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Research Article

Utilization of high- frequency ultrasonic waves for the demulsification of water/oil emulsions

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Abstract

A significant issue in the petroleum business is the presence of intricate emulsions, with the primary difficulty being the development of an effective separation approach for complex water-in-oil (W/O) emulsions. The development of a rigid layer at the water-oil interface is the source of W/O emulsion stability. This study examined the separation of water-in-oil emulsions by ultrasonic-assisted demulsification. We employed an ultrasonic water bath apparatus operating at a frequency of 40 kHz with a power output of 180 W. The emulsion was formulated using 45% water and 55% heavy fuel oil by volume. To improve separation performance, silica particles measuring less than 53 µm were employed at a concentration of 1000 ppm. We conducted the ultrasonic treatment for 10 minutes at a temperature of 70°C. The results showed that this method achieved a separation efficiency of 78%, emphasizing the important role of ultrasonic energy and silica nanoparticles in breaking up emulsions and speeding up the merging of water droplets. The results showed that the ultrasonic technique is a promising eco-friendly technology, suggesting it could be a practical and environmentally safe way to separate oil and water. Furthermore, the results showed that a chemical-derived emulsification breaker (silica particle) outperformed a commercial emulsification breaker (RQ35) in terms of separation efficiency.

1. Introduction

A primary problem in heavy oil production is the separation of water-in-oil (W/O) emulsions. Emulsified water not only heightens the vulnerability of pipelines and equipment to corrosion [1], but also augments the viscosity of heavy oil, leading to energy loss during transit. Demulsification can be accomplished by many combinations of physical, chemical, or biological processes, as is widely recognized [2]. The heavy oil industry actively utilizes processes such as demulsifier application and electrostatic treatment. An effective demulsifier is frequently utilized to enhance the demulsification process. The primary objective of the chemical additives is to destabilize the emulsifying agents [3]. Tight emulsions may form when water and heavy fuel oil depart an oil well's wellbore due to turbulence in the choke valve at the wellhead. The creation of emulsions during heavy fuel oil production is a costly operational challenge [4]. This occurs when formation water and hydrocarbons are vigorously mixed with surfactants and subjected to shear or turbulence inside the reservoir and production pipelines [5].

The water-to-oil ratio, the oil's intrinsic emulsifier systems, and the source of the emulsion dictate the continuous phases of these mixes. The emulsifiers possess a complex chemical composition and exhibit variability in size and form [6]. The necessity for creative and effective demulsification procedures persists as new oil resources are uncovered and production conditions in older fields evolve. The emulsion must be separated to meet the quality criteria for heavy fuel oil regarding

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residual salt and water content before the oil is approved for transportation. Water content must be under 1% [7]. Figure 1 illustrates the overarching issue framework and the sequential stages of the demulsification process (8).

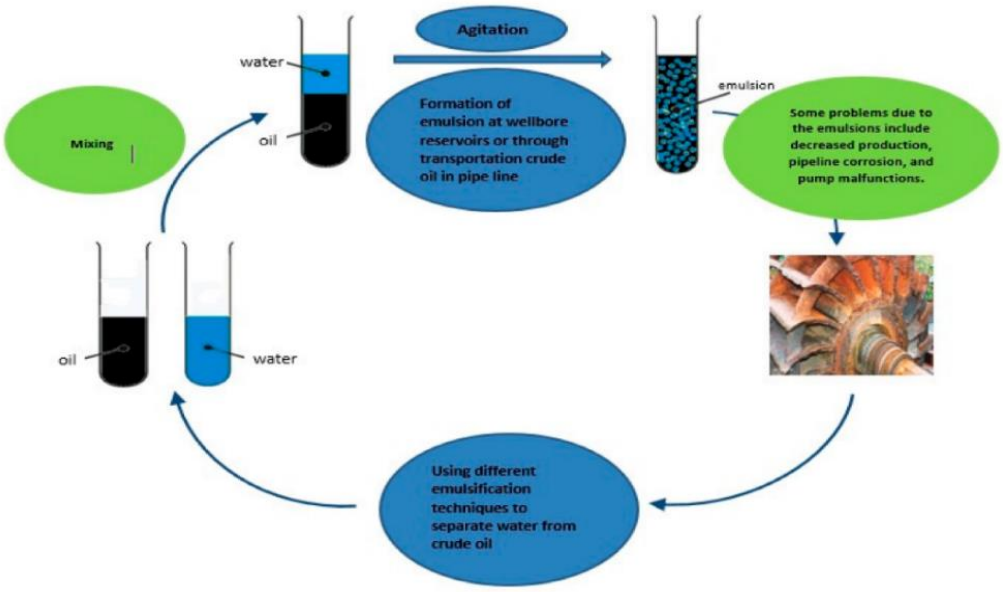

Fig. 1. The general sketch of the problem [8]

The ultrasonic method for demulsifying heavy fuel emulsions relies on condensation and ultrasound's viscosity decrease. Ultrasound causes water droplets to cluster inside heavy fuel oil, separating oil-water phases [9]. Ultrasonic demulsification of heavy fuel oil emulsions is popular due to its simplicity and effectiveness [10]. During ultrasound demulsification, acoustophoresis affects scattered droplets in a standing wave field. The acoustic standing wave can cohesively combine evenly suspended droplets due to density and compressibility differences between the dispersed and continuous phases [11]. Many investigations have shown that ultrasonic energy can demulsify heavy fuel oil emulsions. Temperature, injected water, radiation duration, and radiation energy absorption affect demulsification effectiveness. Ultrasound breaks apart large molecules in oil emulsions, separating oil from water [12]. Sound waves cause minute bubbles in liquid to expand and burst, creating pressures and currents [13]. Some study has promoted ultrasonic technology as a novel and effective way to separate heavy oil from water without demulsifiers [8].

Previous studies have focused primarily on the use of industrial chemicals (demulsifiers) or ultrasound alone, and have often been used on light or medium-grade crude oils. Where it was not used very heavy oil (high viscosity HFO), which contains high levels of asphaltenes and resins. Also, do not use of local natural materials (green demulsifiers) as an environmentally friendly and inexpensive alternative. Inaddition, combining practical analysis with advanced analyses such as FTIR, SEM, XRD, and contact angle to explain the separation mechanism.

Feitosa et al. [14] developed novel cardanol compounds using ethoxylation, formaldehyde polycondensation, hydrogenation, and ethoxylation of formaldehyde polycondensation to test their demulsifier properties. FTIR and ^{1}H NMR measurements were used to describe the additions. Three Brazilian crude oils with 30% brine mixtures and 60 and 240 g/L NaCl salt levels were examined for their capacity to break down emulsions at pH levels 3–10 while agitated at 3200 rpm. We found that ethoxylated compounds need greater demulsification at neutral pH. Saat et al. [15] investigated using coconut oil and its byproducts, notably coconut betaine, to extract water from crude oil mixtures in an environmentally beneficial manner. Each impact research found coconut betaine to be better than coconut oil. At 70 °C, 3 mL coconut betaine in 10 mL crude oil separated 35% water without xylene. Hassan et al. [16] evaluated silica nanoparticles' scientific and commercial benefits for crude oil demulsification. The Balila Central Processing Facility (CPF) in Sudan processes Fula heavy crude oil using an MS Excel model. The primary production cost and net present value (NPV) aspects were sensitivity assessed for numerous flow scheduling options.

Production costs reduce 19% when comparing flow tables with the same plant capacity, but only 3.7% when comparing constant annual crude oil processing. Ye et al. [17] recovered crude oil emulsions using lotus leaves and a simple hydrothermal technique. Their unique wettability and surface shape allow HLLF powder to quickly disrupt W/O emulsions. The DE achieved 88.17% with 1000 mg/L HLLF and 90 minutes at 70°C settling. HLLF's demulsification effectiveness was comparable to numerous commercial demulsifiers. It also demulsified two crude oil emulsions from different oilfields. Azubike et al. [18] evaluated tobacco seed oil, leaf extract, and stem ash demulsifiers on crude oil emulsions. Nicotiana tabacum seed oil, leaf extracts, and stalk ash extract attract and repel water. Formulated demulsifiers are comparable to commercial ones. Bottle testing indicated the demulsifier may destabilize medium- and high-density crude oil emulsions. The novel demulsifier performed like commercial ones.

Chen et al. [19] examined how sound strength, temperature, ultrasound exposure period, and chemical dispersant effect ultrasound water removal from crude oil. Ultrasound was optimal for removing salt from crude oil at 300 W, 90°C, 75 minutes, and 54 mg/L chemical demulsifier. Temperature was the most critical factor, followed by acoustic power, ultrasonic exposure time, and chemical demulsifiers. In a system with 500 mg/L crude oil. Parvasi et al. [10] showed how low-frequency ultrasonography influences oil-water separation. They then conducted studies in a laboratory ultrasonic bath at 25 and 45 kHz without chemical demulsifiers. Experiment with wastewater temperature, ultrasonic power, frequency, and irradiation period on separation efficiency. Under optimal conditions, crude oil emulsion separation efficiency increased 72%. Romanova et al. [20] shown that ultrasonic treatment plus a little additive may break apart stable water-in-oil (W/O) emulsions that are 30 to 45 μm in size and may include "gel." A nano powder AlN suspension in acetone and 1.0 kW ultrasonic treatment eliminated over 99% of the emulsions tested. Depending on the emulsion's composition and qualities, the additive concentration ranged from 4 to 8% vol and the exposure period from 0.5 to 3 minutes. The oil phase may reach 0.5 weight percent water content, whereas the aqueous phase can reach 46 mg L−1 oil concentration using the demulsification technique.

Okereke et al. [21] aims to develop and formulate a cost-effective, environmentally friendly demulsifier utilizing locally sourced raw materials. They conducted an experimental investigation to evaluate its effectiveness in dissolving the crude oil emulsion. The components employed included castor oil, distilled water, starch, camphor, alum, and locally sourced liquid soap. We used a crude oil emulsion sample from a Niger Delta field to evaluate two distinct demulsifier formulations, which we then heated to 60°F. The procedure resulted in the successful use of a demulsifier to segregate water from oil. Abdullah et al. [22] worked on creating two new ionic liquids (ILs) from oleic acid (OA), which is a natural and easy-to-find material, and used them to break down water-in-oil (W/O) emulsions. EAPA-IL and EATA-IL exhibited commendable performance, achieving 100% efficacy at varying doses of demulsifier. The statistics indicated that their performance enhanced with time as their concentration intensified. Furthermore, EAPA-IL and EATA-IL isolated potable water. Gao et al. [23] found reported that they use microscopes, particle size measurements, component analysis, and other methods to understand tiny surface details and how transformer water content changes with different forces during ultrasonic treatment of old oil. The results show that ultrasonic cavitation demulsifies and dehydrates oil samples to 98.24%. As power increases, dehydration follows a "M-type" pattern. Particle size and microscopic investigations show that ultrasonic irradiation disturbs the oil-water interfacial barrier, causing droplets of various sizes to collide, agglomerate, and silt.

Although several studies—such as [21] who employed ultrasonic treatment with nano powder additives, and [23] who investigated ultrasonic demulsification mechanisms in aged oils—have demonstrated the potential of acoustic energy in breaking water-in-oil emulsions, important gaps remain. Most previous works focused on medium-grade or aged crude oils, relied heavily on commercial chemical additives, or required high-energy ultrasonic systems that limit industrial applicability. Moreover, the use of locally sourced, low-cost materials has received little attention, and few studies have systematically examined the combined influence of ultrasonication conditions and particle dosage on demulsification efficiency in very heavy fuel oils with high asphaltene content. In contrast, the present study addresses these gaps by integrating low-frequency

ultrasonication with inexpensive local silica particles and evaluating their combined impact under optimized operational conditions. This approach offers a practical, cost-effective, and environmentally aligned alternative to conventional chemical demulsifiers, advancing the current understanding of scalable demulsification strategies.

2. Heavy Fuel Oils

Heavy fuel oil (HFO) has tar-like viscosity. Bunker fuel or residual fuel oil is a petroleum distillation and cracking byproduct [16]. Thus, HFO is more likely than other fuel oils to include sulfur, nitrogen, and aromatics, which increase combustion emissions [24]. HFO is cheaper than distillates and is used to power marine diesel engines. HFO use and shipment on ships can cause oil spills and discharge harmful compounds and particles such black carbon [25]. HFO comes from petroleum residuals after thermal and catalytic cracking of higher-quality hydrocarbons. Because HFO is often blended with cleaner fuels, its chemical composition might change; carbon levels in blending streams can range from C20 to above C50 [11]. Combined HFOs give specific viscosity and flow for an application. Due to its diversity, HFO has unique physical, processing, and end-use properties. HFO, the final product of cracking, contains paraffins, cycloparaffins, aromatics, olefins, asphaltenes, and molecules containing sulfur, oxygen, nitrogen, and organometals. The ISO 8217 maximum density for HFO is 1010 kg/m3 at 15°C and its viscosity is 700 mm^2/s (cSt) at 50°C[26].

3. Methodology

3.1 Water with Ultrasonic Waves

Ultrasonic baths were designed for cleaning, but sono-chemical research uses them since they are cheap and readily available. The bath coupling fluid is usually submerged in the response vessel, which transports ultrasonic waves. Maintaining isothermal conditions is problematic since the sample's bath placement affects power to the reaction mixture [24]. A Chinese ultrasonic generator, MH-031S was utilized in the experiments. This system is similar to ultrasonic baths, except it includes a metal cover above the transducer at the bottom. Table 1 shows ultrasonic specifications apparatus [27].

Table 1. Specifications of ultrasound cleaner

Device: Ultrasound cleaner	Specifications
Rated Voltage	200-240/50 HZ
power	180 W
Heating power	300 W
Frequency	40 KHZ
Set Time	0-30 min
Set Temperature	

3.2 Magnetic Stirrer

Mixing heavy fuel oil with water and sodium chloride solution using a magnetic stirrer (Model 78-1, JY, Changzhou, China) creates industrial emulsions. A revolving magnetic field causes a stirring rod (or "flea") submerged in a liquid to revolve rapidly, swirling it. A rotating field can be created by stationary electromagnets or a revolving magnet beneath the liquid-filled vessel. Glass containers (beakers or laboratory flasks) are used for most chemical processes, yet glass is transparent to magnetism, therefore magnetic stirring rods work well in them [28]. Separation procedure is shown in Figure 2, and magnetic stirrer device characteristics are stated in Table 2.

Fig. 2. Separation process water/Oil

Table 2. Specifications of 78-1 Magnetic Stirrer

Device: 78-1 Magnetic Stirrer	Specifications
Power Supply	AC 220V/110V 50Hz/60Hz
Speed	0-2400rpm
Motor powers	25W
Heating power	200W
Temperature control range	Room temperature to 100 Celsius
Timer	0-120min
Two-way rotation	yes

3.3 Preparation and Characterization of W/O Emulsions

The Al-Doura refinery in Baghdad, Iraq, supplied Basra Heavy fuel oil, which was used to make water-in-oil emulsions. Table 3 displays this oil's physical characteristics. Heavy fuel oil (55 ml0 with an API density of 15.8 and a water content of 45 ml was used to create water-in-oil emulsions. The heavy fuel oil sample utilized for emulsion preparation had an API density of 15.8 and a kinematic viscosity of 183 mm^2/s at 45 °C. The heavy fuel oil was mixed with a specified volume of 5500 ppm sodium chloride solution in order to prepare the emulsions. At 45 °C, the mixture was agitated using a magnetic stirrer to add water to the oil phase [29]. Various emulsion qualities were prepared: i) 40% water plus 60% heavy fuel oil, and ii) 30% water plus 70% heavy fuel oil.

Table 3: Physical properties of the Basra Heavy oil (Al-Doura refinery)

Heavy fuel oil properties	
sp. gr at 15.6 ºC	0.8724
API at 15.6 ºC	15.8
Density at 15 ºC (g/cm^3)	0.9657
Kinematc Viscosity at 50ºC cst (mm^2/s).	183
Pour point ºC	+3
Carbon residue %w/w	8.1
Sulfur content %w/w	4.5
Water & sediment %v/v	<0.025
Asphaltenes content (wt %)	3.09%
Calorific Value (gross) Keal/kg	10441

For better clarity of the experimental workflow, a schematic diagram illustrating the main stages of emulsion preparation, ultrasonic treatment, and phase separation has been added (Figure 3). The diagram includes the magnetic stirring stage for emulsion formation, silica particle addition, ultrasonic bath treatment, and final gravitational separation. Additionally, all experimental setup

figures (magnetic stirrer and ultrasonic bath) have been improved with clear labeling of key components to enhance readability.

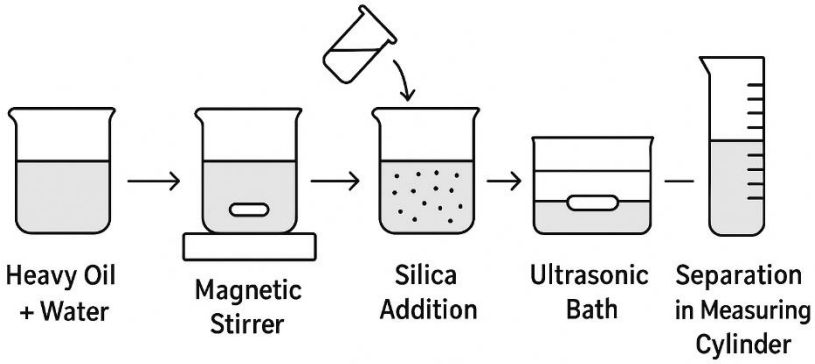

Fig. 3. Emulsion preparation and separation stages

From an economic and environmental viewpoint, silica particles represent a low-cost, widely available, and non-toxic alternative to conventional chemical demulsifiers, reducing both operating cost and secondary pollution risks. In terms of scalability, the combined silica–ultrasound system can be easily integrated into existing refinery separation units with minimal modifications. Moreover, silica can be recovered and potentially reused, enhancing process sustainability and overall cost efficiency. Therefore, this approach offers a practical green demulsification technology that balances efficiency, scalability, and environmental safety.

4. Ultrasonic De-emulsion Experiments

During every experiment involving ultrasonic baths, 100 milliliters of water/oil emulsion were moved into a Becker glass vessel. The vessel was then placed within the ultrasonic bath for 10 minutes at a frequency of 40 kHz, depending on the mode that produced the highest demulsification efficiency. A mixture of 45% water and 55% heavy fuel oil was used in the experiments to test the impact of various frequencies on the emulsion's ability to be removed using ultrasonic baths. The ultrasonic baths were kept at 35°C in temperature. Before each experiment, the vessels containing the oil/water emulsion were kept for 24 h before inserting them into the ultrasonic bath device to maintain the stability of the emulsion. After exposure to ultrasound in the water bath, the conical glass vessels were removed from the ultrasonic baths and emptied into measuring cylinders and left for five minutes after which the reading was taken. The demulsification efficiency (ED) was determined for all experiments in which the water-emulsion separation was visually observed by taking into account the initial water content in the emulsion prior to ultrasound (IWC) and the final water content obtained following ultrasound exposure (FWC), as stated in the following equation (11):

$$ED\% = \frac{I_{WC} - F_{WC}}{I_{WC}} \times 100 \quad (1)$$

Where; I_{WC}: The initial water content in the emulsion before ultrasound, F_{WC}: The final water content obtained after ultrasound exposure.

Cannon-Fenske-Routine Viscometer (ν) was used to determine the kinematic viscosity of heavy oil. The relationship applied to calculate the kinematic viscosity is (30):

$$\nu = K \times t \quad (2)$$

The instrument constant k refers to the timing marks during the visual survey of the meniscus passage. It comes to: k=0.02688 mm^2/S^2.

5. Result and Discussion

5.1 Relationship Between Water Concentration and Silica Addition Ratio At 10 Minutes

Effect of time and temperature on separation efficiency will be considered in the following subsections. Also, 15 experiments were used to determine the separation efficiency of this material.

5.1.1 Separation Efficiency for The Four Days

When testing sample shown in Figure 4 and placing it in the ultrasonic device for 10 minutes before adding any material, the separation ratio was 32% on the first day, and when leaving it for the second day, the separation ratio increased to 34%. While when adding 5000 ppm of silica, that notice a slight increase in the separation ratio, which became 36% on the first day, while on the second day it was 41% as shown in Figure 5.

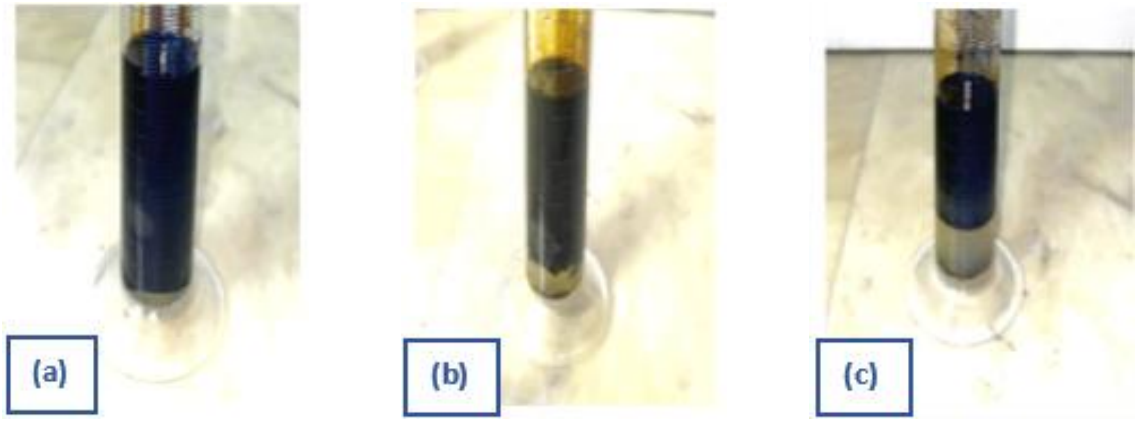

Fig. 4. Samples of the Separation: a) Before any addition, b) 5000 ppm of silica, and c)10000 ppm of silica at 10 min.

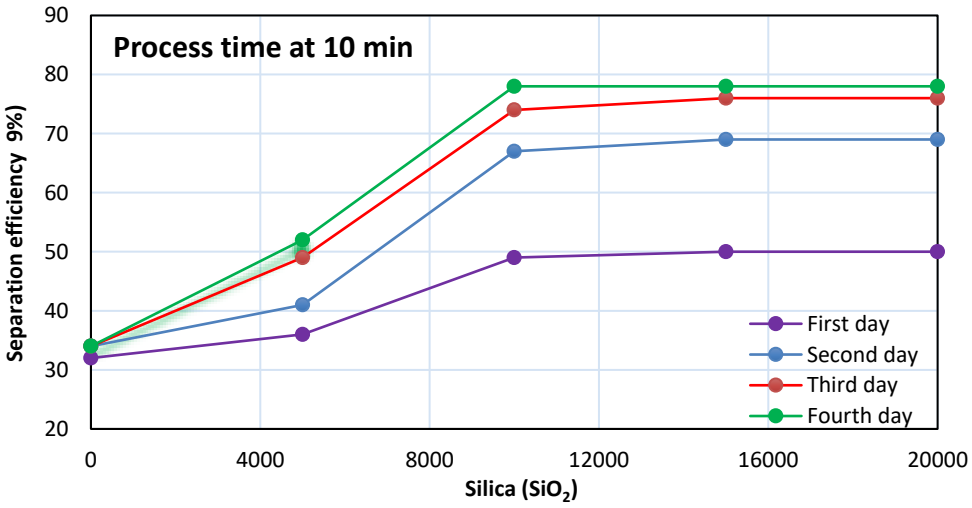

Fig. 5. Water concentration and silica (SiO_2) addition

With the rise in silica content, the separation ratio markedly escalates, peaking at roughly 10,000 ppm. The silica particles serve as nucleation sites for water droplet formation, so optimizing the reversing process and improving the separation of water from oil. Beyond this juncture, the separation ratio either stabilizes or experiences a modest decline, signifying saturation or detrimental effects at elevated doses. Day 2 (red curve) separation ratio increased at identical dosages compared to Day 1 (black curve). This spike may be caused by sample features like oil-water equilibrium or ultrasonic cumulative effects. At concentrations beyond 10,000 ppm, the two curves converge, indicating system efficiency. After two more days, the separation efficiency rose to 49% on the third day and 52% on the fourth, but the ratio did not alter. Silica can cause

agglomeration or bigger particles than drops. Large oil or water molecules make it easier to separate them, making oil and water separation easier. The separation efficiency ratio remains constant upon the addition of silica due to surpassing the optimal concentration. Exceeding this concentration of silica may result in the production of irregular clumps or adverse effects that diminish separation effectiveness. The characteristics of the fundamental combination, including the oil-to-water ratio, viscosity, and surface tension, may be incongruent with the influence of silica.

5.1.2 Effect of Temperature on Oil/Water Separation Efficiency

An increase in temperature leads to a reduction in heavy fuel oil viscosity and a greater density difference between the continuous and dispersed phases. These effects collectively enhance droplet mobility, promote coalescence, and weaken the interfacial stabilizing layer, ultimately improving the efficiency of oil–water separation. Heat may increase the mobility of microscopic water molecules, which collide to form bigger molecules and make droplets easier to separate. Heat weakens and ruptures the emulsion membrane. The disintegration of small paraffin and asphaltene crystals reduces their emulsification ability. Temperature has both positive and negative effects. Temperature can degrade oil's light components, affecting its volume. It may emit light hydrocarbons, causing turbulence that prevents water droplet aggregation. Water droplets containing oil are also threatened by tiny vapor droplets rising quickly. Figure 6 shows how temperature affects oil/water separation (31).

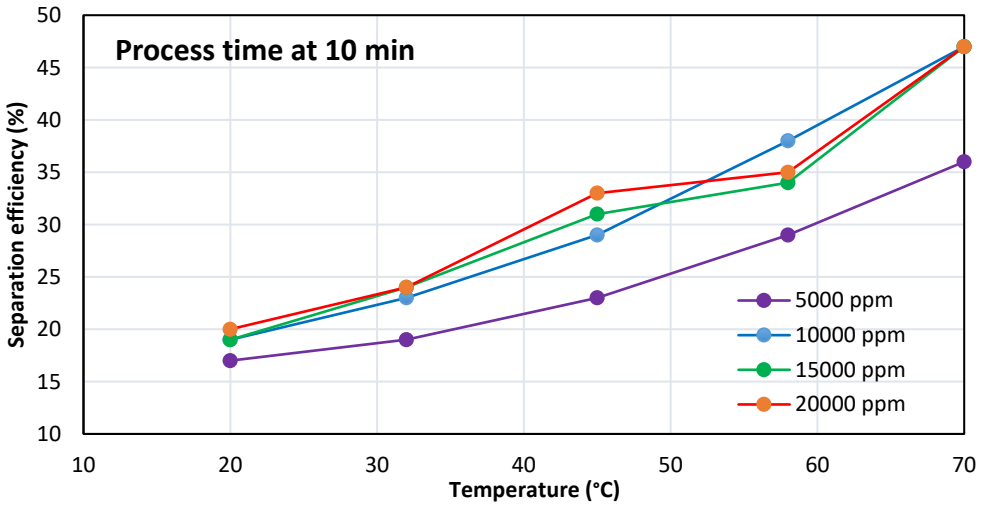

Fig. 6. Effect of temperature on oil/water separation efficiency

5.2 Relationship Between Water Concentration and Silica Addition Ratio At 20 Minutes

Upon evaluating the sample and subjecting it to the ultrasonic device for 20 minutes prior to the addition of any material, the separation ratio was recorded at 34% on the first day, which then rose to 36% on the second day. Upon the addition of 5000 ppm of silica, a marginal enhancement in the separation ratio was seen, increasing to 41% on the first day and 50% on the second day. Upon the addition of 10,000 ppm of silica, a consistent improvement in separation efficiency was seen, reaching 43% on the first day and 50% on the second day, as illustrated in Figure 7. Enhancing surface interactions can expedite the separation process between oil and water, resulting in more effective component separation via altering surface characteristics. Extending the separation duration to 20 minutes may marginally impact the effectiveness of oil/water separation. In physical media, sound waves propagate as vibrations that compress and rarefy the medium, transferring energy from the particles of the material as they oscillate and vibrate. We allowed the samples to enhance the separation efficiency for an additional two days, resulting in a marginal improvement to 40%. Subsequently, on the fourth day, the ratio remained unchanged. Both curves are essentially identical, indicating similar findings and no significant differences between days. Since there is no temporal effect between these two days, the system may be stable and repeatable. Because there

are more silica particles, water mixes back into the oil or the particles combine. Numerous silica particles can form a barrier that hinders water-oil mixing or stabilize the emulsion. At the 20-minute mark, an efficiency variation emerges, potentially signaling the occurrence of supplementary processes over time, such as the redispersion of water or the slow settling of silica particles.

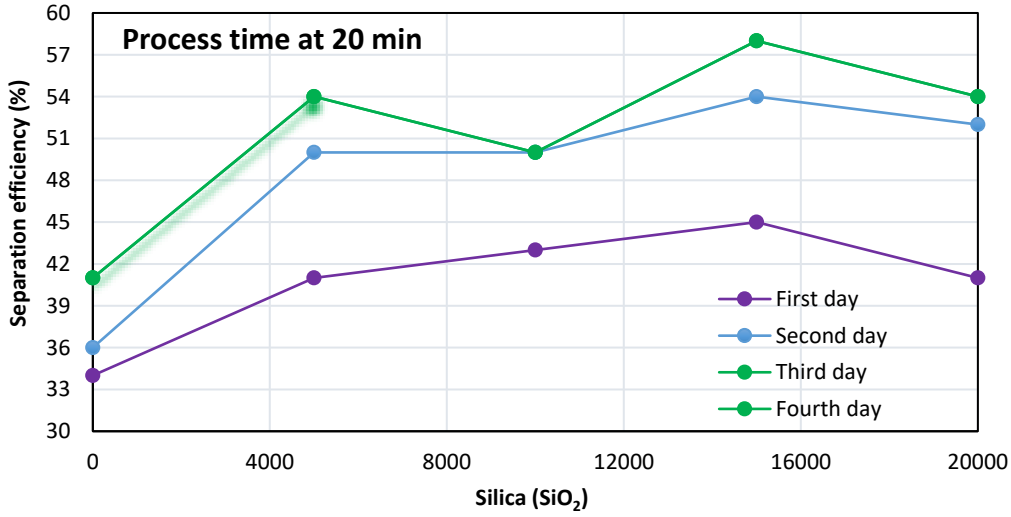

Fig. 7. Water concentration and silica (SiO_2) addition for the four days

5.3 Relationship Between Water Concentration and Silica Addition Ratio At 10 Minutes

The separation rate was 34% on the first day after testing the sample and placing it in the ultrasonic device for 30 minutes before adding any material. The next day, the separation rate increased to 38%. At low concentrations (5,000 ppm), the separation efficiency is minimal (~25-30% on the first day and 35% on the second day). As the concentration of silica rises, the efficiency progressively improves, however lacks a distinct peak observed in prior tests. Figure 8 shows that the separation efficiency stabilized when adding (10000 ppm) and (15000 pm) to 36% on the first day and 47% on the second day, without the decline observed at 20 minutes. This may occur because the particles require more time to scatter uniformly in the medium, resulting in a failure to attain quick saturation, which subsequently diminishes efficiency.

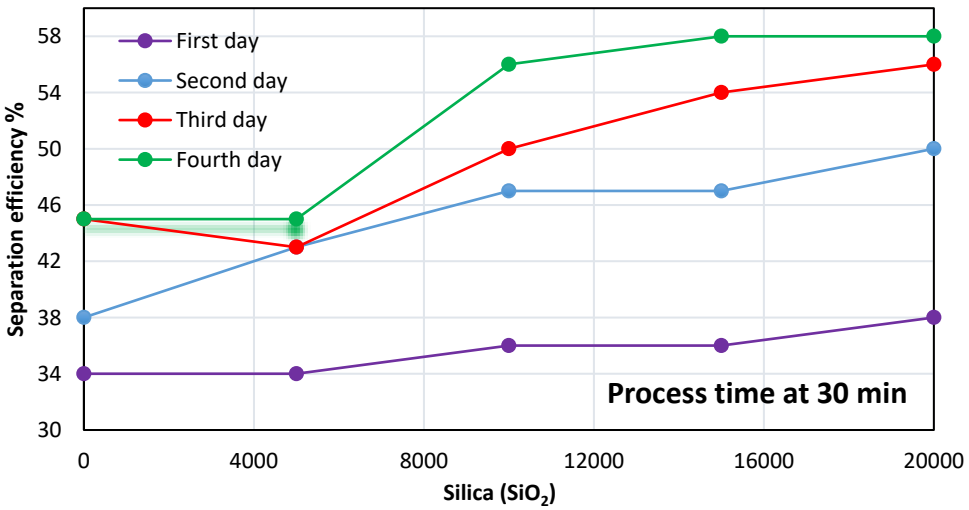

Fig. 8. Water concentration and silica (SiO_2) addition for the four day

The silica particles may exert a cumulative effect, with certain particles persisting in the solution and further enhancing separation after several tests. On Day 1 (black curve), separation efficiency was low and did not grow, suggesting silica had no effect. On Day 2 (red curve), separation efficiency exceeded all concentrations, and the association between concentration and efficiency was almost linear, suggesting silica had a greater impact. The difference between the two days may be due to emulsion stability or silica particle effect. Pressure from ultrasonic waves modifies water-oil interaction, lowering suspended particle size and facilitating separation. Tiny particles separate. Sample separation efficiency rose for two additional days, reaching 54% and 58% on days three and four. Adding 50,000 ppm silica material did not affect the ratio. Silica may stabilize water and oil for a short time before the system stabilizes. When this happens, separation efficiency stabilizes. The balance of contributing elements and silica's process constraints might restrict its separation improvements.

5.4 Effect of Temperature on Oil Viscosity

Heavy oil, a hydrocarbon combination, is viscous at low temperatures and flows poorly. Figure 9 shows that oil viscosity decreases with warming. Heat breaks molecular bonds that slow oil molecules and speeds up flow. As temperature rises, molecules may glide past one other, reducing viscosity and facilitating water-oil separation. Oil and water in the sample may interact at high temperatures, forming more stable emulsions and increasing viscosity. Specific heavy molecules in oil may breakdown at high temperatures, creating viscous substances. Certain substances can interact to change molecular structure and increase viscosity. Gandomkar's source [32]. Table 4 shows a comparison between the studies and the current study.

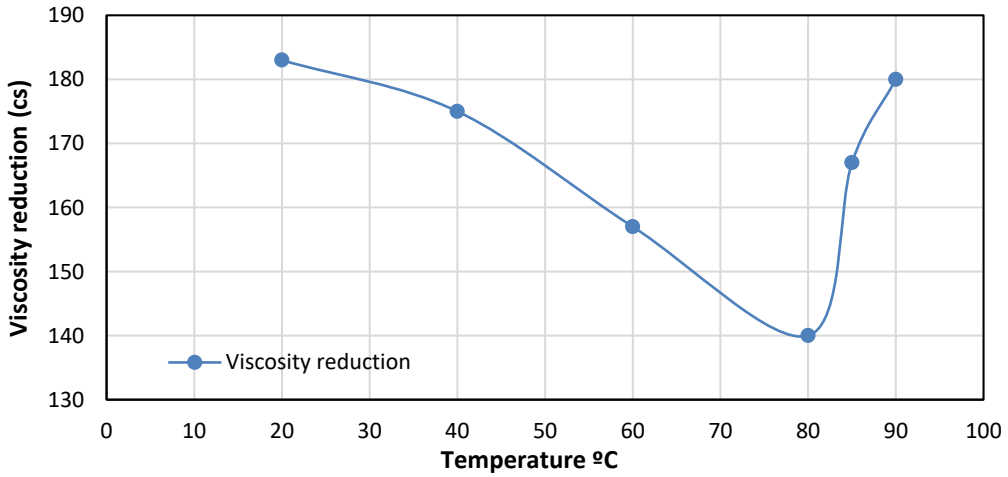

Fig. 9. The impact of temperature on the lowering of ultrasonic viscosity

Table 4. Comparison between the studies and the current study

Researchers	Material used	Results
Current study (Silica particles)	Chemical (Silica particles)	Utilizing ultrasound at a frequency of 40 kHz and a power of 180 W for 10 minutes effectively eliminated up to 78% of heavy fuel oil emulsions
Gao et al. [23]	No demulsifier (ultrasound only)	ultrasonic cavitation demulsifies and dehydrates oil samples to 98.24%.
Okereke et al. [21]	Natural blend (local materials)	achieved over 90% separation efficiency under mild conditions

Although the separation efficiency obtained in the present study is lower than that reported in some previous works such as Gao et al. (2024) and Okereke et al. (2021), this difference can be attributed to variations in oil type, operating conditions, and demulsification mechanisms. Gao et al. achieved very high efficiency (98.24%) using aged transformer oil under optimized ultrasonic

cavitation, whereas the present study targets very heavy fuel oil (HFO) with high viscosity and asphaltene content, which forms highly stable emulsions. Similarly, Okereke et al. reported over 90% efficiency using chemical demulsifiers on lower-viscosity crude oil emulsions, while the present work relies mainly on physical cavitation assisted by silica particles. In addition, differences in ultrasonic power, irradiation time, and temperature also contribute to variations in efficiency. Therefore, despite the lower maximum efficiency, the present results remain competitive considering the extreme stability of HFO, the low cost of silica, and the environmentally friendly nature of the method.

5.5 Commercial Breaker (RQ35) In Breaking Emulsification

Figure 10 shows the results of the commercial emulsification breaker (RQ35) where different concentrations were taken to break the emulsification and the results shown in Table 5 were obtained (33). The commercial breaker gave a low separation rate compared to the prepared natural breaker, but when using a high temperature for the commercial breaker (RQ35), its efficiency increases, and this is what happens in most commercial breakers as they need a high temperature more than (70) m. Therefore, the effect of temperature on the commercial breaker and the prepared breakers was studied to increase the separation efficiency. The commercial emulsification breaker was added at concentrations of (500, 1000, 2000 and 3000) ppm and at different temperatures.

Table 5. Emulsification fraction by commercial breaker (35 RQ)

Amount of demulsifier concentration (ppm)	Amount of water separated (%) Separation time (minutes)					
	10	20	30	40	50	60
500	0	0	0	0	0	5
1000	0	0	0	0	5	10
2000	0	0	5	10	10	15
3000	0	5	10	10	15	20

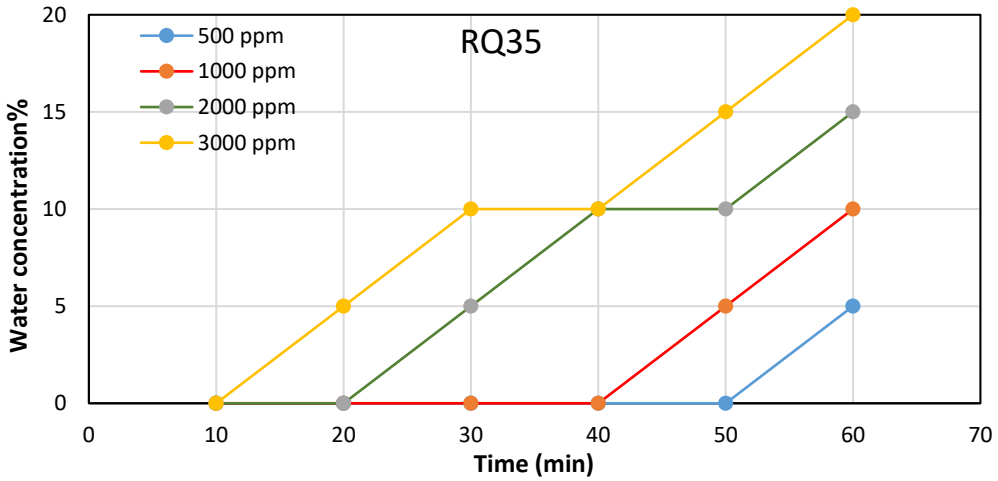

Fig. 10. Relationship between separation ratio and time with commercial emulsion breaker (RQ35)

6. Conclusion

This study demonstrates that applying low-frequency ultrasonication at 40 kHz and 180 W for 10 minutes, particularly at an elevated temperature of 70°C, offers an effective and environmentally conscious method for destabilizing water-in-oil emulsions. Achieving a separation efficiency of approximately 78% using low-cost silica particles highlights the strong capability of acoustic cavitation to weaken interfacial films and promote droplet coalescence. These findings contribute to a deeper understanding of the mechanisms through which ultrasonic energy interacts with

heavy fuel emulsions and provide a foundation for optimizing demulsification strategies in petroleum processing. Beyond its laboratory performance, the method shows clear industrial relevance. Ultrasonic reactors can be scaled up and integrated into existing separation units with minimal modifications, offering a pathway toward practical deployment in refineries and processing facilities. The use of inexpensive and locally sourced silica particles significantly improves cost-effectiveness compared with commercial demulsifiers that often require higher temperatures and present environmental burdens. Additionally, reducing reliance on synthetic chemicals supports greener operational practices and minimizes harmful by-products, aligning the technique with modern industrial sustainability goals. Future research should explore long-term acoustic exposure, the influence of different ultrasonic frequencies, and hybrid separation systems that combine ultrasonication with nanomaterial additives or electromagnetic heating. Advanced analytical characterization could further clarify the interfacial mechanisms involved and support the development of more efficient, scalable, and environmentally friendly demulsification technologies for real-world industrial applications.

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