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Effects of Ultrasonic Treatment and Hydrogen Donor Addition on the Viscosity of Iraqi Heavy Crude Oil

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Abstract

The current investigation examines the combined impacts of ultrasonic radiation and hydrogen donors on the viscosity of heavy crude oil. The impact of exposure time, power, duty cycle, and temperature on the viscosity of Iraqi heavy crude oil with 20.32 API was studied. Also, the viscosity of the oil samples, which were mixed with a hydrogen donor (decalin) and subjected to ultrasonic treatment under optimal conditions, was examined to evaluate the combined impact of ultrasonic radiation and hydrogen donor on the viscosity of crude oil. The viscosity experienced a decrease of 52.34% at 2 min of irradiation, 360 W ultrasonic power, 0.8 duty cycle, 35 ºC, and 8vol% decalin. To validate the outcomes of the experiments, asphaltene content, sulfur content, API gravity, and distillation tests were conducted on both the original and final samples (under optimal conditions). The concentrations of asphaltene and sulfur exhibited a drop of 37.51% and 35.04%, respectively. The results show that cavitation, a heat phenomenon, and the mechanical impact of ultrasound may help break up long carbon chains and reduce the size of asphaltene aggregates, which causes the crude oil's viscosity to drop. Moreover, the findings demonstrated that the simultaneous application of ultrasound and hydrogen donor yielded the most significant decrease in oil viscosity compared with untreated crude oil or treated just with ultrasonic waves.

Keywords: Decalin, Heavy crude oil, Hydrogen donor, Ultrasonic waves, Viscosity.

Introduction

Crude oil is a complicated combination of several hydrocarbons, non-hydrocarbon molecules, and other chemical components. Consequently, the chemical composition of oil exhibits qualitative and quantitative variations [1,2]. A diverse array of chemicals can be found in various oils, exhibiting a wide range of viscosities and densities, making the standard unit of gravity API an essential correlational component [3]. A significant proportion of heavy oil reservoirs were created from conventional oil that formed in deep geological formations and then migrated towards the surface. Upon reaching the surface, the oil underwent degradation processes facilitated by bacterial activity and weathering, resulting in the release of the lighter hydrocarbon components [4]. There is a growing focus on unconventional oil sources, namely heavy oil, and bitumen, as they constitute around 70% of global oil reserves and are gaining prominence due to the depletion of light oil supplies [5], as well as because crude oil is widely recognized as a significant revenue generator for numerous nations and serves as a fundamental resource for multiple industries [6].
Heavy oil is one of the crude oil kinds characterized by its elevated viscosity and inherent resistance to flow. The distinguishing characteristics of unconventional crude oil, in comparison to conventional oil, include elevated density, high carbon-to-hydrogen ratios, and heightened quantities of asphaltenes, heavy metals, nitrogen, and sulfur [7,8].

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Because of this, the processing of heavy crude oils downstream and in pipelines faces major challenges. As a result, it's essential to employ improved specifications before using them to get over these barriers [9-11]. One of the components of crude oil is asphaltene, which consists of polyaromatic nuclei surrounded by aliphatic side chains and rings. They exhibit insolubility in typical alkanes like n-pentane while demonstrating solubility in aromatic solvents [12-14], which may result in issues such as deposition processes, precipitation, and alterations in operational conditions which can have detrimental effects on the wettability and permeability of rocks, thereby impacting production [15,16].

There are several ways to increase fluidity, including heating, mixing high- and low-viscosity oils together and pumping the resulting mixture, mixing and pumping with water, and adding other chemicals, such as surfactants. These techniques are fairly expensive since they either utilize a lot of energy or a lot of different materials, which then require additional treatment of the oil [17]. One of the most safe, promising physical ways [18], and the best alternative methodologies for exerting influence on a fluid, whether under subsurface circumstances or at the surface, is ultrasonic treatment. Under the influence of ultrasound, oil viscosity might decrease due to a variety of factors. The medium's ultrasonic vibrations cause the temperature to rise as a result of energy loss. In addition, ultrasonic waves raise the ambient pressure, which raises the temperature as a result [19]. Ultrasonic waves are employed for the purpose of altering the composition of heavy oil, resulting in a permanent modification of its chemical structure. This process is undertaken with the objective of enhancing the rheological characteristics of the oil and expediting the reduction of its viscosity [20]. This method is considered the most efficient way from a technological, ecological, and economic standpoint to control the rheological characteristics of high-viscosity crude oils [21,22].

Yusof et al.[23] employed ultrasonic radiation technology in an attempt to reduce palm oil viscosity, a type of vegetable oil. They state that an ultrasonic power of 240 watts and a frequency of 40 kilohertz can decrease the viscosity of palm oil by 42.6%. Razavifar and Qajar[24] examined the impact of ultrasonic radiation on the heavy oil viscosity. The study revealed that the application of ultrasound waves led to a reduction in the viscosity of oil, the increasing of ultrasonic frequencies and/or output power resulted in a more significant decrease in viscosity, and the viscosity decreased by 40% at 46 kHz and 50 W for 40 minutes. Dengaev et al.[25] examine the effects of manageable ultrasonic waves, ranging from 20 to 60 kHz in frequency, on the viscosity of crude oil. The authors suggest that it is possible to permanently decrease the viscosity of viscous oils, with the highest reduction in viscosity being 73% at a frequency of 42.1 kHz and a sonication time of 3 minutes.

In the process of upgrading oil, H-donor solvents are preferred. Due to the hydrogenation of free radicals by the hydrogen released from the solvents, which stabilizes intermediate species during upgrading reactions, the upgraded oil's composition shifted in favor of lower molecular weight hydrocarbons [26]. Many attempts have used heavy oil with H-donors assisted by ultrasonic irradiation to enhance the overall quality of heavy oil, such as Qiao et al. [27] in their investigation on the impact of ultrasound waves with hydrogen donor on the characteristics of residual oil, they discovered that the inclusion of a hydrogen donors effectively inhibits the process of recombine of heavy radicals by supplying active hydrogen radicals. This results in a continuous increase in saturate contents beyond their initial levels throughout the entire treatment period, while the proportion of asphaltenes decreases. Gao et al. [28] examined the impacts of tetralin and ethylene glycol addition with ultrasonic irradiation on the lowering of heavy oil viscosity. The results showed that at 6 minutes of radiation time, 18 kHz, and 250 W, the reduction in viscosity reached about 80%. The chemical analysis was conducted using two analytical techniques, namely FTIR and GC, and showed that the oil samples' light components increased after being exposed to ultrasonic treatment. Razavifar et al.[29] conducted a study to examine the impact of ultrasonic waves and a specific solvent, n-heptane, on the viscosity of heavy oil. Their research showed that combining ultrasound and solvent resulted in the most significant reduction in oil viscosity compared to original crude oil, oil treated with either ultrasonic waves or solvent alone. Qajar et al.[30] investigate the combined impact of ultrasonic waves and solvents, specifically toluene (aromatic) and n-heptane (paraffinic), on the viscosity of heavy crude oil. The addition of toluene to the radiated crude oil under optimal conditions led to a substantial 68% decrease in viscosity. Table 1 provides a summary of the previous studies organized by the year in which each study was conducted.

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Table 1. Summary of studies of ultrasound effects on oil viscosity

Authors	Year	Type of oil	Additives	Ultrasound technology	Results	Ref.
Yusof et al.	2015	palm oil	-	Sonicator water bath	Reduction in viscosity by 42.6%	23
Razavifar and Qajar	2020	Crude oil	-	ultrasonic generator (bath-type)	Reduction in viscosity by 40%	24
Qiao et al.	2020	Residual oil	Decalin	Ultrasonic horn	Viscosity decreased by 20%	27
Gao et al.	2021	Heavy crude oil	Tetralin	Ultrasonic horn	The reduction in viscosity more than 80%	28
Razavifar et al.	2022	Crude oil	n-heptane	Ultrasonic horn	The application of ultrasound and solvent yielded the most significant decrease in oil viscosity	29
Dengaev et al.	2023	Heavy oil	-	Ultrasonic generator+ ultrasonic transducers	Reduction in viscosity by 73%	25
Qajar et al.	2023	Heavy crude oil	Toluene	Ultrasonic horn	Reduction in viscosity by 68%	30

Hydrogen donors primarily include polycyclic organic compounds that demonstrate reversible hydrogenation and dehydrogenation within the reaction medium. Through their dehydrogenation process, these entities possess the ability to effectively transfer hydrogen to the heavy oil, leading to the emission of a precise amount of hydrogen. Decalin is an appropriate hydrogen source since it has a high theoretical hydrogen capacity of (64.8 kg H_2/m^3) [31]. The research showed that adding decalin significantly increased the generation of C_4-C_{10} light components and made it easier to break C-S bonds in aliphatic substituents found in resins and asphaltenes [32]. The highly effective hydrogen donation capability of decalin enables it to provide hydrogen to resin and asphaltene [33]. The main objective of this study is to examine the impact of ultrasonic irradiation on the viscosity of Iraqi heavy crude oil with the assistance of H-donor (decalin). The analysis of asphaltene concentration, sulfur content, API gravity, and distillation tests was conducted to obtain comprehensive insights into the structural characteristics of heavy crude oil both at the beginning and after ultrasound treatment.

Materials and Methods

The oil sample utilized in this research was obtained from a heavy crude oil field in Iraq. Table 2 presents the characteristics of the heavy crude oil. The decalin compound, also known as decahydronaphthalene ($C_{10}H_{18}$), was obtained from Riedel-de Haen AG in Germany. The supplied decalin exhibited a high level of purity, specifically 99%. Additionally, it possessed a density of 0.896 g/ml at 25 ºC and a boiling point range of 189-191 ºC.

Table 2. Heavy crude oil's characteristics.

Property	Value
API˚Gravity at 15.6 ºC	20.32
Density at 15.6 ºC	0.932 g/cm^3
Dynamic Viscosity at 40 ºC	42.6 mpa.s
Dynamic Viscosity at 25 ºC	81.2 mpa.s
Asphaltene content , wt%	6.379
Sulfur content , wt%	4.68

Instruments

The experimental setup involved the utilization of an ultrasonic device, specifically the (1200 UPS model, FAPAN, Iran). This device operated at a consistent frequency of 25 kHz and had a power range of 0–1200 W. Additionally, a probe with a diameter of 20 millimeters and a height of 7 centimeters was employed in the experiment. The volume of decalin was determined using a volumetric cylinder and a dropping pipette. The oil samples were kept at a consistent temperature using a water bath. A thermocouple is employed to measure the temperature of a sample of crude oil. The viscosity of oil samples was determined by a DV-II+ Pro viscometer, a device manufactured by the Brookfield Company, USA. The measurements were conducted before and after subjecting the samples to ultrasonic

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irradiation, following the ASTM D2196 test technique. The determination of asphaltene content in crude oil was conducted using the Full Automatic Asphaltene Analyzer (APD-600A, Cosmo Trade & Service Co., Ltd., Japan) following the test technique outlined in IP-143. The Sulfur Analyzer (model Sindie OTG, XOS, USA) was employed to quantify the sulfur in crude oil following the ASTM D7039 test procedure. The specific gravity of oil samples was determined by a 50-ml glass pycnometer using the ASTM D1217 standard test technique. A distillation apparatus (model K45200, Koehler Co., USA) was employed in the process of distilling heavy crude oil to determine the volume percentage at various temperature ranges, following the guidelines outlined in ASTM D86.

Experimental procedure

A 250 mL sample of crude oil was collected and then transferred into a container. Subsequently, the ultrasonic probe was positioned precisely at the center of the container, at a depth approximately equal to half of the oil sample's total volume. To regulate the temperature during ultrasonic treatment, a water bath was used to place a container containing an oil sample. The temperature was measured during the treatment process using a temperature-measuring probe. To reduce the loss of the lighter molecules, a rubber stopper was used. The experimental design is depicted in Fig. 1. Different ultrasonic powers and time intervals were applied to expose crude oil to ultrasonic waves at 25 ºC and a 0.6 duty cycle, which is the ratio of the pulse duration period to the cycle time, it can be determined by dividing the pulse duration period by the sum of the pulse duration and pulse interval periods. After that, the samples were exposed to a 0.2, 0.4, 0.6, and 0.8 duty cycle, and temperatures of 25, 35, 45, and 55 ºC. Next, the heavy crude oil with different concentrations of decalin 2, 4, 6, and 8 vol% was irradiated at optimum conditions. Subsequently, the sample was placed in a hermetically sealed receptacle and allowed to reach equilibrium with the surrounding environment, so facilitating the condensation and reformation of any volatile substances into a liquid state. Finally, the viscosity was measured after cooling down the crude oil. In addition, asphaltene content, sulfur content, API gravity, and distillation tests were determined.

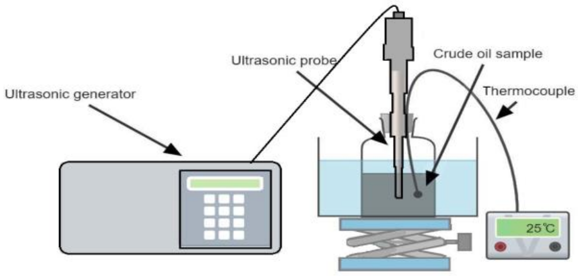

Figure 1. A schematic view of the experimental configuration.

Results and Discussion

Effect of ultrasonic irradiation time

The study investigated the impact of varying ultrasonic powers and irradiation times on Iraqi heavy crude oil viscosity. The experiments were conducted at a duty cycle of 0.6 and a temperature of 25 °C. Fig. 2a shows the effect of irradiation time on gradually decreasing the viscosity of heavy crude oil at a power of 120 W, reaching its maximum reduction at the 8th minute, where it decreased from 81.2 mpa.s to 76.9 mpa.s. Fig. 2b reveals that increasing the exposure time to 5 minutes at 240 W has a positive effect on improving the reduction of viscosity, which reaches its lowest value (75.4 mpa.s). It is clear in Fig. 2c that the high efficiency of the viscosity reduction process when the sonication time was 2 minutes at 360 W, exhibits a reduction from 81.2 mpa.s to 69.6 mpa.s. Fig. 2d shows that the viscosity decreased to 73.7 mpa.s at 1 minute of irradiation time for a power of 480 W. This reduction is because ultrasound waves can break up asphaltene flocculates, which makes heavy crude oil less viscous. Before the optimal irradiation period, the main process that happens is the breaking up of asphaltene clusters within the oil. This results in a reduction in the size of asphaltene particles and subsequently leads to a drop in the viscosity of the oil [34]. It was observed that after the best time (at which the maximum reduction in viscosity was obtained), the viscosity increased because an accumulation of free radicals occurred due to bond breakage. This accumulation leads to the reformation of damaged structures and the production of heavy compounds with increased branching [35].

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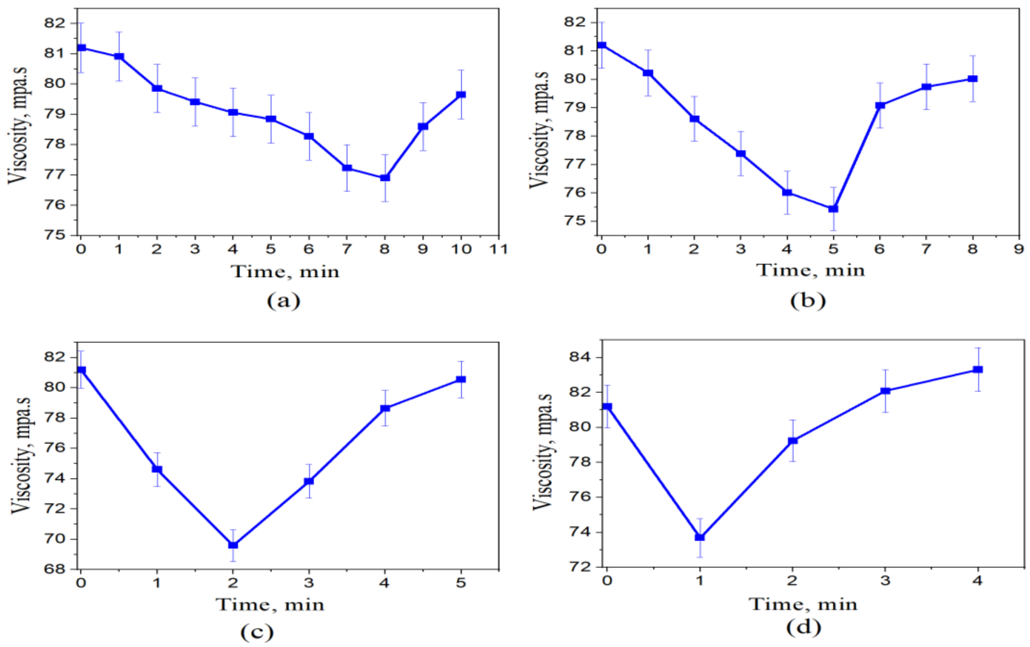

Figure 2. Effect of ultrasonic irradiation time on the viscosity of heavy crude oil at (a) 120 W, (b) 240 W, (c) 360 W, and (d) 480 W ultrasonic power, 0.6 duty cycle, and 25 °C.

Effect of ultrasonic power

Fig. 3 illustrates the influence of ultrasonic power at 2 minutes of irradiation at 0.6 duty cycle and 25 °C on the viscosity of crude oil. This figure shows the impact of ultrasonic treatment on enhancing the reduction of viscosity, with the maximum effect observed at a power of 360 W. The results indicated that as ultrasonic power increased, the heavy oil samples' viscosity decreased significantly. This phenomenon can be attributed to the reality that the cavitation phenomena become more intense and that high energy is transferred to the sample with higher ultrasonic powers. However, after 360 W, cavitation and the boiling effect may raise the viscosity of oil samples because the volatile constituents of crude oil can undergo evaporation [36].

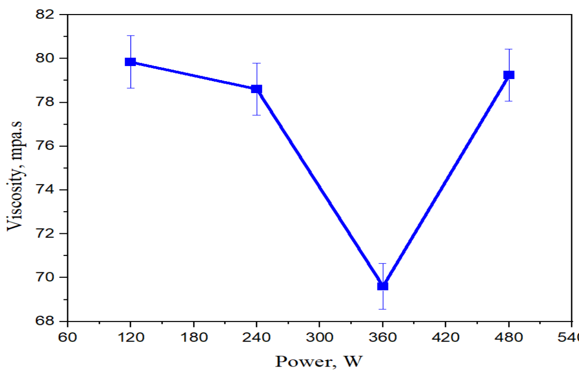

Figure 3. Effect of ultrasonic power on the viscosity of heavy crude oil at 2 min of irradiation, 0.6 duty cycle and 25 °C.

Effect of duty cycle

To study the impact of the duty cycle on crude oil viscosity, samples were exposed to ultrasonic waves at 0.2, 0.4, 0.6, and 0.8 duty cycles at 2 min, 360 W, and 25 °C. Fig. 4 shows that as the duty cycle increased, the viscosity of the heavy crude oil decreased. This reduction is because increasing the pulse duty cycle can make the ultrasonic wave impact stronger and promote the generation of bubbles. The viscosity reached 68.7 mpa.s at 0.8 duty cycle. Operating in continuous mode wastes energy and can result in issues such as tip erosion; for this reason, pulse mode was chosen [37].

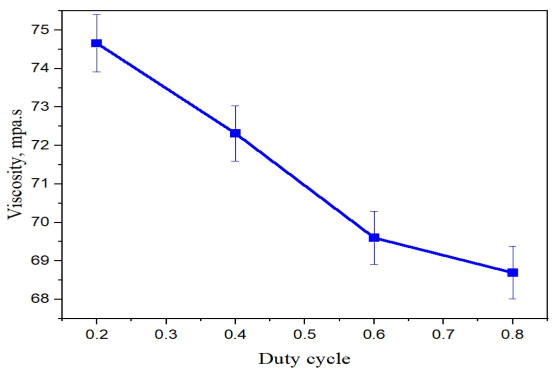

Figure 4. Effect of duty cycle on the viscosity of heavy crude oil at 2 min of ultrasonic irradiation, 360 W ultrasonic power, and 25 °C.

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Effect of temperature

Fig. 5 illustrates the impact of temperature on the viscosity of crude oil at 2 minutes of irradiation, a power of 360 W, and a duty cycle of 0.8. It was concluded that the increase in temperature has a positive effect on the viscosity reduction process. The viscosity decreased to 64.3 mPa·s when the temperature was raised to 35°C. The decrease in viscosity can be attributed to the generation of ultrasonic energy, resulting in elevated temperatures and the formation of cavitation bubbles. Additionally, it leads to the breakdown of complex hydrocarbons, such as asphaltenes, into smaller molecules and free radicals [38]. Furthermore, the viscosity increased at temperatures higher than 35°C; this phenomenon could perhaps be ascribed to the heat-induced boiling effect and the occurrence of cavitation, which facilitates the evaporation of lighter constituents. Consequently, an increase in steam pressure occurs, which can reduce the cavitation threshold of the oil [39].

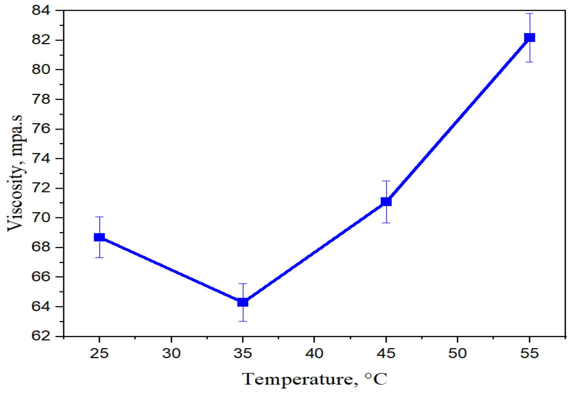

Figure 5. Effect of different temperatures on the viscosity of heavy crude oil at 2 min of ultrasonic irradiation, power of 360 W, and 0.8 duty cycle.

Effect of decalin concentration

This section presents an investigation of the impact of ultrasound waves with varying decalin concentrations (2%, 4%, 6%, and 8% by volume) on the viscosity of crude oil. The samples experienced ultrasound irradiation for 2 minutes at a power of 360 W, a duty cycle of 0.8, and a temperature of 35 °C. The results are depicted in Fig. 6. It can be observed that there is a decrease in oil viscosity as the dosage of decalin increases. The viscosity of the crude oil decreased to 38.7 mpa.s when the concentration of decalin reached 8 volume percent. When comparing the reduction of viscosity by the use of ultrasound alone, adding a hydrogen donor led to increased effectiveness and enhanced outcomes. The decrease in viscosity can be attributed to the presence of H-donor and the capacity of hydrogen atoms to move to the heavy hydrocarbon inside the oil and arrest the polymerization process of the heavy oil molecules through free radicals, thereby improving the overall quality of the crude oil [40].

Hydrogen donors can inhibit the recombination of heavy radicals and supply reactive hydrogen to minimize an increase in large-sized molecules in heavy oil, facilitate the hydrogenation reaction, stop the condensation reaction, and enhance the efficiency of heavy oil upgrading. The active hydrogen free radical, generated through the phenomenon of cavitation, can bind with the macromolecular free radical, eliminating its reactivity, this results in a decrease in asphaltene concentration [41].

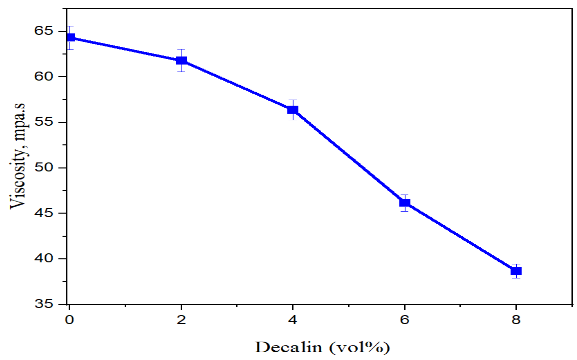

Figure 6. Effect of different concentrations of decalin on the viscosity of heavy crude oil at optimum conditions (2 min of ultrasonic irradiation, 360 W ultrasonic power, 0.8 duty cycle, and 35 ºC).

Asphaltene and sulfur content reduction

As shown in Fig. 7, the crude oil's asphaltene concentration is reduced from 6.379% to 5.227% after ultrasonic treatment. This reduction can be attributed to the deterioration of the structure of the asphaltenes and the disintegration of alkyl side chains and their subsequent fragmentation into lighter constituents [42]. After the addition of decalin, the asphaltene content decreased to 3.986% because hydrogen donors can prevent heavy radicals from recombining, which decreases the amount of asphaltene and the relative molecular mass [27].

The measurement of sulfur content in crude oil was also conducted. According to Fig. 8, it is clear that the use of ultrasonic treatment resulted in a noticeable reduction in the sulfur content of the heavy oil, decreasing from 4.68% to 4.30%. The

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reason for this phenomenon might be attributed to the ability of the cavitation process to break C-S, C-C, C-O, and C-N bonds in heavy oil, as a result of the significant rise in local temperature caused by the collapsing bubbles [43]. On the other hand, with the addition of 8 vol% of decalin with the ultrasonic treatment, the sulfur content was reduced to 3.04% because it will disintegrate into hydrogen and/or light R-radicals. The hydrogen atoms, also known as light radicals, have the potential to get into collisions with the heavier R-radicals present in the heavy oil molecules, limiting the progress of polymerization reactions. Moreover, the breakdown of C-S or C-O bonds facilitates the release of H_2S and H_2O gas molecules from the cavitation chamber, therefore diminishing the sulfur concentration [44].

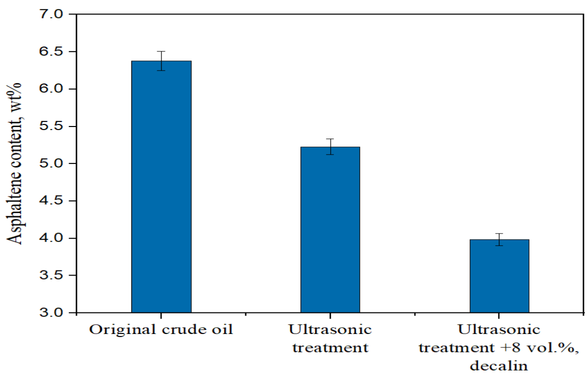

Figure 7. The asphaltene content in crude oil both before and after the ultrasonic treatment with and without H-donor addition.

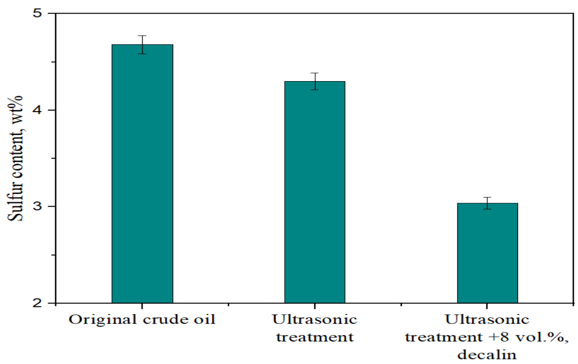

Figure 8. The sulfur content in crude oil both before and after ultrasonic treatment with and without H-donor addition.

API Gravity index and distillation test

Fig. 9 shows the effect of ultrasonic treatment with the addition of decalin on increasing the API gravity of crude oil. The API index of original heavy crude oil was 20.32, which reached 23.56 after ultrasonic irradiation under optimum conditions with the addition of 8 vol.% decalin. The findings from Fig. 10, which represents the distillation curves of a non-irradiated sample and an irradiated sample combined with a hydrogen donor under the best conditions, indicate that only 68% of the original oil sample was distilled and 32% retained within the laboratory cell, while 77% of the irradiation sample was distilled and 23% of it was left as a residue. The results of this test likewise showed a 5 and 11-degree Celsius decrease in the initial boiling point (IBP) and final boiling point (FBP), respectively. The breaking of hydrocarbon bonds by ultrasonic treatment can explain why the API gravity and percentage of distillate went up and the IBP and FBP went down. This also refers to how ultrasound waves and H-donor work together to lower the amount of asphaltene in crude oil and make heavy crude oil hydrocarbons lighter [27].

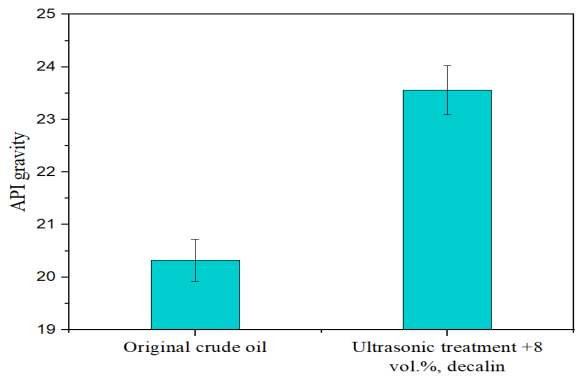

Figure 9. API gravity of the initial crude oil and the crude oil subjected to irradiation under optimal conditions with the addition of a hydrogen donor.

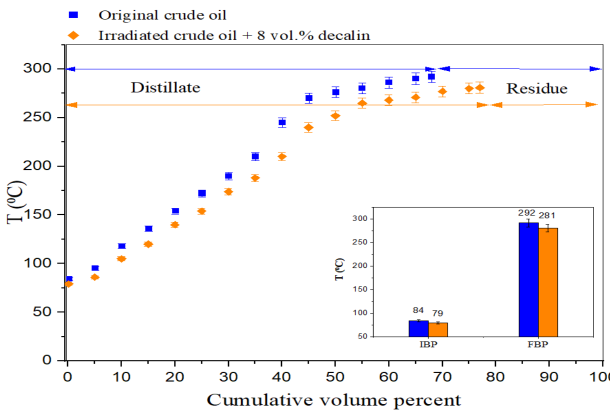

Figure 10. Distillation curve of the initial crude oil and the crude oil subjected to irradiation under optimal conditions with the addition of 8 vol.% decalin.

Conclusion

The present study examined the effect of ultrasonic radiation technology on the viscosity of Iraqi heavy crude oil, and it looked at how ultrasonic technology and a hydrogen donor (decalin) worked together to reduce the viscosity of crude oil (20.32 °API). For the crude oil used in this study, ultrasonic irradiation with a frequency of 25 kHz, an output power of 360 W, a duty cycle of 0.8, a temperature of 35 °C, and a decalin concentration of 8 vol% for 2 min reduced the viscosity of the oil up to 52.34%. Our viscosity studies demonstrated that using a hydrogen donor had a better impact on decreasing viscosity compared to ultrasonication alone. The generation of ultrasonic energy, which reduces the size and structure of asphaltene flocs in crude oil, may account for a decrease in crude oil viscosity. The viscosity rose when ultrasound treatment continued after the optimum time; this phenomenon could be attributed to the re-association of dense oil molecules. Additionally, the viscosity increased at a power higher than the optimum power and elevated temperatures because of the evaporation of volatile components of crude oil due to cavitation and the boiling effect. The results of the experiments also suggest that ultrasonic waves and hydrogen donors work together to reduce the viscosity, asphaltene content, and sulfur content of crude oil. The results of this study suggest using nanoparticles or a combination of nanoparticles and hydrogen donors to assist ultrasonic technology in the process of reducing the viscosity of heavy crude oil.

Acknowledgment

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Authors' Declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images, that are not ours, have been included with the necessary permission for re-publication, which is attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- No potentially identified images or data are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at University of Baghdad.

Authors' Contribution Statement

A.W.A. designed the study, performed the experiments, acquired data, analyzed it, and drafted the MS. H.Q.H. Conception, supervised the findings of this work, revised it, and proofread it.

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آثار المعالجة بالموجات فوق الصوتية وإضافة المادة المانحة للهيدروجين على لزوجة النفط الخام العراقي الثقيل

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الخلاصة

يختبر البحث الحالي التأثيرات المشتركة للإشعاع بالموجات فوق الصوتية والمادة المانحة للهيدروجين على لزوجة النفط الخام الثقيل. تمت دراسة تأثير زمن التعرض للموجات فوق الصوتية والطاقة ودورة التشغيل ودرجة الحرارة على لزوجة النفط الخام العراقي الثقيل الذي يملك قيمة API = 20.32. كما تم فحص لزوجة عينات النفط الخام التي تم خلطها بمانح الهيدروجين (Decalin) وإخضاعها للمعالجة بالموجات فوق الصوتية في ظل الظروف المثالية، لتقييم التأثير المشترك للإشعاع بالموجات فوق الصوتية والمانح للهيدروجين على لزوجة النفط الخام. شهدت اللزوجة انخفاضًا بنسبة 52.34% بعد دقيقتين من التعرض للموجات فوق الصوتية، عند طاقة 360 W ، دورة تشغيل 0.8، 35 درجة مئوية، وأضافه 8% نسبة حجمية من Decalin. للتحقق من صحة نتائج التجارب، تم إجراء فحص محتوى الأسفلتين، محتوى الكبريت، API، واختبار التقطير على كل من العينة الاولية و النهائية (في ظل الظروف المثلى). وأظهرت تراكيز الأسفلتين والكبريت انخفاضا قدره 37.51% و35.04% على التوالي. تشير النتائج إلى أن ظاهرة التجويف وظاهرة الحرارة والتأثير الميكانيكي للموجات فوق الصوتية قد تساهم في تكسير سلاسل الكربون الممتدة وتقليل حجم الإسفلتين المتجمع مما يؤدي إلى انخفاض لزوجة النفط الخام. علاوة على ذلك، أظهرت النتائج أن التطبيق المتزامن للموجات فوق الصوتية والمادة المانحة للهيدروجين أدى إلى انخفاض كبير في لزوجة النفط الخام عند مقارنته بالنفط الخام غير المعالج أو المعالج بالموجات فوق الصوتية فقط.

الكلمات المفتاحية: ديكالين, النفط الخام الثقيل, المادة المانحة للهيدروجين, الموجات فوق الصوتية, اللزوجة.