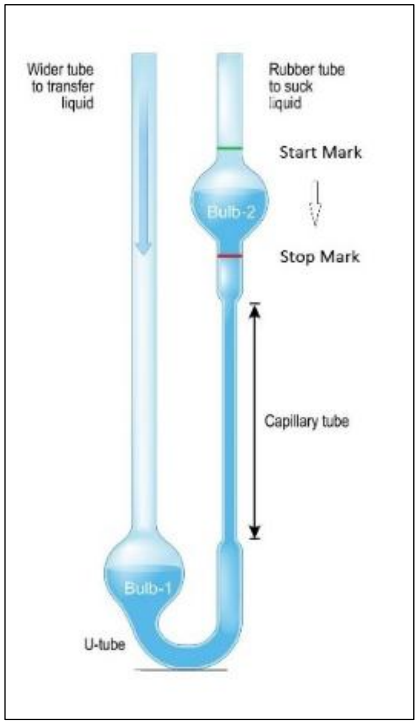

Figure 1. Ostwald viscometer device

After adding the light hydrocarbons to the heavy crude oil sample, the next step involves making sure they are well mixed with the crude oil. To ensure thorough mixing, a specialized ultrasonic bath device is used. This device, known as the Kamal model, of Iranian origin, operates with a power of 50 watts, a frequency of 40 kHz, and a volumetric capacity of 2.5 liters. This device works on the principle of emitting ultrasonic waves through water (a specific amount is required in the device) to effectively mix the oil model with the added solvent. The experiments include preparing four samples of crude oil, each containing 40 ml, in small containers. Then different volumetric concentrations of solvents such as light naphtha, kerosene, and toluene are added to these samples in calculated proportions: 5%, 10%, 15%, and 20% to reduce the viscosity of the crude oil. Next, the samples are placed in an ultrasound machine at 40°C for a specific time (30 & 60 minutes). The water bath device is also operated at the same temperature and the viscosity measuring device is immersed in it. The samples are then tested in a viscosity-measuring device to measure the time it takes the oil sample to move from the upper mark to the lower mark, which will later be used in viscosity calculations.

The standard equation (1) was used to calculate the viscosity after measuring the time.

$$\eta s = \frac{(\eta w \times \rho s \times ts)}{(\rho w \times tw)} \quad \dots\dots\dots (1)$$

Where:

ηs = Viscosity of given sample

ηw = Viscosity of triple distilled water at given temperature

ρs = Density of given sample at given temperature

ts = Time in seconds required by sample to cover distance (Start to Stop Marks) on viscometer

ρw = Density of triple distilled water at given temperature

tw = Time in seconds required by triple distilled water to cover distance (Start to Stop Marks) on viscometer

3. Results and Discussion

3.1 Dose Effect:

A series of experiments were conducted to explore the effectiveness of using three different light hydrocarbon solvents (toluene, kerosene, and naphtha) to study the viscosity reduction of heavy crude oil taken from the East Baghdad oil field. These light hydrocarbons are excellent options for reducing the viscosity of crude oil for transportation purposes due to their strong solvent properties, which effectively dissolve the heavy hydrocarbons present in the crude oil. Toluene, being an aromatic solvent, offers high solvent power and compatibility with crude oil components, while kerosene provides a balance of intermediate volatility and safety with a high flash point. Light naphtha, composed of lighter hydrocarbons, is versatile and economical, making it effective in diluting a wide range of heavier crude oil fractions. Together, these solvents improve the flow characteristics of crude oil, reduce pumping costs, and enhance overall transportation efficiency.

Laboratory experiments were performed at three different temperatures: 21°C, 40°C and 62°C using a water bath to maintain temperature uniformity. The effect of adding different volumes (5, 10, 15, 20 ml) of light hydrocarbon solvents to the crude oil was studied, and the experiment was repeated for each increase in volume and for each solvent to ensure the reliability and uniformity of the experimental results. The heavy crude oil showed a high initial viscosity, with kinematic viscosity values averaging around 24.9 cS. These viscosity measurements provided basic data for evaluating the effectiveness of light hydrocarbons in reducing viscosity. Toluene, kerosene and naphtha were chosen as light hydrocarbons for study. Each hydrocarbon exhibits distinct properties such as boiling point, density and viscosity at 40°C, which influences its potential effectiveness in reducing the viscosity of heavy crude oil. Figure 2 shows the results for the three selected solvents.

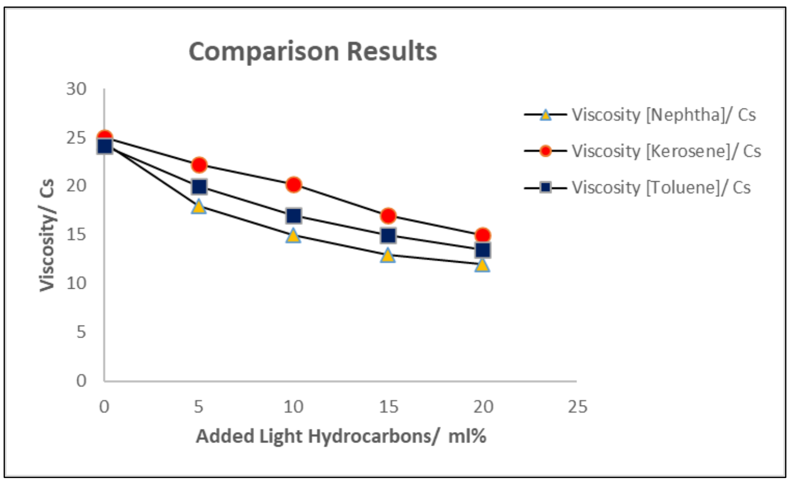

Figure 2: Kinematic viscosity of East Baghdad crude oil as a function of diluent concentration (5-20 vol%) for naphtha, toluene, and kerosene at 40°C and 30 min mixing time.

The viscosity of the heavy crude oil was measured after adding different volumes of each light hydrocarbon. A significant decrease in viscosity was observed with increasing concentrations of light hydrocarbons, with differences observed between them. Experimental results indicate that the addition of toluene, kerosene, and naphtha reduced the viscosity of heavy crude oil. In addition, differences were observed in the effectiveness of each solvent, with light naphtha generally providing the greatest amount of viscosity reduction, followed by toluene and then kerosene. The observed viscosity reduction can be attributed to the interaction between light hydrocarbon and heavy crude oil particles, leading to improved flow characteristics as will be discussed later.

The results in Figure 2 indicate a consistent trend of reducing the viscosity of heavy crude oil with the addition of increasing volumes of light hydrocarbons. Across all three solvents, higher volumes of hydrocarbons added corresponded to lower viscosity values, indicating a dose-dependent effect in reducing viscosity. Among the three solvents, light naphtha produced the most consistent reduction in viscosity, with the lowest viscosity values observed at all volume increments tested. Toluene also showed an effective reduction in viscosity value, although to a lesser extent compared to light naphtha. As for kerosene, while it still contributed to reducing viscosity, it showed a less pronounced effect among the three solvents. These results indicate that the molecular characteristics and interactions of each solvent with heavy crude oil influence their effectiveness in reducing viscosity. Reasonable agreements are obtained with previous results [23-28].

Viscosity reduction ratio (VR%) calculation was performed by measuring the initial viscosity (V_i) of the heavy crude oil sample used, adding the desired volume of solvent and mixing it well with the crude oil, and then measuring the final viscosity (V_f) of the mixture. The viscosity reduction percentage (VR%) is then calculated using equation (2).

$$VR\% = \frac{(Vi - Vf)}{Vi} \times 100 \ldots\ldots\ldots (2)$$

This formula measures the percentage decrease in crude oil viscosity achieved by adding solvent, where a higher percentage decrease indicates a greater decrease in viscosity. This process is repeated for each solvent and concentration level, at a mixing time of 30 min, allowing comparison of viscosity reduction capabilities. Optional steps include presenting the average results of several measurements to obtain a more representative value. By following this procedure, we can evaluate the effectiveness of different solvents in reducing the viscosity of heavy crude oil and optimize the viscosity reduction processes accordingly. Figure 3 shows the results after applying the previous procedure for the percentage decrease in viscosity for three hydrocarbons (naphtha, toluene, or kerosene).

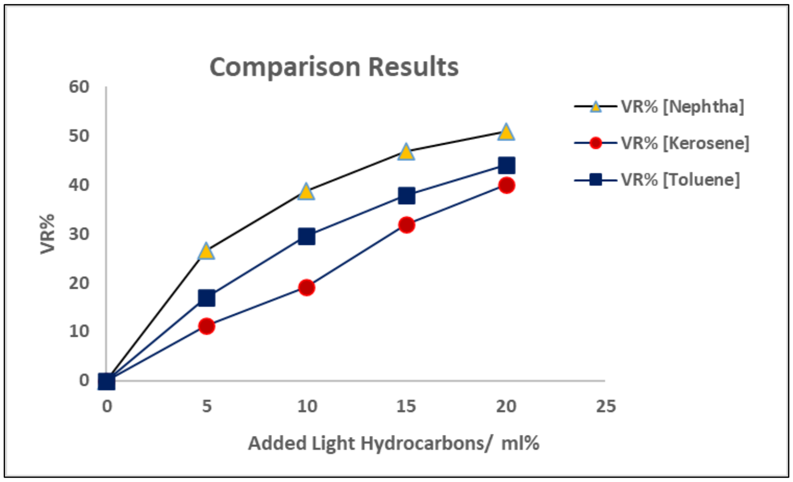

Figure 3: Viscosity Reduction Percentage comparison results for the effect of using different doses of solvents.

3.2 Temperature effect:

The current study confirmed that adding light naphtha to crude oil reduced the viscosity, making the oil easier to transport and process. As we previously indicated, this reduction in viscosity was the result of the interaction of light hydrocarbons in light naphtha with heavier components of crude oil, which changes its general composition. Temperature plays an important and influential role in this process, as it is expected that the higher the temperature, the lower the viscosity of crude oil. This happens because higher temperatures provide more energy to the molecules in the oil, allowing them to move more freely and reducing the intermolecular forces that contribute to reduced viscosity, as shown in the results we obtained here in this study presented in Figure 4.

Figure 4 shows that when light naphtha is added to crude oil, the effect of temperature on viscosity reduction can be better enhanced. The increase in temperature facilitates better mixing between naphtha and crude oil, resulting in a more efficient distribution of light hydrocarbons throughout the mixture. This, in turn, contributes to a more noticeable reduction in viscosity. However, it is necessary to point out that the effect of temperature on viscosity can vary depending on other factors such as the exact composition of the crude oil and the type of solvent used. On the other hand, the use of extreme temperatures can lead to adverse and unexpected effects. At high temperatures, changes in the solubility value may occur, leading to the dissolution of oil components such as waxes or asphaltenes that may condense upon cooling, thus resulting in phase separation and instability. Thermal decomposition of crude oil components and light hydrocarbons may lead to the formation of new compounds, while polymerization reactions can create larger molecules, all of which lead to a change in the viscosity and flow characteristics of the mixture. In addition, the rapid evaporation of light hydrocarbons means that they may evaporate rapidly at extreme temperatures, resulting in a change in the concentration and potency of the solvent. These temperature-induced changes complicate viscosity measurement and other data, posing challenges in industrial applications such as transportation, where unexpected changes in viscosity and phase behavior may affect efficiency. Therefore, precise temperature control is important to manage these complex behaviors and obtain reliable data.

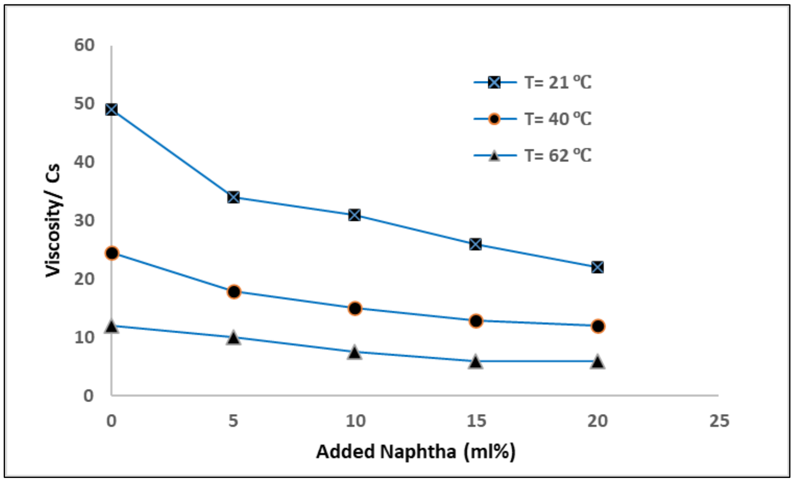

Figure 4: Comparison Results for temperature effect of adding Naphtha.

To understand the mechanism of the effect of temperature on the three solvents that we chose in our study, we found that a temperature rise reduced the viscosity of naphtha, for example, which might predictably lead to a reduction in the viscosity as well for both toluene and kerosene. Toluene, an aromatic hydrocarbon, exhibits stronger intermolecular forces due to its benzene ring structure, but these forces are more easily overcome as temperature rises, allowing the molecules to flow more freely. Likewise, kerosene, which is mainly composed of alkanes, experiences a weakening of van der Waals forces as temperature increases, facilitating easier movement of molecules and thus reducing viscosity. Despite differences in their molecular structures and intermolecular forces, both toluene and kerosene are expected to show a decrease in viscosity with increasing temperature. The high viscosity of heavy crudes is mainly caused by their high molecular weight components, which form ordered structures at low temperatures. Heating these oils disrupts these structures, reducing viscosity. As temperature increases, the oil shows more Newtonian fluid behavior, impacting viscosity significantly. [30]

A good agreement with previous work [24] was obtained. These authors investigated the impact of temperature on the viscosity of various oil/solvent mixtures is evident in the study. As temperature rises, viscosity decreases significantly, especially for liquids with higher viscosities. It is known that heating is more effective in reducing the viscosity of highly viscous oils compared to lighter ones. Their results showed a noticeable increase in VR% as temperature rises. This increase can be attributed to two main factors: the strong relationship between liquid viscosity and temperature, leading to a steep viscosity reduction trend with higher temperatures, and the disruption of ordered structures within the oil phase caused by thermal agitation at elevated temperatures.

3.3 Effect of Mixing Time:

In this experiment, the crude oil samples were diluted with light naphtha as an example of studying the effect of mixing time on the efficiency of viscosity reduction, as mixing time is another critical parameter that affects the effectiveness of viscosity reduction. Mixing time refers to how long to mix crude oil and light naphtha to achieve a homogeneous mixture. Proper mixing timing is essential to ensure thorough mixing between the crude oil and naphtha, allowing the lighter hydrocarbons to spread evenly throughout the crude oil. A short mixing time may lead to incomplete results, leading to the formation of localized areas of different compositions within the mixture, which can hamper the effectiveness of viscosity reduction, as the naphtha component may not be evenly distributed to interact with heavier components of the crude oil. On the other hand, a long mixing time may not provide significant additional benefits and may result in unnecessarily high energy consumption or other process failures. Therefore, it is necessary to determine the ideal mixing time that balances the need for thorough mixing with practical considerations such as energy consumption and process time. Research and optimization are usually required to determine the appropriate mixing time for a particular crude oil and naphtha system. This may involve running experiments with varying mixing times and evaluating the results to determine the point at which additional mixing does not significantly improve the result. By optimizing the mixing time along with other parameters such as mixing speed, researchers can maximize the efficiency of the viscosity reduction process while reducing resource consumption and process time. A model of this experiment is shown in Figure 5.

Figure 5 provides viscosity data for a mixture of crude oil and light naphtha at different ratios of added light naphtha and mixing times (two models were chosen for comparison, namely 30 and 60 minutes). It was found that as the percentage of light naphtha added increased, the viscosity values decreased for both the 30-minute and 60-minute periods, which indicates a decrease in viscosity with the addition of light naphtha. This trend suggests that light naphtha acts as a viscosity-reducing agent in the crude oil blend at these specific periods. In addition, comparing viscosity values at 30 min to those at 60 min reveals that increasing mixing times, as expected, leads to lower viscosities, indicating that increasing mixing times enhances the effectiveness of viscosity reduction.

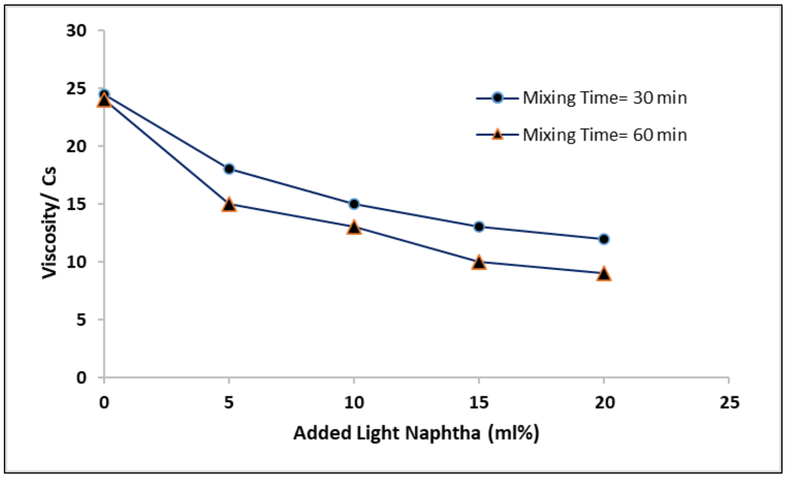

Figure 5: Comparison Results for mixing effect of adding Naphtha.

The decrease in the viscosity of crude oil-light naphtha blends with increasing mixing time and proportion of added light naphtha can be attributed to several mechanisms. First, increasing the mixing time facilitates a better distribution of lighter naphtha particles throughout the crude oil, leading to improved interaction with heavier hydrocarbon components and ultimately a more homogeneous distribution of particle weights. Thus, it will enhance the separation of forces between molecules and thus reduce the high viscosity of the oil. Second, mixing for longer periods allows increased dissolution of heavier hydrocarbons by lighter naphtha, as the solvent can effectively react and dissolve these components. This process further weakens the interactions between molecules and contributes to lowering the viscosity. In addition, the application of a shear effect during mixing enhances shear thinning behavior, where the orientation and arrangement of molecules under tension result in a temporary lowering of the viscosity. Finally, the effects of heat generated during mixing can also contribute to lowering viscosity, as higher temperatures generally reduce viscosity in crude oil due to increased molecular motion and reduced intermolecular forces as mentioned before. All of these mechanisms synergistically reduce the viscosity observed in crude oil and light naphtha mixtures, making them easier to handle and process [31].

3.4 ANOVA Analysis

To strengthen the reliability of the experimental observations, a statistical analysis using analysis of variance (ANOVA) was performed on the viscosity reduction data. Three sets of factors were examined: solvent type versus concentration, temperature versus concentration, and mixing time versus concentration. Because the data were obtained under single measurements at each condition, the analysis was conducted using main-effects ANOVA models without interaction terms, which is the standard approach in the absence of replicates.

The ANOVA results confirmed that concentration was the most influential factor across all conditions, with highly significant effects on viscosity reduction ($p < 0.01$). The analysis further showed that solvent type also had a significant effect ($p < 0.01$), with naphtha consistently outperforming toluene and kerosene in reducing viscosity.

Similarly, temperature exerted a statistically significant influence ($p < 0.01$), demonstrating that viscosity decreases markedly as operating temperature increases. Finally, mixing time showed a statistically significant but less pronounced effect ($p \approx 0.01–0.02$), indicating that longer mixing (60 min) enhanced viscosity reduction compared to shorter mixing (30 min), though the effect was moderate relative to solvent type and concentration.

Effect size calculations (partial η^2) highlighted that concentration accounted for the largest share of variance in viscosity reduction, followed by solvent type and temperature, while mixing time contributed at a smaller but still meaningful level. These results statistically validate the experimental findings shown in Figures 2–5, providing quantitative confirmation that the observed reductions are not random variations but the result of systematic effects.

In summary, the ANOVA analysis supports the conclusion that optimizing solvent concentration is the primary lever for reducing viscosity, while selecting an effective solvent (particularly naphtha), operating at higher temperatures, and allowing adequate mixing time further improve transportability. Together, these statistically significant factors provide a strong basis for designing efficient dilution strategies for East Baghdad heavy crude oil.

4. Mechanism

The observed trends in reducing the viscosity of crude oil showed that naphtha is stronger in reducing the viscosity of crude oil when added to it, followed by toluene and then kerosene. This could be due to several factors, including the following [32-35]:

Molecular Structure and Composition: Light naphtha usually consists of a mixture of relatively light hydrocarbons compared to toluene and kerosene. These lighter hydrocarbons may have better penetration and dispersion properties within heavy crude oil, resulting in more efficient viscosity reduction. Toluene, although an aromatic hydrocarbon like naphtha, may have a slightly higher molecular weight or a different composition, which affects its interactions with the components of the crude oil and thus its ability to reduce viscosity. On the other hand, kerosene, being a heavier and less volatile hydrocarbon compared to naphtha and toluene, may have poorer solubility and penetration properties, resulting in less effective viscosity reduction.

Dissolution and dispersion properties: Light naphtha, with its lighter molecular weight and composition, may have excellent dissolution and dispersion properties, allowing it to dissolve and disperse components of heavy crude oil, and thus reduce viscosity more efficiently. While toluene, being an aromatic hydrocarbon, also has good solubility properties, its viscosity-reducing effectiveness may vary depending on its specific interactions with the components of the crude oil. Finally, kerosene, although capable of reducing viscosity, may have limitations in dissolution and dispersion properties compared to naphtha and toluene, resulting in a relative reduction in viscosity.

Volatilization and evaporation: The volatility of the solvent can affect its ability to penetrate the crude oil and facilitate viscosity reduction. For example, naphtha, being lighter and more volatile, may evaporate more quickly from the mixture, leaving behind a lighter residue and contributing to a further reduction in viscosity. Toluene, being slightly heavier than naphtha, may exhibit lower volatility and evaporation rates, affecting its effectiveness in reducing viscosity. While kerosene, being heavier and less volatile, may have even lower evaporation rates compared to naphtha and toluene, which may restrict its ability to effectively reduce viscosity.

5. Practical Implications

The findings of this study have direct significance for crude oil transportation and pipeline operations. The laboratory evaluation of light hydrocarbon solvents for viscosity reduction demonstrates clear technical feasibility, but their application at field scale requires careful consideration of both economic and environmental factors.

From an economic standpoint, the selection of solvents must weigh cost against viscosity reduction efficiency. Naphtha, although more expensive per unit volume than kerosene, consistently achieved superior viscosity reduction, which may offset its higher cost by reducing required dosage and lowering pumping energy. Kerosene, while cheaper and widely available, provided comparatively lower efficiency, which could translate into higher consumption and overall cost at scale. Toluene exhibited intermediate performance but presents handling and cost challenges that may restrict its large-scale applicability. Thus, the trade-off between solvent efficiency and procurement cost is a key factor in designing cost-effective operations.

From an environmental perspective, the use of organic solvents introduces operational risks that must be managed. Volatile solvents such as naphtha and toluene are prone to evaporative losses, particularly under high-temperature pipeline conditions, which may result in fugitive emissions and elevated safety risks. Leakage or spillage of these solvents can lead to contamination of soil and groundwater, while residues in produced water streams may complicate wastewater treatment. These risks highlight the need for containment systems, vapor recovery units, and rigorous monitoring protocols to mitigate environmental impacts and ensure compliance with safety and environmental regulations.

While the experimental results and ANOVA validation confirm the effectiveness of solvent dilution in reducing the viscosity of East Baghdad heavy crude oil, several limitations must be acknowledged. First, the volatility of light hydrocarbons such as naphtha may lead to solvent losses during large-scale operations, especially under high-temperature pipeline conditions, potentially increasing both economic cost and safety risk. Second, the use of organic solvents introduces environmental side effects, including the risk of emissions, leakage, and solvent residues in produced water streams, all of which may require additional mitigation systems such as vapor recovery units and improved containment. Third, the scalability of laboratory conditions to field operations poses challenges: achieving homogeneous mixing at industrial scale is far more complex than under controlled laboratory conditions, and factors such as flow regime, turbulence, and solvent distribution in long pipelines can significantly influence effectiveness.

Taken together, these limitations underscore the need for integrated strategies that combine solvent selection with environmental safeguards and process optimization. Only by addressing cost-efficiency, minimizing environmental risks, and accounting for scale-up challenges can laboratory-proven methods translate into sustainable, safe, and economically viable industrial practices.

6. Conclusions

This study demonstrated that dilution with light hydrocarbons is an effective method for reducing the viscosity of East Baghdad heavy crude oil. Among the tested solvents, naphtha consistently provided the greatest viscosity reduction efficiency, followed by toluene and kerosene. The influence of operating conditions was also clear: increasing solvent concentration produced the most significant reduction, while elevated temperatures and extended mixing times further enhanced performance. ANOVA analysis statistically confirmed the significance of these factors, with concentration emerging as the dominant determinant of viscosity reduction.

From a practical standpoint, the findings highlight the importance of balancing solvent efficiency with procurement cost and environmental risk. Although naphtha provides superior results, its volatility and higher cost present challenges for large-scale implementation. Environmental concerns related to solvent emissions, leakage, and produced-water contamination underscore the need for robust containment and recovery systems. Moreover, the scalability of laboratory conditions to industrial pipelines remains a critical consideration for field applications.

In addition, to build upon the outcomes of this study, several areas warrant further investigation. First, scale-up testing under real pipeline conditions is necessary to evaluate the robustness of dilution strategies under industrial flow dynamics and mixing regimes. Second, the development of hybrid solvent approaches, such as combining light hydrocarbons with surfactants, nanoparticles, or co-solvents, could improve efficiency while reducing solvent demand. Third, the integration of environmentally friendly additives, including biodegradable solvents or bio-based diluents, should be pursued to align viscosity reduction strategies with sustainability goals. Finally, comprehensive techno-economic and environmental assessments are recommended to provide a holistic evaluation of dilution strategies, ensuring that laboratory-proven methods can be translated into safe, cost-effective, and environmentally responsible industrial practices.

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Conflict of Interest: The first author of this manuscript is the Editor-in-Chief of the Iraqi Journal of Oil and Gas Research. To maintain objectivity, the peer review and editorial decision-making processes were handled independently by other editors of the journal.

ANOVA Result Tables: Available on request from the corresponding author.

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References

[1] C. J. Cleveland, Ed., "Oil Sands and Heavy Oil," in *Encyclopedia of Energy*, Elsevier, 2004, pp. 731–737, doi: 10.1016/B0-12-176480-X/00270-9.
[2] International Energy Agency (IEA), "World oil production by region, 1971–2020," Paris, 2021. [Online]. Available: https://www.iea.org/data-and-statistics/charts/world-oil-production-by-region-1971-2020. [Accessed: Sept. 23, 2025].
[3] U.S. Energy Information Administration (EIA), "Iraq's energy overview." [Online]. Available: https://www.eia.gov/international/analysis/country/IRQ. [Accessed: Sept. 23, 2025].
[4] H. Ritchie and P. Rosado, "Fossil fuels," *Our World in Data*, 2017. [Online]. Available: https://ourworldindata.org/fossil-fuels. [Accessed: Sept. 23, 2025].
[5] R. Martínez-Palou, M. Mosqueira, B. Zapata-Rendón, E. Mar, C. Bernal-Huicochea, J. Clavel-Lopez, and J. Aburto, "Transportation of heavy and extra-heavy crude oil by pipeline: A review," *J. Petrol. Sci. Eng.*, vol. 75, pp. 274–282, 2011, doi: 10.1016/j.petrol.2010.11.020.
[6] A. Hart, "A review of technologies for transporting heavy crude oil and bitumen via pipelines," *J. Petrol. Explor. Prod. Technol.*, vol. 4, pp. 327–336, 2014, doi: 10.1007/s13202-013-0086-6.
[7] E. D. Attanasi and R. F. Meyer, "Natural Bitumen and Extra-Heavy Oil," in *Survey of Energy Resources*, 22nd ed., World Energy Council, 2010, pp. 123–140.
[8] X. Dong, H. Liu, Z. Chen, K. Wu, N. Lu, and Q. Zhang, "Enhanced oil recovery techniques for heavy oil and oil sands reservoirs after steam injection," *Appl. Energy*, Apr. 2019, doi: 10.1016/j.apenergy.2019.01.244.
[9] C. Temizel, C. Canbaz, M. Tran, E. Abdelfatah, B. Jia, D. Putra, M. Irani, and A. Alkouh, "A comprehensive review of heavy oil reservoirs: Latest techniques, discoveries, technologies and applications in the oil and gas industry," in *Proc. SPE Middle East Oil and Gas Show and Conference*, Manama, Bahrain, Mar. 2019, doi: 10.2118/193646-MS.
[10] R. G. Santos, W. Loh, A. C. Bannwart, and O. V. Trevisan, "An overview of heavy oil properties and its recovery and transportation methods," *Brazilian J. Chem. Eng.*, Apr. 2014, doi: 10.1590/0104-6632.20140313s00001853.
[11] F. Souas, A. Safri, and A. Benmounah, "A review on the rheology of heavy crude oil for pipeline transportation," *Petrol. Transp. Logistics Rev.*, 2020, doi: 10.1016/j.ptlrs.2020.11.001.
[12] D. M. Escojido, O. Urribarri, and J. Gonzalez, "Part 1: Transportation of heavy crude oil and natural bitumen," in *Proc. 13th World Petroleum Congress*, Buenos Aires, Argentina, Oct. 1991.
[13] M. Ramirez de Santiago, "Strategy for pipeline transportation of heavy crude oil by dilution and with emulsified water: Complex fluids and hydrodynamics," Project lecture in process, 2024, doi: 10.13140/RG.2.2.33155.48160.
[14] Q. Bu-Ali, Z. M. Redha, M. Jung, H. Abdulla, and O. Ahmed, "An experimental design approach investigating the effects of operating variables on the viscosity of heavy crude oil-in-water emulsions using lecithin as a natural surfactant," *Petroleum Science and Technology*, vol. 39, no. 23–24, pp. 1098–1115, 2021.
[15] A. Huc, J.-F. Argillier, G. Renard, A. Quignard, and N. Alazard, *Heavy Crude Oils: From Geology to Upgrading, an Overview*, 2011.
[16] A. Tirado, G. Felix, F. Trejo, M. Varfolomeev, C. Yuan, D. Nourgaliev, V. Sámano, and J. Ancheyta, "Properties of heavy and extra- heavy crude oils," in *Heavy and Extra-Heavy Crude Oils*, Wiley, 2023, ch. 1, doi: 10.1002/9781119871507.ch1.
[17] Y. Liu, J. Bai, P. Guo, W. Zhang, L. Zhong, C. Lyu, *et al.*, "Experimental study on water-in-heavy-oil droplets stability and viscosity variations in the dilution process of water-in-heavy-oil emulsions by light crude oil," *Energies*, vol. 17, no. 2, p. 332, 2024.
[18] J. A. Muñoz and J. Ancheyta, "Techno-economic study of the effect of different distillates and crude oil diluents on the transportation by pipeline of heavy crude oil," *Ind. Eng. Chem. Res.*, vol. 63, no. 4, pp. 2063–

2072, 2024.
[19] A. Saniere, I. Hénaut, and J.-F. Argillier, "Pipeline transportation of heavy oils, a strategic, economic and technological challenge," *Oil Gas Sci. Technol. – Rev. IFP*, vol. 59, no. 5, pp. 455–466, 2004, doi: 10.2516/ogst:2004031.
[20] J. Gao, C. Li, D. Xu, P. Wu, W. Lin, and X. Wang, "The mechanism of ultrasonic irradiation effect on viscosity variations of heavy crude oil," *Ultrason. Sonochem.*, vol. 81, p. 105842, 2021, doi: 10.1016/j.ultsonch.2021.105842.
[21] E. Al-Fatlawi and R. K. Abbas, "Reducing the viscosity of Missan heavy crude oil using low molecular weight hydrocarbon compounds," in *AIP Conf. Proc.*, vol. 3079, no. 1, Apr. 2024.
[22] L. M. Daza-Barranco, A. C. Duncke, P. R. de Souza Mendes, J. G. Alvarado, and A. Pérez-Gramatges, "Effect of kerosene aromaticity as a solvent on bulk and interfacial properties of Brazilian heavy crude oil with high asphaltene content," *Can. J. Chem. Eng.*, vol. 102, no. 1, pp. 203–216, 2024.
[23] A. Khalaf, A. Abdullah, and R. Al-Sabur, "Effect of temperature on the performance of naphtha and kerosene as viscosity reduction agents for improving flow ability of Basrah-Iraq heavy crude oil," *Adv. Res. Fluid Mech. Therm. Sci.*, vol. 84, pp. 135–147, 2021, doi: 10.37934/arfmts.84.1.135147.
[24] A. H. S. Dehaghani and M. H. Badizad, "Experimental study of Iranian heavy crude oil viscosity reduction by diluting with heptane, methanol, toluene, gas condensate and naphtha," *Petroleum*, vol. 2, no. 4, pp. 415–424, 2016, doi: 10.1016/j.petlm.2016.08.012.
[25] D. A. Shafeeq and R. I. J. Mohammed, "An experimental investigation for flow characteristics of heavy oil in pipelines using dilution technique with different solvents," *Iraqi J. Oil Gas Res.*, Apr. 2024, doi: 10.55699/ijogr.2024.0401.1058.
[26] I. I. Mukhamatdinov, I. S. S. Salih, M. A. Khelkhal, and A. V. Vakhin, "Application of aromatic and industrial solvents for enhancing heavy oil recovery from the Ashalcha Field," *Energy Fuels*, 2020, doi: 10.1021/acs.energyfuels.0c03090.
[27] A. Soleimani, M. A. Subasti, and S. Movahydrad, "An investigation on the viscosity reduction of Iranian heavy crude oil through dilution method," *Iran. J. Chem. Chem. Eng.*, 2020, doi: 10.30492/IJCCE.2020.38039.
[28] F. H. A., N. A. Sami, A. A. Abdulrazak, and J. S. Angwai, "The performance of toluene and naphtha as viscosity and drag reducing solvents for the pipeline transportation of heavy crude oil," *Petrol. Sci. Technol.*, vol. 33, no. 8, pp. 952–960, 2015.
[29] ASTM D445-97, "Standard test method for kinematic viscosity of transparent and opaque liquids (the calculation of dynamic viscosity)," *ASTM International*, West Conshohocken, PA, USA, 1997, doi: 10.1520/D0445-97.
[30] B. Yaghi and A. Al-Bemani, "Heavy crude oil viscosity reduction for pipeline transportation," *Energy Sources*, vol. 24, pp. 93–102, 2002, doi: 10.1080/00908310252774417.
[31] F. K. Al-Zuhairi, R. A. Azeez, N. M. Alawi, and H. M. Nguyen, "Enhancing some properties of local Iraqi crude oil using solvent deasphalting process," *Iraqi J. Oil Gas Res.*, vol. 2, no. 1, 2022, doi: 10.55699/ijogr.2022.0201.1011.
[32] J. Qajar, M. Razavifar, and M. Riazi, "A mechanistic study of the synergistic and counter effects of ultrasonic and solvent treatment on the rheology and asphaltene structure of heavy crude oil," *Chem. Eng. Process. Intensif.*, 2024, doi: 10.1016/j.cep.2023.109619.
[33] A. M. Doust, M. Rahimi, and M. Feyzi, "Effects of solvent addition and ultrasound waves on viscosity reduction of residue fuel oil," *Chem. Eng. Process. Intensif.*, vol. 95, pp. 353–361, 2015, doi: 10.1016/j.cep.2015.07.014.
[34] O. A. Alomair and A. S. Almusallam, "Heavy crude oil viscosity reduction and the impact of asphaltene precipitation," *Energy Fuels*, vol. 27, no. 12, pp. 7267–7276, 2013, doi: 10.1021/ef4015636.
[35] S. Mortazavi-Manesh and J. M. Shaw, "Effect of diluents on the rheological properties of Maya crude oil," *Energy Fuels*, vol. 30, no. 2, pp. 766–772, 2016, doi: 10.1021/acs.energyfuels.5b02367.