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Full Length Article

Alumina nanofluid enhances the heavy-oil upgrading process

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Upgrading heavy crude oil remains one of the most critical and technically demanding processes in the petroleum industry, primarily due to the inherently poor quality of the various types of crude oil and the complexities associated with their transport and refining. This study investigates the impact of a nanofluid—composed of aluminum oxide nanoparticles dispersed in a kerosene solvent and stabilized with the surfactant sodium dodecylbenzenesulfonate—on enhancing the quality of crude oil extracted from an East Baghdad field. This nanofluid was applied using ultrasonic irradiation to ensure uniform dispersion and stability. The results demonstrated a substantial improvement in various crude oil properties. The viscosity was reduced significantly, from 58.15 cP to 5.58 cP, representing a 90.4% improvement. The API gravity increased markedly, from 19.63 to 30.49. Furthermore, the heavy metal content decreased considerably, with vanadium reduced from 109.67 ppm to 9.02 ppm (92% reduction) and the nickel content showing an 85% decrease. The sulfur content also declined sharply, from 4.422% to 0.77%, indicating an 83% improvement. These findings confirm the high efficacy of nanofluid-assisted ultrasonic treatment as a promising technique for upgrading heavy crude oil and enhancing its refining and transportation potential.

1. Introduction

Crude oil has been described as one of the most important sources of energy worldwide, and its demand is rising steadily because most industries, facilities, and institutions rely on petroleum-based products to generate electricity (Khamees et al., 2025a). Crude oil market prices can change considerably due to various factors (Coleman, 2012), the most prominent being ease of transportation. Light crude oil typically commands a higher price than heavy crude oil due to its lower viscosity, which allows it to flow easily through pipelines, thereby reducing transportation costs (Santos et al., 2014). In contrast, heavy crude oil requires extensive treatment, including the addition of additives and the use of extra energy to improve its flow, which typically leads to higher operational costs (Speight, 2013). Purity and the presence of trace metals are other significant value-determining factors of crude oil. Oil with more contaminants and metallic elements is less useful, and both the quality and cost-effectiveness are reduced when their concentrations are higher (Uddin, 2017). In particular, sulfur content is a vital quality parameter: crude oil with less than 0.5% sulfur is considered “sweet,” while oil with a higher concentration is referred to as “sour” (Ahmed et al., 2025; Humadi et al., 2025).

Various standard parameters are employed to assess the quality of crude oil, including density, American Petroleum Institute (API) gravity (Furqon et al., 2025), viscosity, and sulfur content (Khamieva et al., 2025). In addition, the levels of heavy metals—primarily nickel and vanadium—are of great interest (Khamees et al., 2025b). Crude oil is usually classified as heavy (API <22), medium (API 23–31), or light (API >32) based on its API gravity (Hakimi et al., 2025). Another essential indicator of oil quality is viscosity, with less viscous oil being easier to transport and process and high-viscosity oil requiring more energy to pump due to associated costs and logistical issues (Ilyin et al., 2024; Li et al., 2024).

In addition, High levels of vanadium and nickel have a negative impact on refinery operations due to their tendency to concentrate on refining equipment, which often accelerates the corrosion process, increases the need for maintenance, and may lead to fouling in heat exchangers and pipelines (Ahmed et al., 2023a).

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Moreover, the use of crude oil with high amounts of vanadium and nickel can lead to the formation of solid deposits in refining systems, thereby reducing operational efficiency and promoting the need for cleaning and maintenance (Baritto et al., 2025). Nonconformance to environmental requirements may arise due to the presence of vanadium and nickel, which influence the quality of final products, such as gasoline and diesel (Al-Otaibi et al., 2024; Sellaro, 2022). Burning products with a higher vanadium and nickel content can lead to increased air pollutant emissions, thereby causing greater environmental damage (Vishnyakov, 2023). All of these factors necessitate additional processing methods or high-maintenance procedures, which are largely driven by business decisions, making the production of crude oil with high concentrations of these minerals even more expensive (Li et al., 2023). Overall, the vanadium and nickel content in crude oil is essential for processing and product quality (Akhtar et al., 2024). Heavy oils have a high concentration of sulfur, nitrogen, oxygen, and heavy metals and are viscous and dense (Abdul-Majeed et al., 2021; Mukhamatdinov et al., 2025). Most heavy-oil reservoirs are difficult to produce at a commercial scale because the oil exhibits low mobility—primarily from high viscosity—and unfavorable flow behavior (Khamees et al., 2024a, 2024b), and refining the resulting product into valuable substances is even more difficult and costly (Malozyomov et al., 2023). Consequently, heavy crude oil is usually more expensive than light crude in terms of market price and demand for illuminating oils (Pirouzfar et al., 2023). The above challenges have sparked interest in research on developing upgrading strategies to improve the quality of heavy crude oil (Yang et al., 2022).

High sulfur content is one of the most serious disadvantages of heavy crude oil. Crude oil with a high sulfur content—often termed “sour” crude—degrades the quality of refined products, such as diesel and gasoline, resulting in a failure to meet environmental regulations (Fayad et al., 2022; Khan et al., 2021). Other harmful chemical effects include reactions between sulfur and other constituents of crude oil, which form corrosive compounds that stimulate wear and destroy refinery infrastructure (Salem et al., 2023). Furthermore, the burning of sulfur-rich fuel yields sulfur oxides (SOx), which cause widespread atmospheric pollution and acid rain (Dai et al., 2024). These gases not only negatively affect the health of humans and animals—especially by causing respiratory conditions such as asthma (Salem et al., 2024)—but also damage environmental conditions in soil and water bodies (Liao et al., 2025). The sulfur level of crude oil also necessitates additional desulfurization processes, thereby increasing the complexity of refining and raising costs (Pham et al., 2024). Another problem with sulfur is that it presents logistical difficulties during transportation and storage (Du et al., 2024). Generally, a high sulfur content in crude oil poses a significant challenge to the petroleum industry, necessitating suitable measures to mitigate its negative implications (Haruna et al., 2022). As a result, interest in upgrading heavy crude oil has been substantial among researchers and industry professionals. A major goal of such upgrading efforts is to eliminate trace metals and break down heavy, complex products by using special additives and specialized technologies to reduce parameters such as density, viscosity, and asphaltene concentration (Ahmed et al., 2023b; Ali et al., 2025). However, alongside technical development, economic analyses must be conducted carefully to identify cost-effective approaches to upgrading that can achieve the desired improvements with the least financial strain (Adeola et al., 2022).

Among the approaches attracting interest are hydrogen donation, which introduces diverse agents, and processes that accelerate hydrogenation capability. For example, methane and cyclohexane have been used to facilitate the transfer of hydrogen and crack heavy fractions (Zhao et al., 2022; Zhou et al., 2023). Microwave technology has proven to be a powerful method of enhancing heavy and extra-heavy crude oils, with Yatimi et al. (2024) demonstrating that different microwave frequencies produce distinct chemical reactions. Furthermore, it has been noted that asphaltene's ability to contain higher amounts of microwave radiation can greatly influence its concentration in crude oil (Kairgeldina et al., 2024). Ultimately, it is hoped that heavy crude upgrading will focus on the selective elimination or reduction of undesired compounds as well as the cracking of heavy compounds, using new technologies and functional additives now available through catalytic or thermal methods (Varfolomeev et al., 2023), which are typically selected based on a thorough economic evaluation of their cost-effectiveness (Gomaa et al., 2024; Li et al., 2021). Notable strategies for upgrading both heavy and extra-heavy crude oil include the use of supercritical fluids, which have proven to be effective in breaking down asphaltenes and significantly reducing coke formation during the course of thermal treatments (Djimasbe et al., 2022; Sun et al., 2021). Additionally, the concentration of asphaltenes and resin fractions can be minimized when supercritical hydrogen or oxygenated fluids are used, resulting in significant decreases in metals such as nickel and vanadium (Xu et al., 2024). One widely employed and effective method for upgrading heavy crude oil is dilution, in which suitable solvents are introduced to reduce viscosity, enhance flow properties, and lower metal concentrations (Türkmenoğlu et al., 2025). Hussein et al. (2014) investigated enhancing the transport of East Baghdad crude oil by incorporating polar solvents—such as toluene, methanol, and xylene mixtures—as well as dispersants. These agents facilitate the dispersion of asphaltene clusters, which are responsible for high viscosity. Hussein et al.'s (2014) study, which examined solvent concentrations of 4, 8, 10, and 12 wt% and dispersant concentrations ranging from 0.5 to 1 wt% at 40 °C, found that oil viscosity decreased significantly with increased solvent concentrations, reaching a minimum of 21.78 cP at 110 °C with 12 wt% toluene. Other solvent types also yielded considerable reductions, with viscosity values of 27.51 and 28.41 cP.

In parallel with these advancements, nanotechnology has emerged as a transformative tool for upgrading crude oil. Nanoparticles serve not only as catalysts but also as agents capable of modifying fluid properties, such as viscosity and wettability (Suwaid et al., 2023). Guo et al. (2018) demonstrated the use of monodispersed cobalt and nickel nanoparticles to desulfurize heavy oil and effectively enhance its overall quality. Similarly, Alaei et al. (2017) employed exfoliated molybdenum disulfide nanoparticles, which exhibited superior catalytic activity compared to traditional oil-soluble catalysts, resulting in enhanced upgrading efficiency and optimized operational conditions. It has been demonstrated that nano oxides of metals can reduce viscosity and increase the saturation of hydrocarbons under certain temperature and pressure conditions, depending on the properties of the heavy oil (De la Cruz Parejas et al., 2021). Omajali et al. (2017) used scattered bionanoparticles in conjunction with other catalysts for the upgrading heavy oils. Guo et al. (2018) utilized monodispersed nickel and cobalt nanoparticles to reduce the sulfur content of heavy crude oil, thereby improving the oil's quality. Other studies have utilized dispersed bionanoparticles combined with other catalysts to promote the upgrading of heavy oils.

The use of microwave technology for upgrading heavy and extra-heavy crude oil is a new process under consideration (Gharibshahi et al., 2022). Since the heating rate—measured over time—can be crucial in the traditional upgrading process (García-Duarte et al., 2024), process time is a primary consideration with this technology. A modern method is to use ultrasound—an advanced and effective technology in the petroleum industry—to refine the specifications of heavy crude oil. This technique involves sending high-frequency sound waves through oil, which catalyzes chemical reactions and improves the oil's physical properties (Adamou et al., 2024). The main benefits of using ultrasound include (1) reducing viscosity, thereby facilitating transportation and storage processes; (2) reducing sulfur content, thereby reducing pipes and equipment corrosion; and (3) improving density, thereby increasing production and refining efficiency (Dengaev et al., 2023a; Myltykbayeva et al., 2024). A traditional and widely used method for upgrading and improving the specifications of heavy crude oil involves solvents, which play a vital role in petroleum engineering (Li et al., 2025). Solvents are used to separate and purify the various components of crude oil, thereby improving its physical and chemical properties (Aljamali et al., 2021). The main benefits of using solvents include (1) improving crude oil density, thereby increasing production and refining efficiency; (2) reducing viscosity, thereby facilitating transportation and storage; (3) reducing sulfur content, thereby reducing pipe and equipment corrosion; and (4) improving transparency, thereby making oil more suitable for refining (Santos et al., 2017; Yarmola et al., 2023). Like microwaves, nanoparticles are a modern technology that enhances the properties of heavy crude oil and contributes to improving its quality.

They are nanomaterials used as chemical catalysts to improve the extraction and refining processes, and their main effects include (1) reducing viscosity, thereby helping improve the movement of oil in pipes and increases extraction efficiency; (2) increasing transparency by improving the properties of crude oil, thereby making it ready for refining; (3) increasing the efficiency of the extraction process by improving chemical reactions; and (4) reducing environmental pollutants resulting from extraction and refining processes (Jia et al., 2025). Nanotechnology plays a crucial role in enhancing the process of upgrading heavy crude oil through the use of nanoparticles—characterized by their small size and large surface area—to enhance the efficiency of the chemical reactions employed in oil production (Hebert et al., 2025). The use of surfactants in the upgrading of heavy crude oil is another advanced and effective technology for enhanced oil recovery. Surfactants enhance the properties of crude oil by reducing its viscosity and increasing its API gravity, thereby facilitating transportation and refining operations (El-Hoshoudy et al., 2019). They are also used to enhance recovery, as they increase the contact area with crude oil, thereby increasing extraction efficiency. Although enhanced oil recovery (EOR) has provided numerous solutions to the challenge of recovering heavy and extra-heavy crude oil, the integration of nanotechnology with polymer-based EOR processes has emerged as a key research direction in the field. Nanoparticles enhance oil recovery through their effects on viscosity, wettability, and asphaltene dispersion properties. When mixed with polymers, they form stable, functional polymer nanofluids that increase viscoelasticity and sweep characteristics when displacing oil. Salem et al. (2024), who focused on increasing interaction between fluids and porous media as well as on improved rheological behavior, indicated that nanoparticle-enhanced polymer flooding is much more effective in mobility control and oil recovery than simple polymer flooding. By conducting an overview of the essential peculiarities of polymeric nanofluids, focusing on factors such as the alteration of EOR performance by nanoparticle size, polymer type, and concentration, they provided additional evidence for this. They also quantitatively evaluated and empirically linked the nanoparticle–polymer system as an EOR setting, suggesting that the specific resolution of such a system in each reservoir group is crucial. Together, this research provides a broader perspective on both existing and emerging technologies for heavy oil extraction, with polymeric nanofluid technologies proven to be not only technically efficient but also highly economically promising. The results indicate that polymer–nanoparticle hybrids offer a scalable, nonthermal option for improved oil recovery. Future studies should focus on streamlining their application in field conditions.

The current study investigates the process of upgrading heavy crude oil in an oil field east of Baghdad using nanofluids (Al_2O_3/kerosene) in the presence of ultrasound. This technology involves synthesizing a stable nanofluid—created by adding alumina to kerosene—that enhances the properties of heavy crude oil. This study is novel in its use of nanofluids in the upgrading process. While the use of nanoparticles, solvents, or solvents with surfactants is common in upgrading processes, the preparation of a kerosene-based nanofluid is novel and has not previously been employed. The importance of this upgrading method lies in the fact that kerosene-based nanofluids are cheaper, as the price of a liter of kerosene is significantly lower than that of ethylene, methylene, or other solvents commonly used for nanofluid preparation.

2. Materials and methods

2.1. Materials application

2.1.1. Feedstock

A sample of crude oil from an East Baghdad field was used for the experiments. The solvent used to prepare the nanofluid was kerosene. The specifications of the sample and kerosene are presented in Tables 1–3. We conducted experiments to determine the viscosity, density, sulfur content values, and vanadium and nickel ratios of the sample before and after the addition of the nanofluid. The device used to calculate viscosity was the ASTM D446 viscometer—also known as an Ostwald viscometer—which is a tubular U-viscometer (Fungilab, Spain). Total sulfur was determined by energy-dispersive X-ray fluorescence in accordance with ASTM D4294 using a PETRA 4294 sulfur analyzer (XOS, USA). Vanadium and nickel were measured with a rotating disc electrode optical emission spectrometer (RDE-OES; SpectrOil 120, Spectro Scientific—an AMETEK company, USA). Density and API gravity were determined with an automatic density meter (DDM 2911 PLUS; Rudolph Research Analytical, USA). The specifications of the nanomaterials used in the experiments are shown in Fig. 1. In these experiments, alumina nanoparticles (Al_2O_3) were used.

2.1.2. Gamma-alumina

The nano-gamma-alumina used in the experiment was supplied by Skyspring Nanomaterials, Inc. (USA; Average particle size

Table 1
Approximate weight percentages by carbon number range.

Component	Approximate Weight Percentage (%)
C1–C4 (light gases)	1–2%
C5–C6 (light naphtha)	3–5%
C7–C11 (heavy naphtha)	7–10%
C12–C20 (kerosene and diesel)	15–20%
C21–C35 (heavy distillates)	20–25%
C36+ (residuum)	35–40%
Sulfur	3–5%
Metals (V, Ni, Fe)	<0.1% (~100–150 ppm)
Water/impurities	0.5–2%

Table 2
Approximate weight percentages by carbon number range.

Fraction	Approximate Percentage (%)
Saturates	20–25%
Aromatics	30–35%
Resins	20–25%
Asphaltenes	15–20%

Table 3
Specifications of the heavy oil and kerosene used in the experiments.

Test	Crude Oil (from East of Baghdad)	Solvent (Kerosene)
Viscosity at 25 °C	58.15 (cSt)	1.65 (cSt)
API at 60 °F	19.63°	47.6°
Density at 86 °F (g cm^{-3})	0.9201	0.79
Asphalting content wt.%	6.294	0.16
Sulfur content wt.%	4.422	0.08
Water content vol%	2.7	0.036
Vanadium	109.67 ppm	0.85 ppm
Iron	0.78 ppm	0.35 ppm
Nickel	42.65 ppm	0.57 ppm
N content (wt%)	1.53	0.06
H content (wt%)	10.11	13.51
C content (wt%)	85.15	86.31

(APS): 50 nm). The nanoparticle element analysis using X-ray fluorescence (XRF) is presented in Tables 4 and 5. Some of these analyses were conducted at the IBN SINA laboratories, while other properties were provided by the manufacturing company.

2.1.3. Surfactant

Sodium dodecylbenzenesulfonate (SDBS; CAS no. 25155-30-0 and 98% purity; Sigma-Aldrich, St. Louis, MO, USA) was added to the alumina nanoparticle solution to enhance the stability of the nanoparticles' dispersion in crude oil. Sodium dodecylbenzene sulfonate is a chemical compound belonging to the sulfonate group (molecular formula: $C_{18}H_{29}NaO_3S$, molar mass: 348.48 g/mol, appearance: solid, melting point: exceeds 300 °C [572 °F], solubility: soluble in water).

2.2. Nanofluid preparation process

The process of preparing the nanofluid was as follows. First, 100 mL of kerosene was placed in a glass beaker. Then, 0.4% (4000 ppm) of the nanoparticles (Al_2O_3) were weighed and added to the solvent, followed by 0.02% (200 ppm) of the SDBS surfactant. The components were mixed with a mixing motor for half an hour, and the glass beaker was placed in an ultrasonic machine for an hour (as illustrated in Fig. 2). Subsequently, the prepared nanofluid was placed in 10 ml tubes to monitor its stability and the distribution of nanoparticles within the solvent (kerosene) to ensure that they did not clump and were deposited in the solvent. The nanofluid was monitored, and the sample was followed 1, 2, and 3 weeks as well as 1, 2, and 3 months after preparation (as shown in Fig. 1). It was found to be very stable, as no nanoparticle deposits or agglomerates appeared inside the solvent. Additionally, the stability and distribution of nanoparticles within the kerosene were measured using a transmission electron microscope (TEM). This test was performed on a nanofluid at the TEM Laboratory at Kashan University, Iran.

Table 4
Gamma-alumina nanoparticle analysis.

Al_2O_3	Ca	Fe	Cr	Na	Mn	Co
99.5%	25 ppm	80 ppm	4 ppm	70 ppm	3 ppm	2 ppm

2.3. Nanoparticle characterization

Several tests—X-ray diffraction (XRD), thermogravimetric analysis (TGA), atomic force microscopy (AFM), and surface area, pore volume, and pore size measurements—were conducted on alumina nanoparticles in Kashan University laboratories to determine their properties in terms of size, distribution, and temperature tolerance.

2.4. Experimental setup and procedure

After completing the nanofluid preparation and ensuring its stability, the process of upgrading heavy crude oil from the East Baghdad field commenced. The goal of this process was to improve the oil's specifications by reducing its viscosity and density as well as its vanadium, nickel, and sulfur content. The upgrading process was executed as follows. Multiple 100 ml samples of heavy crude oil were taken (as shown in Fig. 3), and 20% by weight of the nanofluid was added at a volumetric ratio of 1:5. The crude oil sample with the added nanofluid was then placed in an ultrasonic device set to a temperature of 20 °C. The sample was subjected to ultrasound for durations of 15, 30, 45, and 60 min, with samples

Table 5
Aluminum oxide nanopowder (gamma) properties.

Property	Value
Purity	99+%
Average particle size distribution	50 nm
Color	white
Specific heat capacity	880 J/(Kg.K)
Density	3890 kg/m^3
Surface area	138 m^2/g

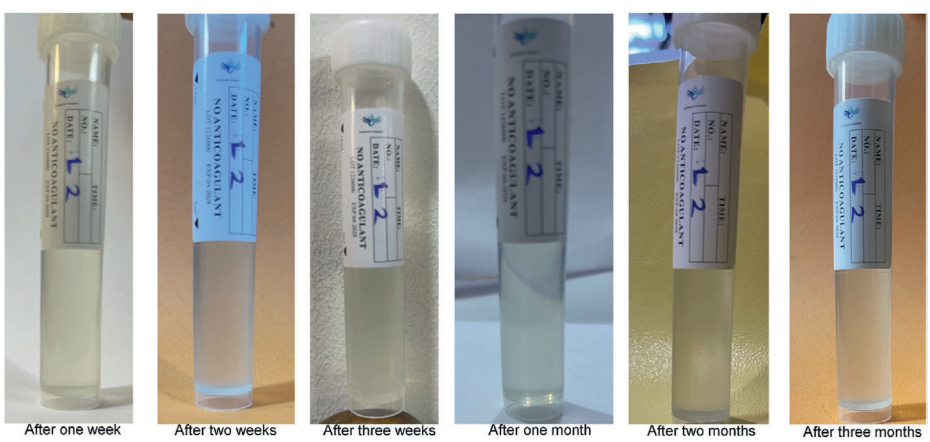

Fig. 1. Nanofluid monitoring with the naked eye over three months.

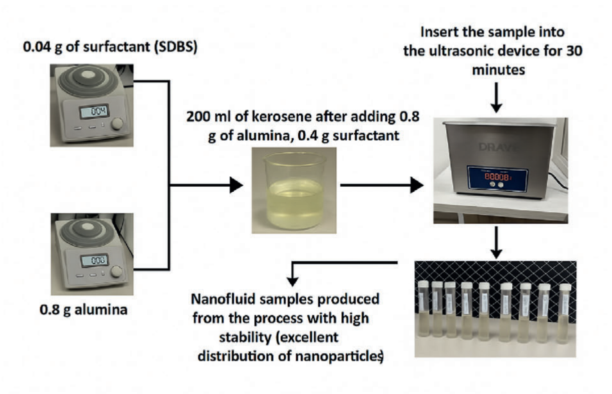

Fig. 2. Schematic illustration of the nanofluid synthesis process (Al_2O_3/kerosene).

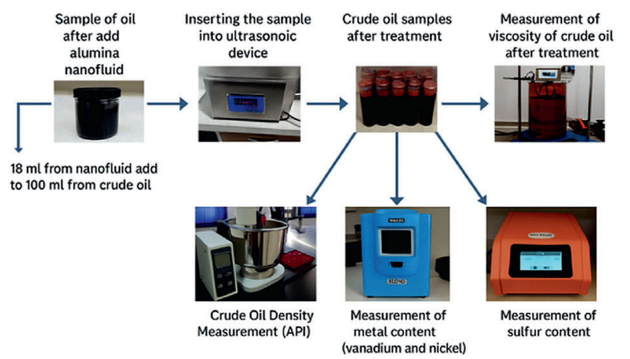

Fig. 3. Schematic illustration of the upgrading process of heavy crude oil using an Al_2O_3/kerosene nanofluid.

taken after each period. This process was repeated with the ultrasonic device set to temperatures of 40 °C, 60 °C, and 75 °C. Finally, all samples were collected and prepared for viscosity, density, vanadium, nickel content, and sulfur content analysis.

2.4.1. Viscosity treatment

Viscosity is one of the most essential characteristics of crude oil because it is considered a measure of the oil's quality. The lower (higher) the viscosity, the higher (lower) the crude oil's value and the easier (harder) and less (more) costly it is to transport through pipelines. Therefore, one of the primary goals of this study was to reduce the viscosity of heavy crude oil from an East Baghdad field, characterized by high viscosity. After the nanofluid was added to the crude oil and exposed to ultrasonic waves, samples were taken at specific time intervals and temperatures, and their viscosity was measured to determine the effect of the nanofluid. This was done according to the ASTM D446 standard using an Ostwald viscometer, which is used to measure the viscosity of a liquid with a known density, as shown in Fig. 3. As shown in Fig. 4, this method involves determining the time it takes for a known volume of liquid to flow through a micro-glass tube (viscometer) under the effect of gravity. The viscometer is placed in a water bath to control the temperature. The time it takes for the liquid to descend through the viscometer is multiplied by the constant of the device, as indicated by the following law:

$$\nu = t \times K$$

where:v: kinematic viscosity (cSt), t: Flow time (s), K: Viscometer constant.

$$K_1 = 0.0372$$

$$K_2 = 0.0264$$

2.4.2. API density treatment

Calculating the API gravity of crude oil and petroleum products is important for several reasons. The most important of these is determining the quality of the oil, since this indicator depends on its density relative to water. The higher the API gravity, the lighter the oil and the higher the quality and value, as more gasoline and light distillate are produced during refining. In the refining process, knowing the API gravity of crude oil helps determine the appropriate refining processes, equipment, and units to be used.

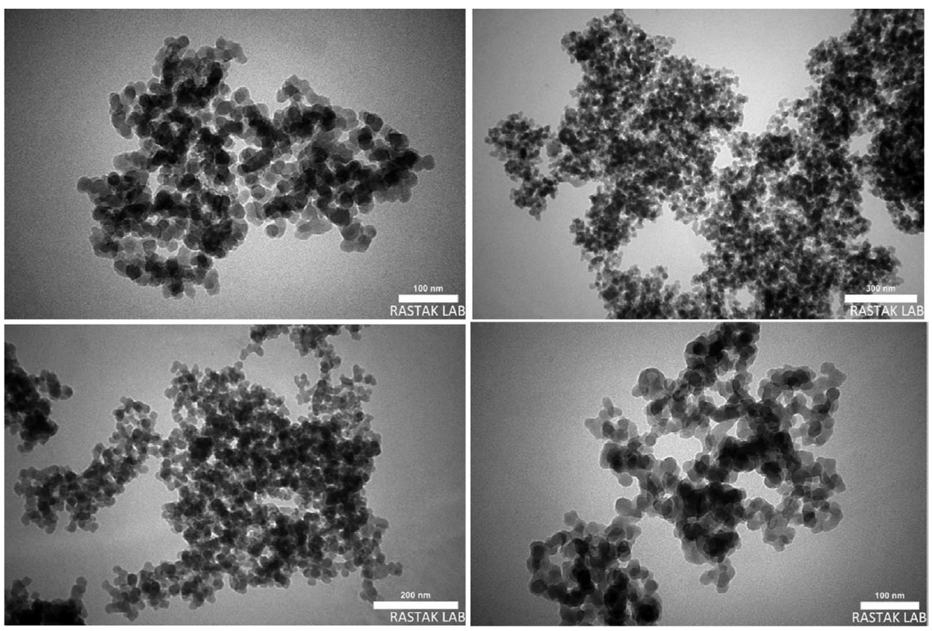

Fig. 4. Transient electron microscope image of the Al_2O_3/kerosene nanofluid.

Light crude oil can be processed very easily, whereas heavy crude oil requires more complex—and consequently, more expensive—refining techniques. During transportation and storage, the API gravity significantly affects crude oil's flow characteristics. It is easier and cheaper to transport and store light oil than heavy oil. Therefore, one of the main objectives of this study was to reduce the density of heavy crude oil and increase its API gravity value. The density and API gravity of the crude oil samples containing nanofluid that had been subjected to ultrasonic waves and different temperatures at specific time intervales were measured to determine how the nanofluid affected the API gravity. The crude oil density and API gravity were calculated using an ASTM D 446 device, as shown in Fig. 4.

2.4.3. Vanadium and nickel treatment

Vanadium, a low-concentration element found in crude oil, can negatively affect the quality of petroleum products and refinery equipment. Additionally, high levels of nickel in crude oil cause chemical corrosion and damage to oil equipment, as nickel reacts with acidic gases such as hydrogen sulfide, leading to damage to equipment, pipes, and oil tanks. Therefore, it is essential to find effective ways to remove or reduce the concentration of these elements. One of the main objectives of this study was to investigate the removal or reduction of vanadium and nickel content from crude oil from an East Baghdad field using nano-alumina. To achieve this goal, the effect of different operating conditions on the process of removing vanadium was studied.

2.4.4. Sulfur treatment

Crude oil contains a variety of different elements, including sulfur, whose percentage ranges between 0.05% and 6%. Sweet crude oil is classified as oil with a sulfur content of less than 0.5%, while sour crude contains 1% sulfur or more. The presence of a high sulfur content in crude oil can lead to many types of harm, including (1) environmental pollution—sulfur oxides released into the atmosphere during combustion are major pollutants that negatively impact the environment; (2) equipment damage—sulfur can cause damage to the equipment and machinery used in oil operations, increasing the cost of maintenance and repair; and (3) pipe damage—sulfur can damage oil pipelines, affect oil flow, and increase the risk of fire. Therefore, one of the objectives of this study was to reduce the percentage of sulfur in heavy crude oil. Unlike light oil, the percentage of sulfur in heavy oil is typically high, so we aimed to treat acidic heavy oil by reducing its sulfur percentage to less than 1% to prevent the damage it causes. Fig. 3 shows the XOS Petra 4294, the device used to measure the percentage of sulfur in crude oil in this study.

3. Results and discussion

The process of transporting heavy crude oil from oil field to refinery is economically and technically challenging. High density, low API gravity, and high viscosity result in additional capital expenditures for larger pipeline dimensions, insulation, and frequent installation of pumping stations. The results obtained from this study, which aimed to reduce the viscosity and improve the API gravity of heavy crude oil from a field east of Baghdad, showed that adding nanofluid at different temperatures (20 °C, 40 °C, 60 °C, and 75 °C) achieved these goals.

3.1. Nanoparticle characterization

3.1.1. Transient electron microscopy

TEM is a highly advanced technique used to explore the internal structure of materials at the nanoscale. It operates by transmitting a focused beam of high-energy electrons through an ultrathin specimen to produce images with exceptional resolution that reveal the material's morphology and internal arrangement. The process involves four main steps: (1) electron generation—a beam of electrons is produced using an electron source, such as a heated filament, (2) beam focusing—magnetic lenses are used to accurately direct and concentrate the electron beam, (3) sample preparation—the specimen is placed on a thin metallic grid to allow electrons to pass through, and (4) image capture—as electrons pass through the sample, differences in density and structure affect their trajectory, which are recorded digitally or on a phosphorescent screen for detailed analysis. TEM is especially valuable in the characterization of nanoparticles due to its ability to:

- Examine nanoparticle shape and crystallinity.
- Analyze physical attributes, such as strength and structural resilience.
- Detect defects, voids, and lattice distortions.
- Support the development of enhanced nanomaterials for industrial and medical use.

The TEM image in Fig. 4 shows that the synthesized Al_2O_3 nanoparticles were almost spherical, with an average particle size of approximately 14 nm—closely aligning with the 12 nm crystallite size calculated using the Debye–Scherrer equation derived from XRD analysis. Although this particle size was slightly larger than that reported by Nafari et al. (2020), who observed a size of 10 nm, the nanoparticles still had a large specific surface area of 181 m^2/g, confirming their suitability for nanofluid preparation. Furthermore, the image showed a uniform distribution of the nanoparticles within the kerosene solvent, indicating excellent dispersion stability. This suggests that issues such as aggregation or sedimentation were minimal, allowing the nanofluid to function effectively in enhancing the properties of the heavy crude oil.

3.1.2. Thermal weighing analysis

TGA is a powerful technique employed to monitor changes in a material's mass as a function of temperature or time in a controlled atmosphere. A sample is subjected to a continuous heating process within a precision-controlled furnace, and the corresponding weight variations are recorded in real time. This method provides critical insights into the thermal characteristics of materials, including their thermal stability, decomposition behavior, and moisture content, as well as the presence of volatile components. In the context of nanomaterials, TGA serves as a vital tool for investigating thermal responses and evaluating both the physical and chemical stability of nanoparticles upon heating. As depicted in Fig. 5, the alumina nanoparticles exhibited remarkable thermal stability. The TGA curve revealed only a minimal decrease in mass with increasing temperature. Starting from a normalized weight of 100% at room temperature (approximately 16 °C), the material retained 98% of its mass at 200 °C, indicating negligible decomposition or moisture loss. Even under extreme thermal conditions, such as heating up to 900 °C, the nanofluid demonstrated a weight retention of 92%, confirming that only a small fraction of its mass was lost. This behavior highlights the excellent thermal resilience of alumina nanoparticles, making them highly suitable for applications that involve elevated temperatures and prolonged thermal exposure.

3.1.3. X-ray diffraction

XRD is a fundamental analytical technique employed to investigate the crystallographic structure and phase composition of solid and crystalline materials. It operates by directing a beam of X-rays onto a prepared sample, where the interaction between the

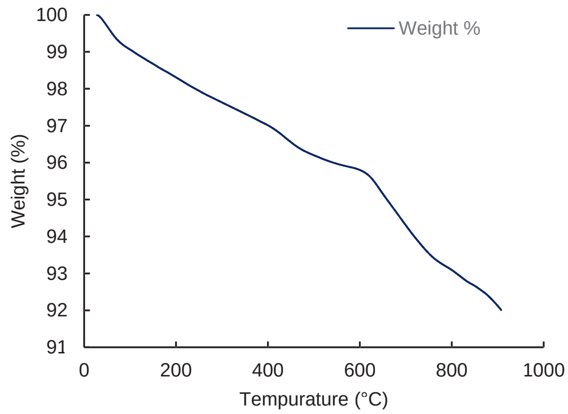

Fig. 5. Thermal weighing analysis of alumina (Al_2O_3).

incident radiation and the atomic lattice causes the electrons to oscillate, subsequently emitting secondary electromagnetic waves. These diffracted waves form characteristic patterns that are measured and interpreted to reveal detailed information about the material's internal structure. In the case of nanoparticles, XRD plays a critical role in identifying crystal phases, estimating crystallite size, and analyzing the degree of crystallinity. This structural insight is crucial for understanding a material's mechanical strength, hardness, and thermal stability—properties that directly impact its performance across various industrial applications. Specifically, in the context of heavy crude oil upgrading, XRD analysis provides valuable data on the behavior of nanoparticle additives and their potential to enhance process efficiency. The diffraction pattern presented in Fig. 6 illustrates the crystalline nature of the synthesized alumina nanoparticles, confirming their suitability for high-performance nanofluid formulations.

3.1.4. *Atomic force microscopy*

AFM is a microscopic technique used to photograph and study nano surfaces and structures with high resolution. It uses a sharp nanoneedle that moves over the surface of the sample and measures changes in force between the needle and the surface to determine the surface properties. AFM works as follows: (1) a sharp nanoneedle is moved over the surface of the sample, (2) changes in force between the needle and the surface are measured over time, and (3) an image of the surface is generated based on emerging forces. AFM nanoparticle examination can be used for the following purposes: (1) studying surface structure and nanoformations; (2) accurately measuring surface roughness; (3) studying mechanical properties to measure hardness, elasticity, and corrosion resistance; and (4) studying chemical reactions between substances. Fig. 7 shows that the surface roughness of the alumina was very low, giving it high stability when added to the solvent; that its mechanical properties included high rigidity and elasticity, along with good corrosion resistance; and that a small percentage of particles in predominated, with the average particle being tiny and large particles being rare and almost nonexistent. This provided a strong indicator of the quality of the nanoparticles used, as they provided a large surface area and enabled better functionality.

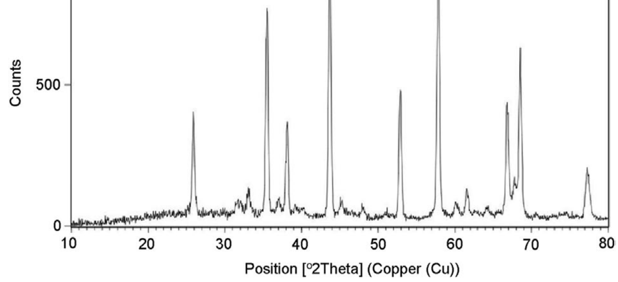

Fig. 6. X-ray diffraction of alumina (Al_2O_3).

3.2. *Effect of the novel nanofluid on viscosity*

Once the viscosity stability of the treated crude oil samples was measured, the correlation between viscosity and exposure time at a constant temperature was determined to evaluate the effects of nanofluid addition and ultrasonic treatment duration. Under isothermal conditions, viscosity decreased continuously with increased time in the ultrasonic device, as depicted in Fig. 8(a). This tendency suggests that extended exposure to ultrasound promotes the distribution of nanoparticles and affects the inner molecular structure of heavy crude, resulting in a reduction in resistance to flow. At 20 °C, viscosity decreased significantly after 15 min, from 58.15 cP to 33.06 cP. This reduction continued over time to 28.94 cP at 30 min, 23.25 cP at 45 min, and 17.57 cP at 60 min—equivalent to an overall reduction in viscosity of approximately 68%. The effect was greater at 40 °C, at which the viscosity reduced significantly, to 14.89 cP, after 60 min, representing an improvement of 71%. The improvements were even greater at high temperatures. Viscosity decreased by 75.7% at 60 °C, from 28.78 cP at 15 min to 10.13 cP at 60 min. The most significant impact occurred at 75 °C, at which the reduction in viscosity was observed to reach 5.58 cP—the lowest recorded value—at 60 min, representing a 90% reduction. This indicates that the combination of nanofluid addition and ultrasonic exposure to enhance the viscosity of the heavy crude oil was synergistic in nature and worked effectively under various thermal conditions (Fig. 8(b)).

The effect of nanofluid addition on crude oil flow behavior is depicted in Fig. 9(a), with constant ultrasonic exposure times applied at various temperatures. When the exposure time was 15 min, the viscosity decreased slightly to 33.06 cP (notably, but as expected) with an increase in temperature, compared to its value of 58.18 cP at 20 °C. As the temperature increased to 40 °C, the viscosity dropped further to 30.66 cP, and it decreased to 28.78 cP at 60 °C. At 75 °C, the lowest value was recorded, of 24.13 cP. These findings indicate that an increase in temperature contributed to a reduction in viscosity. When the ultrasonic exposure time further increased to 30 min, an additional reduction in viscosity was observed, and at 20 °C, it fell to 28.94 cP, as opposed to 30.06 cP at 15 min. At temperatures of 40 °C and 60 °C, the values reduced to 24.68 cP and 21.39 cP, respectively. The most significant decrease occurred at 75 °C, at which the viscosity was recorded at 17.46 cP. Following this trend, the subsequent exposure times were extended, with the final interval of 60 min and a temperature of 75 °C recording the lowest viscosity of 5.58 cP. The viscosity improvement percentages are shown in Fig. 9(b); at 75 °C, they were 58.5%, 70%, 79.5%, and 90.4% after 15 min, 30 min, 45 min, and 60 min, respectively. These results underscore the synergistic effect between thermal energy and ultrasound-induced nanofluid dispersion in breaking intermolecular cohesive forces, resulting in the enhanced flowability of heavy crude oil. When the liquid was heated, the molecules gained greater kinetic energy, which reduced the forces of attraction between them and, thus, the resistance of the liquid to flow decreased. The effect of

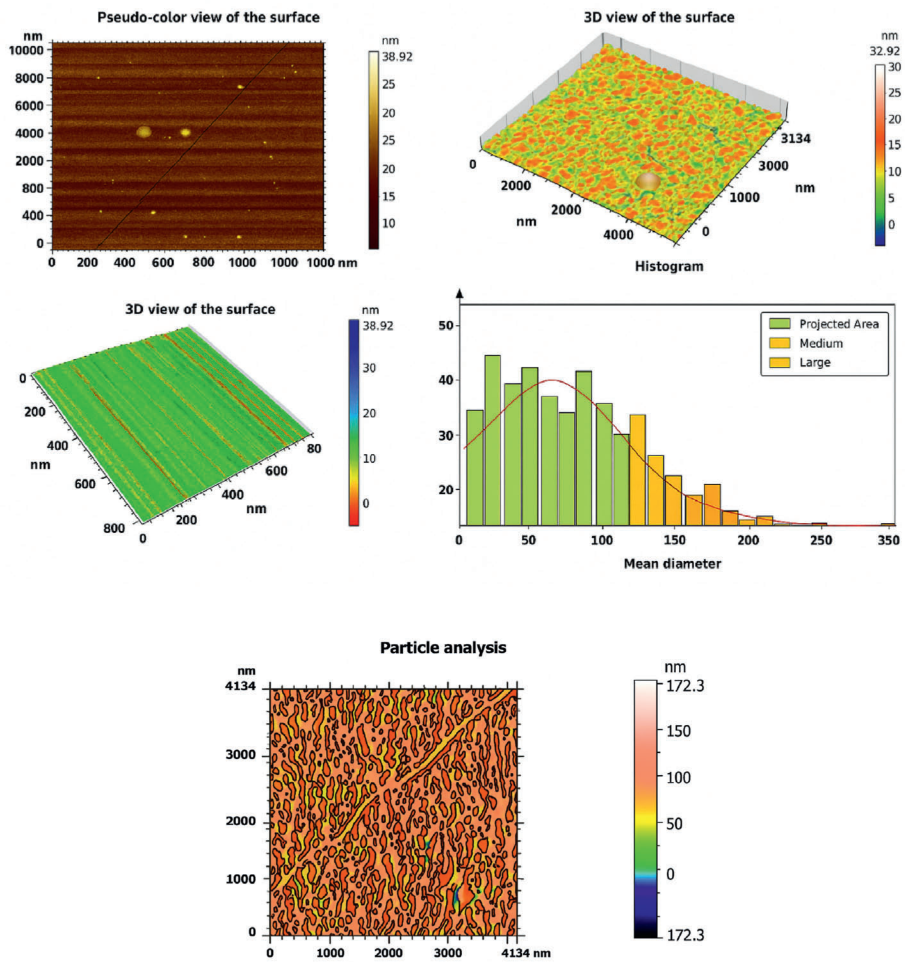

Fig. 7. Atomic force microscopy (AFM) analysis of alumina (Al_2O_3).

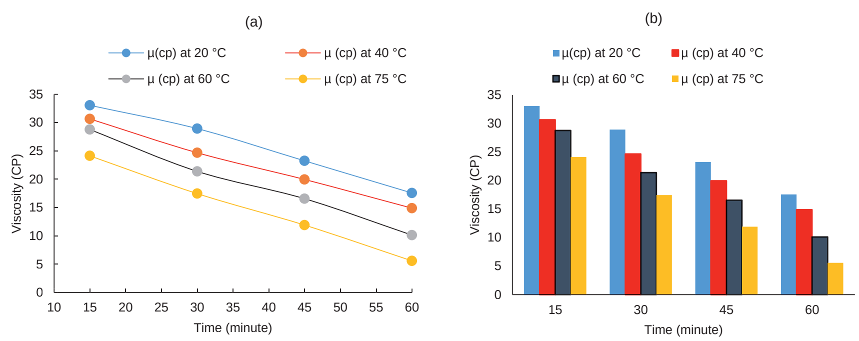

Fig. 8. Effect of Al_2O_3/kerosene nanofluid addition on the viscosity of crude oil.

temperature on viscosity can be expressed using the Arrhenius equation (Punith et al., 2021):

$$\mu = A\ exp\left(\frac{-E}{R\,T}\right)$$

where μ refers to viscosity, A is a constant depending on the material, E is the activation energy of viscosity, R is the general gas constant, and T is the absolute temperature in Kelvin.

Ultrasound reduces viscosity by sending high-frequency sound waves (20 kHz or more) through liquid and breaking the bonds between molecules. This sound energy reduces the attractive forces between molecules, thereby decreasing the liquid's resistance to flow (Salman et al., 2013). In liquids, ultrasound also results in the formation of microbubbles, which quickly collapse and release energy, thereby reducing viscosity (Peleg, 2018), and improving homogeneity, as it helps distribute molecules evenly

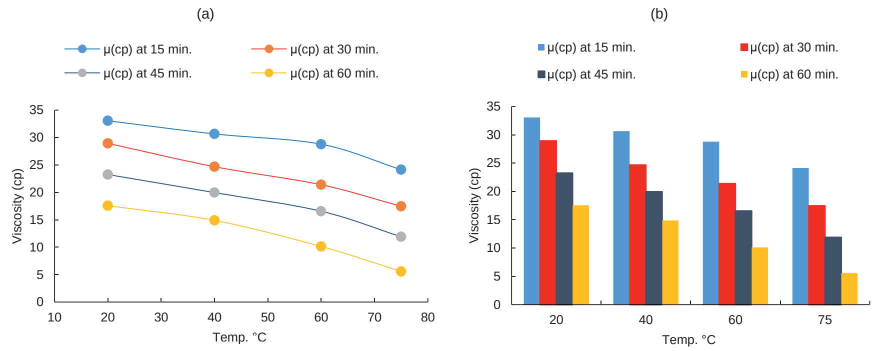

Fig. 9. Effect of Al_2O_3/kerosene nanofluid addition on crude oil viscosity.

(Messaâdi et al., 2015). This reduces the agglomeration of particles and leads to a decrease in overall viscosity (Mozie, 2017; Shahid et al., 2022).

The crude oil sample exhibited a viscosity of 58.15 cP prior to any treatment. Based on prior experiments conducted in this study, the optimal test conditions were identified as 75 °C and 60 min, under which the most substantial changes in viscosity occurred. Therefore, the present comparison between Al_2O_3 nanofluid and kerosene focuses on these specific conditions. Under these optimized conditions, the Al_2O_3 nanofluid significantly reduced the viscosity to 5.58 cP, achieving a 90.4% decrease. In contrast, kerosene alone lowered the viscosity to 33.98 cP, corresponding to a 41.6% decrease. This substantial difference clearly demonstrates the superior capability of the nanofluid in modifying the rheological behavior of heavy crude oil. This improved performance can be attributed to enhanced molecular-level interactions and dispersion facilitated by the nanoparticles. These findings reinforce the potential of Al_2O_3 nanofluids as advanced agents for viscosity reduction and crude oil upgrading compared to traditional diluents, such as kerosene. Fig. 10 shows the effects of both the nanofluid (Al_2O_3/kerosene) and kerosene on viscosity, along with a comparison between them.

3.3. Effect of the novel nanofluid on API gravity

After obtaining the API gravity values of the tested samples, the relationship between API gravity and time was plotted at a constant temperature to determine the effect of adding the Al_2O_3/kerosene nanofluid to crude oil and the impact of sample residence time in the ultrasound device on API values. The relationship between API gravity and temperature was determined by fixing the sample residence time in the ultrasound device. This is clear in Figs. 11 and 12. Fig. 11 shows that the API gravity increased with an increase in the sample residence time in the ultrasound device after adding the nanofluid at a constant temperature. Therefore, the longer the time, the higher the API value. The figure also shows that the maximum API gravity value at 20 °C occurred when the time was equal to 60 min, with an API value of 29.23, and that the API improvement percentage at this temperature was 49%. This percentage increased at 40 °C and reached 51% at 60 min. At 60 °C, the API gravity improvement percentage was 53% at 60 min. The maximum API gravity value obtained was 30.49 at 60 min and 75 °C. The most significant improvement was observed at 75 °C, with a value of 55%, as shown in Fig. 11(a) and (b).

Fig. 12 illustrates the relationship between API gravity and temperature under varying sonication durations. It is evident that there was a direct correlation between the increase in temperature and the corresponding rise in API gravity value. Specifically, Fig. 12 (a) demonstrates that at 20 °C, the API gravity value was 26.56, increasing to 26.87 at 40 °C and reaching 28.02 at 60 °C. Likewise, Fig. 12(b) confirms that for all sonication times, the API gravity values at 40 °C consistently exceeded those recorded at 20 °C. For instance, at a sonication time of 15 min, the API gravity value at 40 °C was 26.87, compared to 26.56 at 20 °C; at 30 min, the values were 27.77 and 27.65, respectively. A further temperature increase to 75 °C resulted in a more pronounced API gravity improvement; at 15 min, the API gravity value reached 28.02, rising to 29.14 at 30 min, 30.13 at 45 min, and peaking at 30.49 after 60 min of sonication. These results demonstrate that elevated temperatures not only reduce the viscosity of heavy crude oil but also enhance

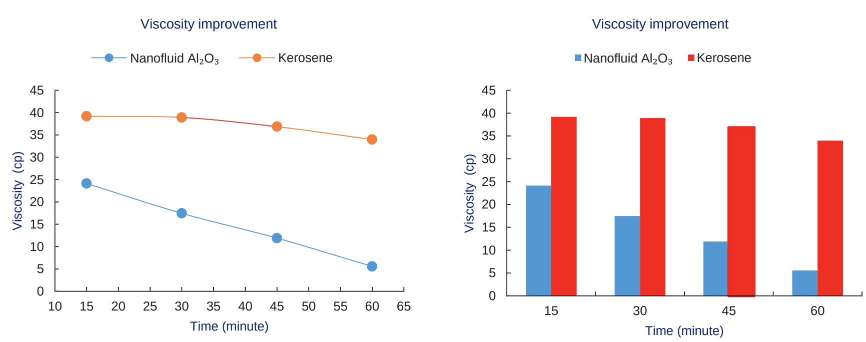

Fig. 10. Comparison of the effects of Al_2O_3/kerosene nanofluid and pure kerosene on crude oil viscosity.

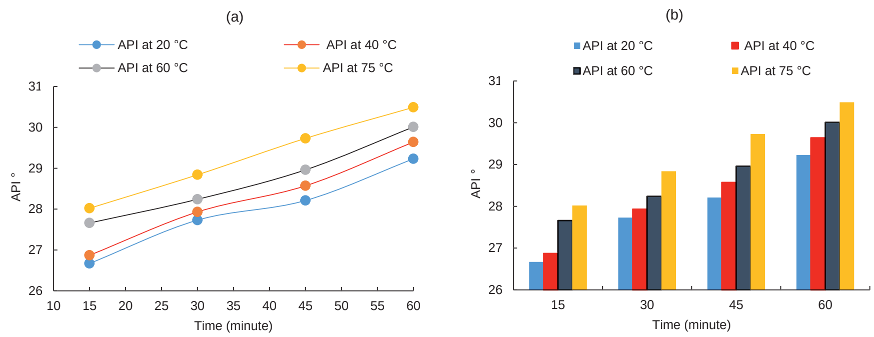

Fig. 11. Effect of Al_2O_3/kerosene nanofluid addition on crude oil API gravity at a constant temperature.

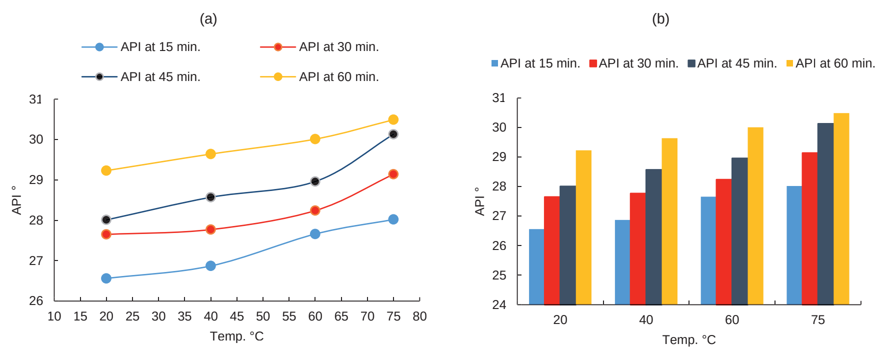

Fig. 12. Effect of Al_2O_3/kerosene nanofluid addition on the API gravity of crude oil at a constant exposure time.

its fluidity—primarily by promoting the breakdown of high molecular weight components and facilitating more effortless flow (Chakma, 2023; Dukhin et al., 2017; Li et al., 2010; Zhao et al., 2021). This thermal enhancement may also induce partial thermal cracking at certain thresholds, contributing to the fragmentation of heavier compounds into lighter fractions, thereby increasing API gravity. Additionally, the role of nanofluids becomes increasingly evident at elevated temperatures. Nanoparticles function as catalytic agents that assist in decomposing heavy molecular structures while simultaneously adsorbing metallic impurities, such as nickel and vanadium, thereby enriching the oil with lighter components and improving its overall API gravity rating. Moreover, the integration of ultrasonic technology further amplifies this upgrading process. Ultrasonic waves generate intense mechanical agitation and cavitation phenomena within the fluid matrix, producing localized high-energy microenvironments. These conditions facilitate the rupture of molecular bonds in heavy hydrocarbons, converting them into lower-molecular-weight species (Peleg, 2018). Ultrasound enhances the dispersion of nanoparticles throughout the crude matrix, thereby increasing their catalytic efficiency in reducing viscosity and degrading heavy fractions. It is also effective in targeting and degrading compounds containing sulfur, nickel, and vanadium, leading to improved crude oil quality and elevated API values.

The crude oil examined in this study initially exhibited an API gravity of 19.63, which categorized it as heavy crude. Following treatment with two upgrading agents—alumina-based nanofluid and kerosene—a consistent improvement in API gravity was observed over four treatment durations (15, 30, 45, and 60 min). A comparative evaluation revealed that while both agents positively influenced the oil's density profile, the nanofluid demonstrated markedly superior performance across all time intervals. At 15 min, the API gravity increased to 28.02 with the nanofluid compared to 22.73 with kerosene. This initial enhancement reflects the rapid interaction between alumina nanoparticles and heavy crude components. As treatment continued, the gap widened: at 30 min, the values were 28.84 for the nanofluid and 23.26 for kerosene, and by 45 min, they were 29.73 versus 24.74, respectively. After 60 min, the nanofluid-treated sample achieved 30.49, while the kerosene treatment resulted in a more modest 25.61. Importantly, the experimental results revealed that the optimal condition for API gravity enhancement was achieved at a treatment temperature of 75 °C. Under these thermal conditions, the interaction between the oil matrix and the additive—particularly in the nanofluid system—was significantly intensified, facilitating better dispersion and molecular interaction and ultimately resulting in a more substantial reduction in density. This increase of over 10 API gravity units from the original value not only reclassified the crude oil from heavy to borderline medium grade in the case of the nanofluid but also underscores the effectiveness of nanotechnology-based additives when applied under optimized thermal conditions. In contrast, kerosene, although effective to a lesser extent, demonstrated a limited capacity for deep upgrading under similar circumstances. Fig. 13 illustrates the effect of both the nanofluid (Al_2O_3/kerosene) on viscosity and the effect of kerosene on API gravity, along with a comparison between them.

3.4. Effect of the novel nanofluid on vanadium and nickel content

After obtaining the vanadium and nickel content values in the examined samples, the relationship between these metals and the

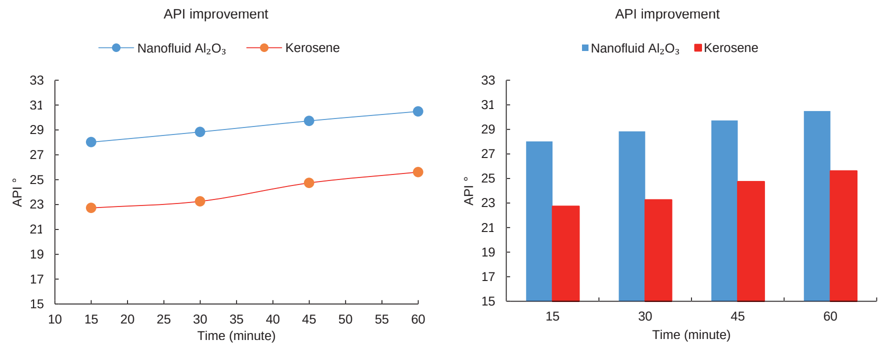

Fig. 13. Comparison of the effects of Al_2O_3/kerosene nanofluid and pure kerosene on crude oil API gravity.

time variable at a constant temperature was plotted to determine the effect of nanofluid addition and sample time in the ultrasonic device on the vanadium and nickel content in crude oil. Fig. 13 shows that the vanadium content in crude oil decreased over time as the sample remained in the ultrasonic device following the addition of the nanofluid at a constant temperature. Fig. 14(a) and (b) show that the vanadium content in crude oil at 20 °C was 63.84 at 15 min, 56.57 at 30 min, and 45.86 at 45 min. The lowest value was 39.6 ppm, which was at 60 min. Fig. 14(a) shows that at 40 °C, the vanadium content was 56.61 ppm at 15 min, 41.98 ppm at 30 min, and 33.68 ppm at 45 min and that its lowest value was 27.3 ppm at 60 min. Fig. 14(a) shows that the vanadium content was inversely proportional to the time the sample stayed in the ultrasonic device (at a constant temperature). Fig. 14 also shows that the lowest vanadium content was obtained when the temperature was increased to 75 °C and the time was extended to 60 min, resulting in a value of 9.02 ppm. From Fig. 14(b), it is clear that the vanadium improvement percentages At a temperature of 20 °C, vanadium removal was 42% at 15 min, 48% at 30 min, 58% at 45 min, and reached its maximum of 64% at 60 min. When the temperature increased to 40 °C, the vanadium improvement percentages rose from 48% at 15 min to 62% at 30 min and then to 69% at 45 min; the highest percentage was 75% at 60 min. Thus, the vanadium improvement rate increased with both temperature and sample residence time in the ultrasonic device, with the most significant improvement rate of 92% achieved at 75 °C and a residence time of 60 min. Temperature affects the concentration and behavior of vanadium; as the temperature increases, the solubility of organic and mineral compounds containing vanadium increases, leading to a more homogeneous distribution of vanadium in the liquid phase of crude oil (Sagdeev et al., 2020). High temperatures can lead to the decomposition of complex organic compounds that contain vanadium, which may alter its chemical form and increase its propensity to precipitate or react with other materials in the oil (Zhu et al., 2021). Heat helps release vanadium from its organic compounds, facilitating its separation using nanofluids (Shokrlu et al., 2014). As for the effect of increasing the sample residence time in the ultrasonic device, ultrasound is used in the treatment of crude oil to improve its properties and reduce its impurities, including lowering the percentage of vanadium by breaking the bonds between vanadium and organic compounds. Ultrasound waves cause strong mechanical vibrations within crude oil, which helps break the bonds between vanadium and the organic compounds that carry it and facilitates its subsequent separation using nanofluids. Ultrasound also creates microscopic bubbles within the liquid, which collapse rapidly and produce a high level of energy, breaking down complex vanadium-bearing compounds, making it easier to extract from the oil. Ultrasound can also trigger chemical reactions that convert vanadium into inorganic compounds that can be easily precipitated or separated. When ultrasound is used as part of physical or chemical processing, such as solvent extraction or nanofluidization, it can accelerate the removal of vanadium from crude oil (Peleg, 2018).

Fig. 15(a) and (b) show the temporal and thermal evolution of nickel concentration in heavy crude oil subjected to ultrasonic treatment in the presence of nanofluids. At 20 °C, there was a progressive decline in nickel content as the sonication duration increased. Beginning at 20.23 ppm after 15 min, the concentration dropped to 18.67 ppm at 30 min and 15.87 ppm at 45 min, and it reached a minimum of 13.12 ppm at 60 min. This trend confirms the inverse relationship between sonication time and nickel content at a constant temperature. The effect of temperature elevation became apparent when examining the results at 40 °C. At 15 min, the nickel content decreased to 15.74 ppm and to 13.55 ppm at

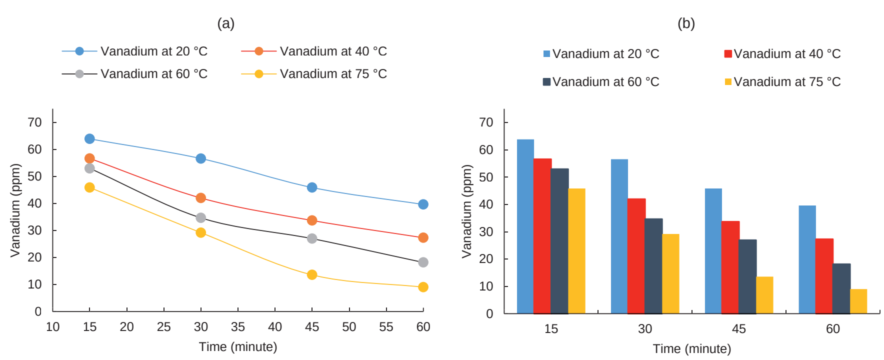

Fig. 14. Effect of nanofluid (Al_2O_3/kerosene) addition on crude oil vanadium content at constant temperature.

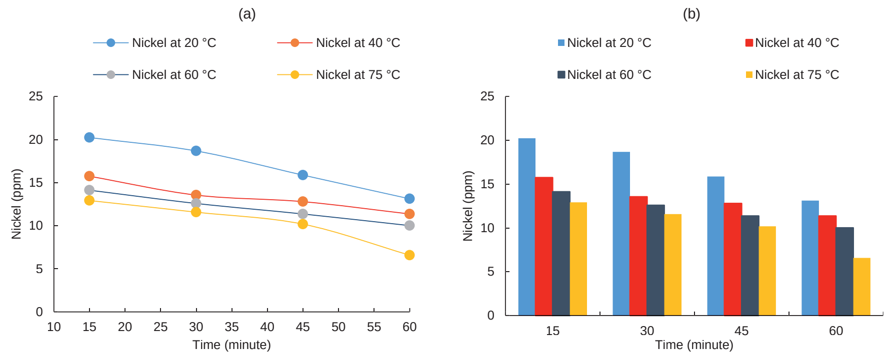

Fig. 15. Effect of nanofluid (Al_2O_3/kerosene) addition on nickel content in crude oil at constant temperature.

30 min, and it continued to 11.36 ppm at 60 min. The most significant reduction in nickel was recorded at 75 °C and 60 min, at which the content had dropped to 6.58 ppm, indicating the combined role of temperature and sonication in promoting metal removal. Fig. 15(b) quantifies the improvement rates in nickel removal. At 20 °C, the enhancement rose from 53% at 15 min to 56%, 63%, and 69% at 30, 45, and 60 min, respectively. In contrast, increasing the temperature to 40 °C for 15 min boosted the improvement to 63%, underscoring the influence of temperature on metal separation efficiency. The highest recorded enhancement was 85% at 75 °C and 60 min, reinforcing the synergistic effect of thermal and ultrasonic conditions. Thermally, elevated temperatures enhance the solubility and release of nickel from complex organic matrices within crude oil. This occurs due to the thermal decomposition of nickel–organic compounds, facilitating their separation into the liquid phase. Moreover, nanofluids provide catalytic surfaces for nickel interaction; temperature elevation promotes these surface reactions, potentially leading to nickel adsorption or transformation into more separable species (Dengaev et al., 2023b). In the presence of nanocatalysts, higher temperatures may enhance hydrogenation reactions, converting nickel from organically bound forms into more accessible inorganic states (Alhalili, 2023). Ultrasound further amplifies this separation process through multiple mechanisms. First, it facilitates the cleavage of bonds between nickel and hydrocarbon chains, releasing the metal into the surrounding medium (Bhupathi et al., 2023; Langeslay et al., 2018). Second, cavitation phenomena generated by ultrasonic waves induce the formation and collapse of microbubbles, creating localized energy surges that break down heavy compounds and free nickel atoms for subsequent interactions with nanoparticles. In addition, ultrasound significantly improves nanoparticle dispersion, maximizing contact between the active surface of nanomaterials and dissolved nickel species, thereby enhancing removal efficiency (Chen et al., 2005). Finally, ultrasound may trigger chemical transformations between nickel and nanofluid components, converting nickel into metastable compounds that are more readily separated from the crude matrix (Otumudia et al., 2022).

Fig. 16(a) illustrates the relationship between vanadium content in crude oil and temperature after the addition of nanofluids, with the stabilization time of the sample in the ultrasonic device held constant. The relationship between temperature and vanadium content was inverse, as, at a time constant of 15 min, the vanadium content at a temperature of 20 °C was 63.84 ppm and decreased as the temperature increased. At 40 °C, the vanadium concentration was 56.61 ppm, and it continued to decline to 52.94 ppm at 60 °C, then to 45.86 ppm at 75 °C. When the time was changed to 30 min, the vanadium content was 56.57 ppm at 20 °C and decreased to 41.98 ppm at 40 °C and to 34.64 ppm at 60 °C. At 75 °C, the vanadium content was 29.17 ppm. Thus, it continued to decline as the temperature increased, reaching its lowest value at 75 °C and 60 min, at 10.18 ppm. Fig. 16(b) confirms that the vanadium improvement rate increased as the temperature increased, as, at a time constant of 15 min, the improvement rates were 42% at 20 °C and 48% at 40 °C, and they increased to 52% at 60 °C and 58% at 75 °C. Fig. 16(b) shows that the relationship between temperature and the vanadium improvement rate was direct; as the temperature increased, the vanadium improvement rate also increased. The best vanadium improvement rate was achieved at 75 °C and 60 min, with an improvement of 91%.

Fig. 17 illustrates the relationship between nickel content and temperature, with the stabilization time of the sample in the ultrasonic device held constant. The figure shows that the relationship was reversed: The higher the temperature, the lower the value of the nickel content in the sample. Fig. 17(a) shows that at 15 min, the nickel content was 20.23 ppm at 20 °C, 15.74 ppm at

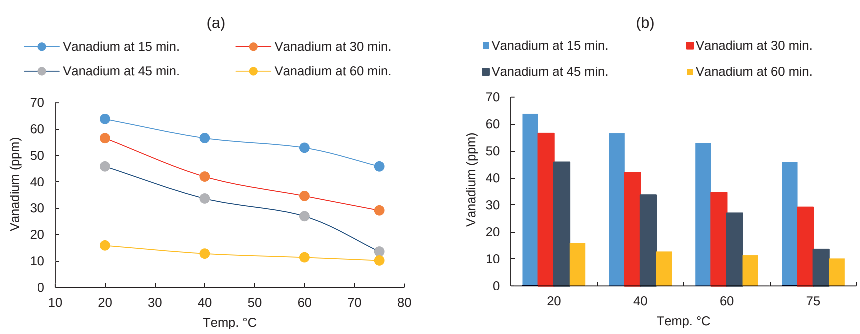

Fig. 16. Influence of Al_2O_3/kerosene nanofluid on vanadium and nickel concentrations in crude oil under a fixed retention time.

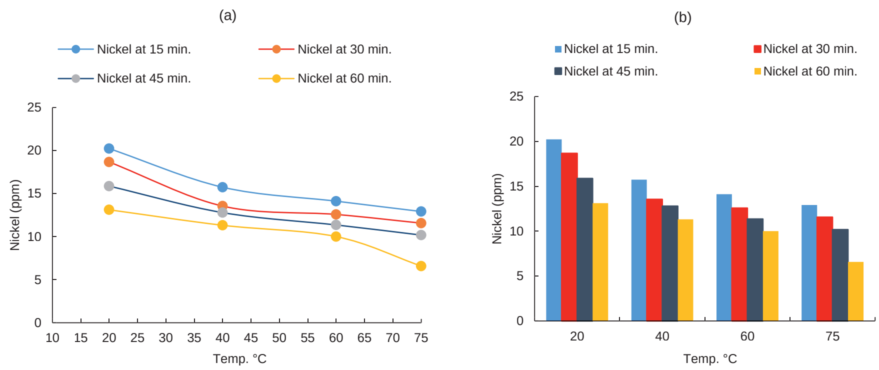

Fig. 17. Effect of nanofluid (Al_2O_3/kerosene) addition on vanadium and nickel content in crude oil at constant time.

40 °C, and 14.12 ppm at 60 °C. At 75 °C, the nickel content was 12.92 ppm. Fig. 17(b) shows that the nickel content at 40 °C was lower than at 20 °C for all times. At 15 min, it was 15.74 ppm at 40 °C and 20.23 ppm at 20 °C, while at 30 min, it was 13.55 ppm at 40 °C and 18.67 ppm at 20 °C. Therefore, the higher the temperature, the lower the nickel content. The figure also shows that the value of the nickel content at 75 °C had the lowest magnitude. At 75 °C, the concentration was 12.92 ppm at 15 min, 11.57 ppm at 30 min, and 10.18 ppm at 45 min; the lowest value of 6.58 ppm was recorded at 60 min.

3.4.1. Comparison of the effects of alumina nanofluid and kerosene on vanadium content

The untreated crude oil used in this study had a vanadium content of 109.67 ppm—a level considered critically high due to its adverse impact on refining catalysts and equipment. Two distinct upgrading agents—alumina-based nanofluid and kerosene—were applied under controlled thermal conditions to evaluate their efficacy in reducing vanadium concentrations over various treatment durations. At 15 min, the nanofluid reduced the vanadium level to 45.86 ppm, while kerosene achieved a more modest reduction to 75.20 ppm. As treatment time increased, the nanofluid consistently outperformed kerosene; at 30 min, it lowered the content to 29.17 ppm, compared to 61.38 ppm with kerosene, and at 45 min, the values were 13.56 ppm and 45.86 ppm, respectively. After 60 min, the nanofluid achieved a minimum vanadium concentration of 9.02 ppm, while kerosene reached 35.98 ppm. These values correspond to a 91.77% reduction in vanadium content using the nanofluid, compared to a 67.21% reduction achieved with kerosene. This sharp contrast confirms the superior extraction and immobilization capacity of the nanofluid, likely due to the high surface area and active adsorption characteristics of the alumina nanoparticles. Moreover, experimental evidence indicates that the optimal condition for vanadium removal was attained at 75 °C after 60 min of treatment, under which the nanofluid's performance peaked. These findings underscore the potential of nanotechnology-based approaches to significantly improve crude oil quality, particularly in reducing toxic metal content, thereby making the feedstock more suitable for environmentally responsible refining processes. Fig. 18 illustrates the effects of the nanofluid (Al_2O_3/kerosene) on viscosity and of kerosene on vanadium, along with a comparison.

3.4.2. Comparison between the effects of alumina nanofluid and kerosene on nickel content

The untreated crude oil sample had a nickel concentration of 42.65 ppm—a level that poses serious challenges during refining due to its detrimental impact on catalysts and the production of harmful emissions during combustion. To mitigate this, two upgrading agents—alumina-based nanofluid and kerosene—were evaluated across different treatment durations (15, 30, 45, and 60 min) and under controlled thermal conditions. At the 15-min interval, kerosene reduced the nickel content to 38.00 ppm, while the nanofluid achieved a significantly better reduction to 12.92 ppm. This early distinction highlights the nanofluid's rapid interaction and higher affinity toward nickel ions. As treatment time progressed, the nanofluid consistently outperformed kerosene; at 30 min, the nickel concentration dropped to 11.57 ppm with the nanofluid compared to 34.27 ppm with kerosene; at 45 min, the values were 10.18 ppm and 29.18 ppm, respectively. Ultimately, at 60 min, the nanofluid achieved a minimum nickel content of 6.58 ppm, while kerosene reached 22.50 ppm. These

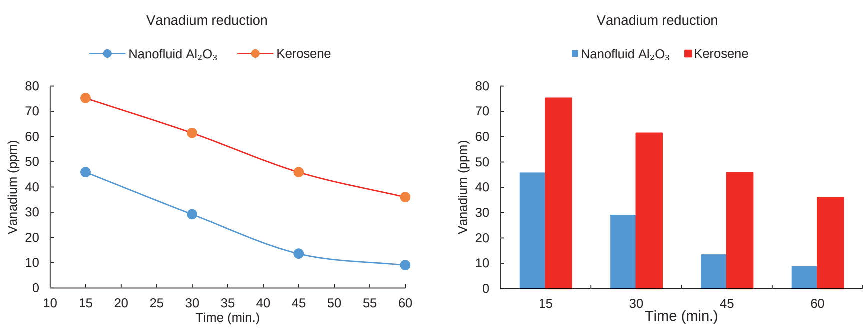

Fig. 18. Comparison of the effects of Al_2O_3/kerosene nanofluid and pure kerosene on the vanadium content in crude oil.

final values correspond to a reduction of approximately 84.57% in nickel content with the nanofluid, compared to a 47.25% reduction achieved with kerosene. This disparity highlights the effectiveness of alumina nanoparticles in adsorbing or deactivating nickel compounds, likely due to their high surface reactivity and ability to interact with trace metal species at the molecular level. Furthermore, based on the experimental outcomes, the optimal conditions for nickel reduction were observed to be 75 °C and 60 min of treatment, at which the combined influence of thermal activation and nanoparticle dispersion was maximized. The significant decline from 42.65 ppm to 6.58 ppm demonstrates the promising role of nanofluid-assisted upgrading techniques in producing cleaner crude oil, with lower heavy metal content and enhanced suitability for downstream refining operations. Fig. 19 illustrates the effects of the nanofluid (Al_2O_3/kerosene) on viscosity and kerosene on nickel, along with a comparison.

3.5. Effect of the novel nanofluid on sulfur content

After determining the sulfur content of the analyzed samples, the relationship between sulfur content and exposure time—while maintaining a constant temperature—was investigated to assess the influence of nanofluid addition and the duration of sonication on sulfur reduction in crude oil. As illustrated in Fig. 20(a) and (b), the sulfur content decreased progressively with extended exposure to ultrasonic treatment following the introduction of the nanofluid. Notably, at a fixed temperature of 20 °C, the sulfur content reached its minimum value of 2.04% after 60 min of treatment, corresponding to an improvement of approximately 54%. This reduction became more pronounced at higher temperatures, reaching 78% at 40 °C and peaking at 81.4% at 60 °C. These results underscore the synergistic effect of temperature and sonication time in enhancing sulfur removal efficiency in the presence of nanofluids. The best sulfur content improvement in crude oil was achieved at a temperature of 75 °C, with an 83% reduction, and the sample's survival time in the ultrasonic device was 60 min. Fig. 20(b) shows that the lowest sulfur content, at 0.77%, was achieved by adding the alumina nanofluid at a temperature of 75 °C and with a reaction time of 60 min. This value could be reduced to 0.5% or less by increasing the proportion of nanofluid added to the crude oil sample since the sulfur content in crude oil was reduced from 4.422% to 0.77% when 18% of the nanofluid was added to the crude oil sample. Fig. 21(a) and (b) illustrate the relationship between sulfur content and temperature when the sample survival time was fixed in the ultrasound device. The goal of showing this relationship was to observe the effect of temperature increase on sulfur content. This relationship turned out to be reversed: the higher the temperature, the lower the sulfur content in crude oil after the addition of liquid nano-alumina. Nanoparticles are used in fluids to enhance oil recovery and enhance the removal of impurities. Nanoparticles, such as iron oxide (Fe_3O_4), titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3), can catalyze chemical reactions that break down complex sulfur compounds (Rostami et al., 2020; Sakthipandi et al., 2024). These materials enhance the interactions between desulfurization agents and crude oil, increasing the efficiency of organic sulfur removal (Razzaq et al., 2025). An increase in temperature accelerates the chemical reactions responsible for breaking down sulfur compounds (Costa et al., 2020) while reducing the viscosity of heavy crude oil, making it easier to separate sulfur compounds (De et al., 2025). Ultrasound helps break down heavy crude oil molecules and stimulate chemical reactions (Sah et al., 2025). This creates cavitation, which results in the formation of tiny bubbles that collapse rapidly, resulting in high local temperatures and

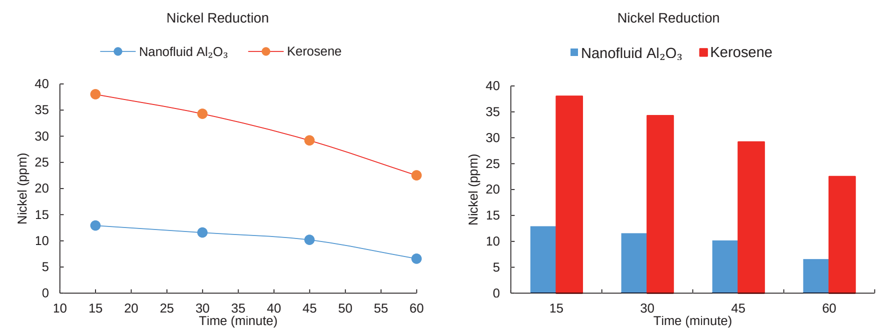

Fig. 19. Comparison of the effects of Al_2O_3/kerosene nanofluid and pure kerosene on nickel content in crude oil.

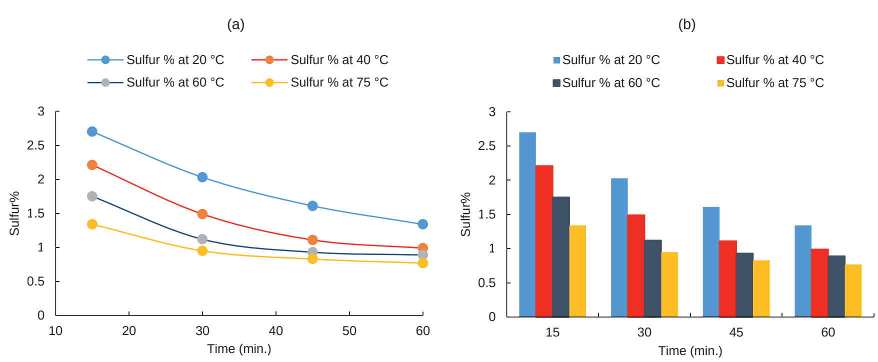

Fig. 20. Effect of nanofluid (Al_2O_3/kerosene) addition on crude oil sulfur content at a constant temperature.

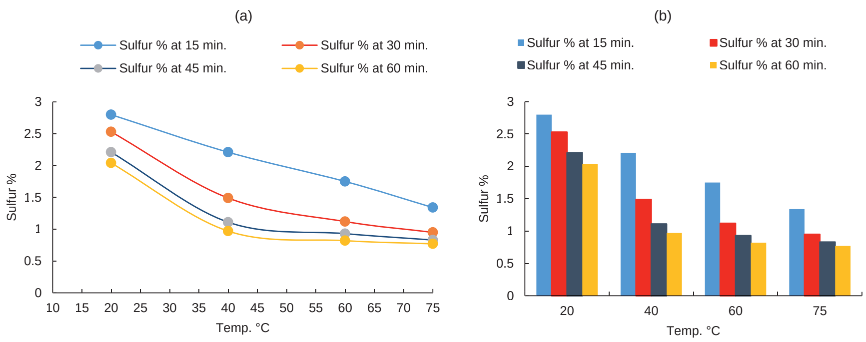

Fig. 21. Effect of nanofluid (Al_2O_3/kerosene) addition on crude oil sulfur content at a constant time.

pressures that help break down the chemical bonds in sulfur compounds (Saleh, 2022). When ultrasound is used in conjunction with catalysts and nanomaterials, desulfurization efficiency is enhanced, particularly when combined with thermal and chemical processes (Haruna et al., 2022; Katasonova et al., 2021).

The initial sulfur content of the crude oil in this study was 4.42 wt%—a value considered critically high and environmentally unfavorable, particularly in the context of fuel standards and refining efficiency. To address this, the sulfur removal performance of alumina-based nanofluid and kerosene was evaluated over various treatment times (15, 30, 45, and 60 min) under thermal conditions optimized at 75 °C. At the 15-min mark, the nanofluid reduced the sulfur content to 1.34%, while kerosene achieved a less pronounced reduction to 3.85%. With an increase in treatment duration, both agents maintained lower sulfur levels, yet the nanofluid consistently outperformed kerosene. At 30 min, the sulfur content dropped to 0.95% with the nanofluid, compared to 2.94% with kerosene, and at 45 min, the values reached 0.83% and 2.51%, respectively. Finally, at the 60-min interval, the nanofluid treatment reduced the sulfur content to 0.77%, compared to 1.99% achieved using kerosene. These final values reflect a remarkable sulfur reduction of approximately 82.57% with the nanofluid, compared to the 54.98% achieved by kerosene. The significantly greater efficiency of the nanofluid may be attributed to the high surface area and adsorptive affinity of the alumina nanoparticles, which likely interacted with sulfur-bearing compounds through both physical adsorption and potential catalytic effects. Furthermore, the data confirmed that the optimal condition for sulfur removal was achieved at 75 °C after 60 min, at which the nanofluid's performance reached its peak. The substantial reduction from 4.42% to 0.77% highlights the potential of nanoparticle-assisted desulfurization as a viable method for improving crude oil quality that aligns with increasingly stringent environmental standards. Fig. 22 illustrates the effects of the nanofluid (Al_2O_3/kerosene) on viscosity and kerosene on nickel, along with a comparison.

3.6. General comparison between the Al_2O_3 nanofluid and kerosene in enhancing heavy crude oil properties

Table 6 presents a general comparison of the effects of the alumina nanofluid and kerosene on improving the properties of heavy crude oil. The table clearly shows that the impact of alumina nanofluid was significantly greater than that of kerosene in improving all properties.

3.7. Mechanism and kinetics of the Al_2O_3 nanofluid in upgrading heavy crude oil

Nanofluids—that is, liquids containing nanoparticles suspended in a solvent—are used to improve the flow properties of heavy crude oil and break down complex hydrocarbon compounds. The main mechanisms of this process include catalytic cracking. Nanoparticles, such as metal oxides (Al_2O_3, NiO, CoO, Fe_2O_3), act as catalysts to break down long hydrocarbon chains into smaller, lighter fractions (Hamidi et al., 2021). These reactions occur at increased temperatures and reduce viscosity and improve the quality of crude oil (Siddique et al., 2025). Nanofluids enhance heat transfer, which contributes to the upgrading process. Heavy crude oil contains high levels of asphaltenes and waxes, which

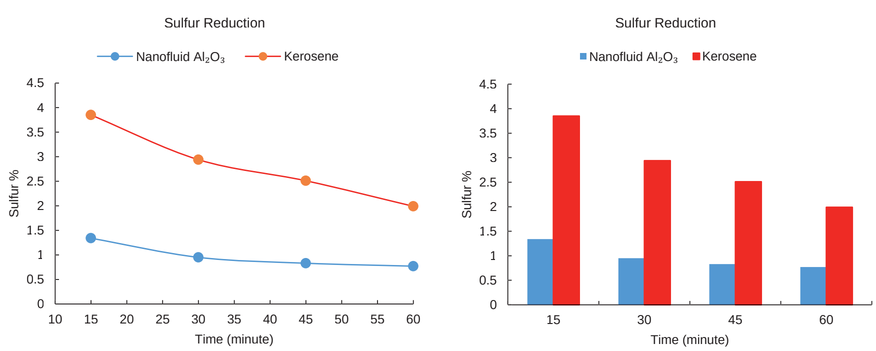

Fig. 22. Comparison of the effects of Al_2O_3/kerosene nanofluid and pure kerosene on sulfur content in crude oil.

Table 6
Comparison of alumina nanofluid and kerosene in improving the properties of heavy crude oil.

Time (min.)	API		Viscosity		Vanadium		Nickel		Sulfur	
	Al_2O_3 Nanofluid	Kerosene	Al_2O_3 Nanofluid	Kerosene	Al_2O_3 Nanofluid	Kerosene	Al_2O_3 Nanofluid	kerosene	Al_2O_3 Nanofluid	Kerosene
15	28.02	22.73	24.13	39.18	45.86	75.2	12.92	38	1.34	3.85
30	28.84	23.26	17.46	38.92	29.17	61.38	11.57	34.27	0.95	2.94
45	29.73	24.74	11.9	36.85	13.56	45.86	10.18	29.18	0.83	2.51
60	30.49	25.61	5.58	33.98	9.02	35.98	6.58	22.5	0.77	1.99

clump and block pipes (Boshagh et al., 2022). Nanoparticles help break down these materials and prevent their deposition, which keeps the oil flowing smoothly (Albayrak et al., 2022). Nanoparticles reduce the activation energy required for chemical reactions to occur, thereby accelerating catalytic processes. The efficiency of nanofluids depends on the extent of dispersion and distribution of nanoparticles within the crude oil (Khalaf et al., 2024). The larger the surface area of the particles and the smaller their size, the higher the reaction rate due to increased contact between the particles and the hydrocarbons (Dhokale, 2019). The sustainability of the catalytic activity of nanoparticles can impact the reaction's efficiency. Some particles may agglomerate or lose their activity over time (Maity et al., 2010), and their stability can be enhanced by using encapsulating materials, such as polymers or surfactants, to maintain their effectiveness (Al-Shargabi et al., 2022). The process of improving heavy crude oil plays a major and vital role in enhancing the quality of heavy oil, making it more valuable and widely used. There are several reasons why the process of improving crude oil is important, including increasing its economic value by converting heavy oil—rich in minerals and unwanted elements—into desirable crude oil. In addition, the improvement process leads to a reduction in pollution. Since heavy oil contains a high level of sulfur, improving it helps reduce the pollution caused by the sulfur and by harmful metals. Improving heavy oil also enhances the efficiency of combustion and refining processes, thereby reducing energy consumption and increasing productivity. This study focused on the process of upgrading crude oil from an East Baghdad field, which was classified as heavy oil. As shown in Fig. 23, the process involved improving both the viscosity and density of the crude oil

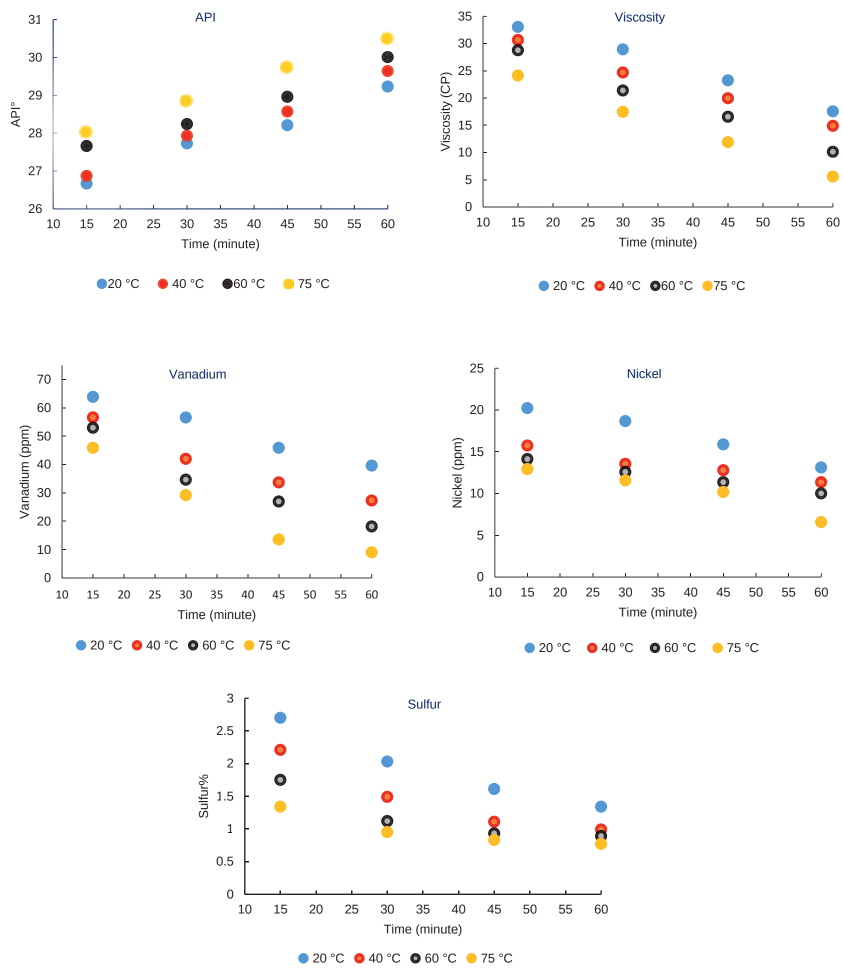

Fig. 23. Upgrading heavy crude oil using Al_2O_3/kerosene nanofluid: Variation of viscosity, API gravity, vanadium, nickel, and sulfur content with time.

while also reducing its percentage of vanadium, nickel, and sulfur. The viscosity decreased when the sample dwell time in the ultrasonic device increased at a constant temperature, while the API gravity values rose with increased time. The proportion of vanadium, nickel, and sulfur in oil from eastern Baghdad gradually decreased with an increase in time. With the presence of nanoparticles in crude oil, when the temperature increases, the properties of heavy crude oil change in that its viscosity decreases and fluidity improves. High temperatures lead to the breakdown of heavy molecules, reducing viscosity and improving the flow rate, which facilitates the transportation process. At certain temperatures, partial thermal cracking may occur, leading to the decomposition of heavy compounds into lighter components, thereby increasing the API value. The nanoparticles present in the nanofluid act as catalysts that help break down heavy compounds and absorb certain metal impurities, such as nickel and vanadium, thereby increasing the percentage of light compounds and improving API values (Khan et al., 2022). Ultrasound contributes to improving the API value of heavy crude oil in the presence of nanofluids by enhancing the quality of heavy oil, including the breakdown of heavy compounds into lighter ones. It causes strong mechanical vibrations within the fluid, which help break down large molecules into smaller and lighter ones (Hill et al., 2019); creates microscopic bubbles that collapse rapidly, generating enough energy to break the bonds between heavy molecules and convert them into lighter compounds; and helps improve the distribution of nanoparticles within crude oil, increasing their efficiency in breaking down heavy compounds and reducing viscosity (Al-Moubaraki et al., 2021). Ultrasound can also help break down compounds containing nickel, vanadium, and sulfur, improving the quality of crude oil (Vrignaud et al., 2011). Each of these factors enhances API gravity.

4. Conclusion

In this study, a nanofluid was prepared by adding aluminum oxide (Al_2O_3) and surfactants to kerosene. After ensuring the stability and distribution of nanoparticles over 3 months of monitoring and a TEM examination, the process of upgrading heavy oil from an East Baghdad field was carried out using a sound wave device. Heavy oil samples were exposed to sound waves for 15, 30, 45, and 60 min in the ultrasonic device at temperatures of 20 °C, 40 °C, 60 °C, and 75 °C. This process was carried out after 18% of the nanofluid was added to the crude oil samples. Experimental results showed that the nanofluid prepared from 100 ml of kerosene was supplemented with 0.4 g of alumina (aluminum oxide) and 0.04 g of surfactant (10% by weight of alumina). After preparing the samples at the specified temperatures and placing them in the ultrasonic device for 15, 30, 45, and 60 min, viscosity measurements showed that the percentage of viscosity improvement using the alumina nanofluid was 90.4% at 60 min and 75 °C. The viscosity values were 58.15 cm before the nanofluid enhancement process and 5.58 cm after the improvement process. Meanwhile, the API gravity values were 19.63 before the nanofluid addition process and 30.49 after it. Regarding vanadium content, the amount was 109.67 ppm—which was high—before the addition of the nanofluid. After the addition of the nanofluid and the use of the ultrasonic device, the percentage of vanadium—9.02 ppm—was considered low for crude oil, with an improvement rate of 92%. The nickel improvement rate was 85%, with the amount of nickel decreasing from 42.65 ppm to 6.58 ppm after adding nanofluid and performing the upgrading process. Regarding sulfur, the percentage of sulfur before treatment was 4.422%, which was very high and would cause multiple problems. However, after treatment with the nanofluid and the ultrasonic device, the percentage of sulfur decreased to 0.77%, resulting in an 83% improvement. This percentage could be increased to 90% if 30% of the nanofluid were added to the crude oil. The results obtained from this study show the significant impact of nanofluids on upgrading heavy crude oil to improve its specifications, thereby meeting consumer aspirations, increasing demand, and ultimately enhancing market value. This study contributes to the literature on two fronts. First, the use of new technology in the upgrading process—specifically, the addition of nanofluids—leads to a significant improvement in the properties of crude oil from the field east of Baghdad. Second, the cost of the upgrading process is low compared to commonly used solvents, such as ethylene, methylene, hexane, heptane, or naphtha, as the price of kerosene is significantly lower than that of these solvents.

CRediT authorship contribution statement

Luay Ahmed Khamees: Writing – review & editing, Writing – original draft, Software, Formal analysis, Conceptualization. **Ghassan H. Abdul-Majeed:** Supervision, Methodology, Investigation, Funding acquisition. **Ayad A. Alhaleem:** Visualization, Validation, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

EOR	Enhanced oil recovery
T	Temperature
μ	Kinematic viscosity
cP	Centipoise
API	American Petroleum Institute
Gamma-alumina	Nano-aluminum oxide
Al_2O_3	Aluminum oxide
Min	Minute
SDBS	Sodium dodecyl benzene sulfonate
ppm	Parts per million
°C	Degree Celsius
TEM	Transient electron microscope
TGA	Thermal weighing analysis
XRD	X-ray diffraction
AFM	Atomic force microscopy
Al_2O_3/kerosene	Alumina nanofluid base kerosene
E	Activation energy of viscosity
A	Constant depends on the material

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