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ULTRASONIC WAVE TREATMENT OF HEAVY OIL TO REDUCE VISCOSITY AND ENHANCE FLOW ABILITY IN PIPELINES

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Abstract

Ultrasonic wave technology is a physicochemical method that could be deservedly used to improve the rheological properties of crude oil for smoother and economical transport in piping systems. This study examines the possibility of upgrading Iraqi heavy fuel oil (HFO) and crude oil by ultra-sonication through experimental investigation using ultrasonic technology and the catalyst. Several variables that affected the process's efficiency were examined, including the effect of adding Ethanol to HFO as a catalyst. The ethanol added to HFO as a catalyst was used at a concentration of 20 vol.%. During the tests, crude oil and HFO samples were subjected to ultrasound effect at a power of 400, 500, 600, 700, and 800 W for 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 minutes and at a frequency of 28 kHz. Experimental results showed that using ultrasonic waves with a power of 400 W for 6 min of treatment at a frequency of 28 kHz led to a reduction in the viscosity of crude oil by 50%. The viscosity reduction was 87% when the ultrasonic treatment duration was increased to 8 min at the same power value. Furthermore, it has been shown that adding 20% ethanol to HFO without sonication will reduce the oil viscosity by 25.8%, while applying 700 W of ultrasound to the mixture over 8 min at 28 kHz resulted in an 88% reduction in viscosity. The achieved results demonstrate a novel methodology to improve the Iraqi crude oil and HFO flow rate by viscosity reduction using ultrasonication technique. The ultrasonic treatment has proven to be an efficient and cost-effective technology to reduce viscosity and enhance the flow ability in pipelines.

Keywords: Crude oil, Drag reduction, Ethanol, Heavy fuel oil, Optimisation, Ultrasound, Viscosity reduction.

1. Introduction

The International Energy Agency, 2009 stated that the first decade of the twenty-first century showed a tremendous increase in the worldwide demand for crude oil from 1.0 to 1.8% because of the scarcity of fossil fuels and the rising demand for energy [1-3]. Therefore, one of the most crucial sources for supplying energy in the future is heavy and ultra-heavy crude oil, which has densities of less than l0 and 20 API, respectively [4, 5]. However, due to their higher density, greater viscosity, and lower fluidity, they are particularly challenging to process and transport. It is necessary to create practical and cost-effective ways to decrease their viscosities to address the production and transportation issues, which are still highly challenging from a technical standpoint [6, 7].

There are several primary approaches for producing low-viscosity oil, like heating [8], gas injection [9], chemical additives, and physical treatment [10, 11]. One of the most promising physical techniques for enhancing the rheological characteristics of crude oil in reservoirs or pipelines is the employment of ultrasonic wave technology, which is, in theory, both affordable and environmentally friendly.

In 2015, Doust et al. [12] investigated the impact of solvent concentration, temperature, and ultrasonic irradiation time on lowering the viscosity of residual fuel oil (RFO). The key aspect of this study is the use of ultrasonic irradiation with a power of 280 W for improving RFO quality and reducing viscosity at a low frequency of 24 kHz. It was discovered that applying ultrasonic irradiation for 5 min at a starting temperature of 20 °C caused the kinematic viscosity of RFO to drop from 4940 cst to 2679 cst. The combination of solvent and ultrasonic irradiation caused an enhanced viscosity to drop and promoted API gravity.

The 5 min of ultrasonic irradiation, 50 °C temperature, and 5% by volume of acetonitrile loading produced the greatest viscosity reduction at 133 cst. Also, Wang et al. [13] investigated the effect of ultrasound on ultra-heavy oil viscosity reduction. The initial viscosity of the ultra-heavy oil was 1250 mPa.s. Testing was done on a 100 - 1000 W power output range and a wave frequency range of 18–25 kHz causing oil viscosity to be dropped by 65.8% at 100 W, 18 k HZ within 30 min.

Huang et al. [14] examined the viscosity-temperature characteristics of two types of residual oil projected to ultrasound emitted from the ultrasonic system having a horn diameter of 15 mm, a power of 100-1000 W, an exposure period of 1 sec stop 1 sec, 2 sec stop 2 sec, and a frequency range of 20 to 24 kHz. It was found that under 900 W of ultrasonic power, 14 min of exposure, 2 sec of exposure mode, and 2 sec of interruption time, a viscosity reduction rate of up to 63.95% could be accomplished.

Further, Gao et al. [15] investigated the impact of ultrasound waves with irradiation times of 6 and 12 min at 18 kHz and 250 W power on the viscosity of some samples like heavy crude oil, heavy oil containing $C_{10}H_{12}$ at a mass ratio of 3:1, and heavy oil containing $C_{10}H_{12}$ and $(CH_2OH)_2$ at a mass ratio of 6:1:1. It was found that the viscosity of the oil sample decreases by around 20% after 6 min of ultrasonic irradiation, and the rate of viscosity reduction rises to about 60% when $C_{10}H_{12}$ and $(CH_2OH)_2$ were added to heavy oil.

In summary, the application of ultrasonic therapy results in a decrease in asphaltenes, which are chemical compounds undergoing conversion. It is important to note that these compounds cause the high viscosity of heavy crude. Other components that have exhibited degradation include naphthenic, aromatic, saturated, and resinous hydrocarbons [16-18].

The present work aims to optimise operating conditions and enhance the physicochemical characteristics of Iraqi heavy fuel oil and crude oil by conducting experiments and applying ultrasound technology to these oils. The main scope of these experiments is to reduce the viscosity of Iraqi crude oil and heavy fuel oil by using ultrasonic treatment technology for the first time, increase the flow ability of Iraqi crude oil because of suppressing turbulence, lowering energy dissipation through friction, saving in the energy consumed by the pumps to transport oil, and optimising the operating variables to find the optimum conditions.

This study hypothesises that the drop in viscosity induced by ultrasonic irradiation may have been a result of the breakage of long chains and the reduction of heavy components resulting from acoustic cavitation.

2. Ultrasonic Waves Working Mechanism

When ultrasound waves propagate through a liquid, a phenomenon known as acoustic cavitation occurs due to the cycles of expansion and compression (low and high pressures) resulting from longitudinal waves of certain frequencies within the liquid molecules. Acoustic cavitations are formed in areas where low pressures are produced where this bubble grows, and due to the increased (high) external pressure, the cavitation bubbles burst.

Following the collapse of the bubbles, free radicals are created, which set off several chain reactions. This is how the chemical reaction operates. Free radicals can break down significant, complicated compounds because of their highly aggressive reaction activity. They originally come from water linked to crude oil and are reactive due to the presence of an unpaired electron [19].

Two highly reactive free radicals, the hydrogen ion, H^+ and the hydroxyl radical, OH^-, are created due to the energy produced during cavitations and the extremely high temperature. The C-C bonds of saturated hydrocarbons (alkanes) are then broken, resulting in the formation of more primary radicals and secondary radicals, which then interact to create shorter-chain alkenes and gaseous compounds like H_2, CH_4, and C_2H_4 [20]. After this, large substances like resins and asphaltenes start to degrade. While the remaining asphaltenes are changed into resins, some are converted into gas oil. The saturated component of the newly generated light compounds is then obtained by converting the resin fraction into gas oil [20].

Ultrasound causes a shift in the colloidal structure of hydrocarbons, releasing low-molecular-weight molecules associated with the asphaltenes structure; also, the effects of cavitations diminish intermolecular connections, resulting in reduced viscosity. It has also been demonstrated that acoustic vibrations inhibit the intermolecular interaction of asphaltenes [20, 21]. The mechanisms of the ultrasound process are depicted in Fig. 1 [22]. This technology can be applied in heavy fuel oil tanks and crude oil storage tanks before being transported in pipelines.

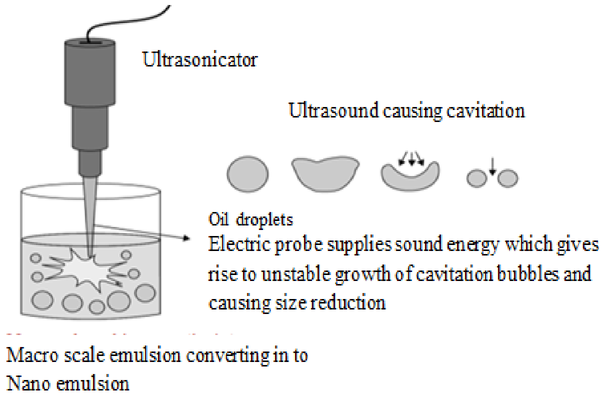

Fig. 1. Mechanisms of the ultrasound process [22].

3. Materials and Methods

3.1. Materials

Two samples of materials were utilised in the experiment tests:

3.1.1. Iraqi crude oil and heavy fuel oil

The tests were carried out using Basra oil, which was provided by the Al-Doura refinery. The physical specifications of the tested crude oil are shown in Table 1.

Table 1. Physical properties of crude oil and HFO.

Properties	Crude oil	Heavy fuel oil
Sp.gr @ 15.6 ºC	0.8724	0.9718
API @ 15.6 ºC	30.7	14.1
Density @ 15 ºC (g/cm^3)	0.8719	0.97
Kinematic viscosity @ 10ºC (cSt)	29.45	330.9
Asphaltenes content (wt.%)	2.0	2.527

3.1.2. Ethanol (CH_3CH_2OH)

99.9% pure ethanol was used, a clear, colourless liquid with a distinctive vinous flavour and pungent taste. It has a flash point of 12.8 °C and a density of 0.775 gm/cm^3.

3.2. Measuring instrument

In an enclosed flow loop system, the viscosity reduction approach utilising ultrasound technology was applied. As seen in Figs. 2 and 3, the experiment was conducted in a re-circulatory flow facility. This system includes a control unit, an oil pump, a pressure gauge, an ultrasonic horn, a 2-m-long piece of PVC pipe with a 1.27-mm diameter, an oil tank, and a viscometer. The ultrasonic generator works with electric power ranging from 400, 500, 600, 700, and 800 W at a frequency of 28 kHz. The oil tank's ultrasonic horn was put at a depth that was roughly 0.5 times that of the oil samples in the tank. The time of ultrasonic irradiation was chosen at a range of 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 minutes; moreover, the temperature was set at 20°C. Table 2 illustrates the specifications of some system components.

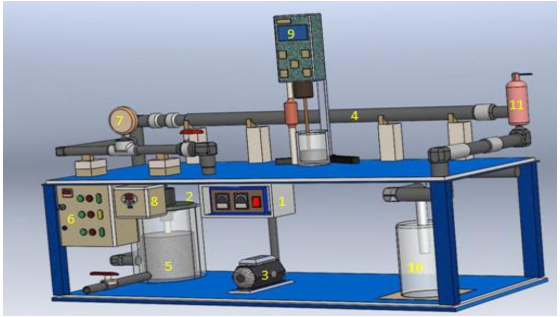

Fig. 2. Experimental system's schematic diagram: 1. Ultrasonic generator, 2. ultrasonic horn, 3. oil pump, 4. oil pipe, 5. oil tank, 6. control unit, 7. pressure gauge, 8. AC drive, 9. Viscometer, 10. cylinder & 11. Valve.

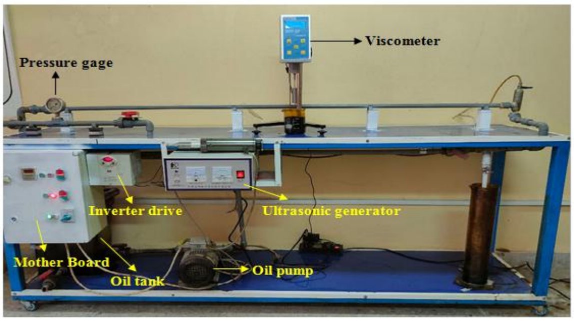

Fig. 3. The experimental setup.

Table 2. Specifications of setup devices.

Device	Type	Specifications
Ultrasonic generator	HC-SG-28800	220 V, (27.5-28.5) kHz, (400-800) W
Oil pump	WCB75	110/220 V, 1000 W
Viscometer	BDV-5S	10 - 10^5 mPa.s, Accuracy ±1% full-scale range in use

3.3. Experimental setup

Five litres of Iraqi crude oil and heavy fuel oil were placed in the experimental system tank sequentially. Four different values of ultrasonic power of 400, 600, 700, and 800 W were projected to crude oil and heavy fuel oil, respectively, for various times of 0-10 min. The crude and heavy fuel oil samples were withdrawn from a pipe at each case and the operating variables were set. Samples were acquired to show the long-term effects of ultrasonic waves on viscosity reduction. Viscosity measurements were performed before and after the application of powers during specific times. With the help of software (STATISTICA and WinQSB), the optimum conditions were determined after the set of experiments was completed.

3.4. Fluid flow parameters

The pressure drop, power consumption, Reynolds number, and friction factor are the commonly adopted parameters to evaluate the pipe flows [23-25]. Figure 4 shows the oil pipe parameters and Eqs. (1) to (5) are the suggested prediction methods of the pipe flow parameters.

Fig. 4. Geometries of the oil pipe test section.

$$\Delta p = \frac{128\,\mu l}{\pi D^4} \quad (1)$$

$$P_E = Q.\Delta v \quad (2)$$

$$R_e = \frac{\rho u D}{\mu} \quad (3)$$

$$f = \frac{\Delta p.D}{2L\rho u^2} \quad (4)$$

$$API = \frac{141.5}{SG} - 131.5 \quad (5)$$

where Δp is the pressure drop in pa, Q is the flow rate in m3/s, PE is the power consumption for pumping in W, Re is Reynolds number, ρ is the density in kg/m3, μ is the viscosity in cp, u is the mean velocity, D is the diameter of the pipe in m, f is the friction factor, and L is the pipe length in m, SG is the specific gravity.

4. Results and Discussion

The results obtained for the effect of ultrasonic powers of 400, 600, 700, and 800 W at a frequency of 28 kHz and treatment times of 0-10 min at a temperature of 20 °C on reducing the viscosity of Iraqi crude oil and (HFO) will be carefully analysed and discussed. In the following sections, the impact of viscosity reduction on some factors like Reynolds number, pressure drop, and power consumption for oil pumping, as well as the optimisation results, will be scientifically analysed and discussed.

4.1. Impact of ultrasonic on crude oil

Figure 5 depicts the effect of ultrasound on the viscosity and API number of crude oil. The decrease in viscosity was greatly influenced by the amount of ultrasound energy and the length of time during which the crude oil was exposed. As the ultrasound power increased from 400 to 600 W and the irradiation time from 0 to 6 min, the viscosity of the crude oil gradually decreased from 24 cp to a peak value of 12 cp. This indicates that oil samples typically exhibit strong cavitation when exposed to ultrasound at a specific intensity.

It is generally accepted that acoustic cavitation has three effects: mechanical, chemical, and thermal. High temperatures and high pressures are produced by the thermal effect in the local solution, which encourages the mutual dissolution of various liquids. The collected oil sample is often stirred vigorously by mechanical impact. Viscosity decreased for the first time in experiments using crude oil. The contents of functional groups elevated, indicating that there may have been a chain-breaking effect. The content of heavy components was reduced, indicating that the heavy components were probably broken down by ultrasound.

On the other hand, the viscosity of crude oil gradually increased to 17 cp when the power increased to 800 W during a time reached 10 min. Due to the impacts of high local temperature and pressure, there may be re-association of molecules and volatilisation of light components and/or charring of oil samples when the radiation strength and time are constantly increasing. The Reynolds number is extremely correlated to viscosity which increases with decreasing the viscosity of fluid.

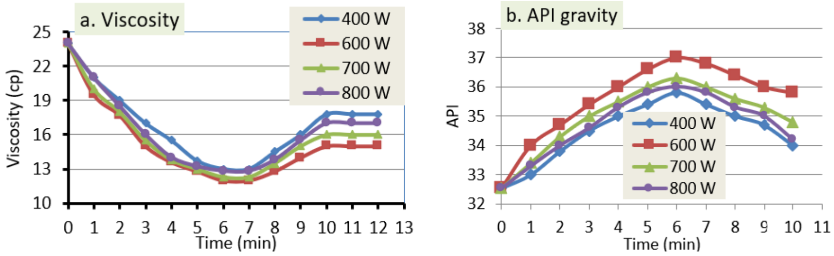

Fig. 5. Effect of ultrasound on the measured values of (a) viscosity and (b) API gravity of crude oil.

On the other hand, API increases from 32.5 to 37.6 as the peak value. Because of the impact of ultrasound on increasing the temperature and pressure of crude oil, the molecules of the material move faster and take up more space. This leads to a decrease in the density of the material, thus increasing the attractiveness of the API. After 6 min, the API gravity slowly decreased until it reached 34, 35.8, 35, and 34.6 at 400, 600, 700, and 800 W, respectively, at 10 min.

Figure 6 indicates the impact of ultrasonic waves on friction factor, pressure drop, and power consumption. The friction factor reduces from 0.02813 when there is no treatment to a minimum value of 0.001445 when applying ultrasound with 400 W within 6 min. Because viscosity is the resistance to fluid flow, it is one of the factors of fluid friction. So, the decrease in viscosity leads to a decrease in the coefficient of friction and this causes a drop in the pressure from 47.6 to 24.4 kPa and a decrease in the power consumption to a minimum value of 15 W. In contrast, as wave power and time grow, friction and pressure drop progressively with rising viscosity to approach 0.02, 30 kPa, and 22 W, respectively.

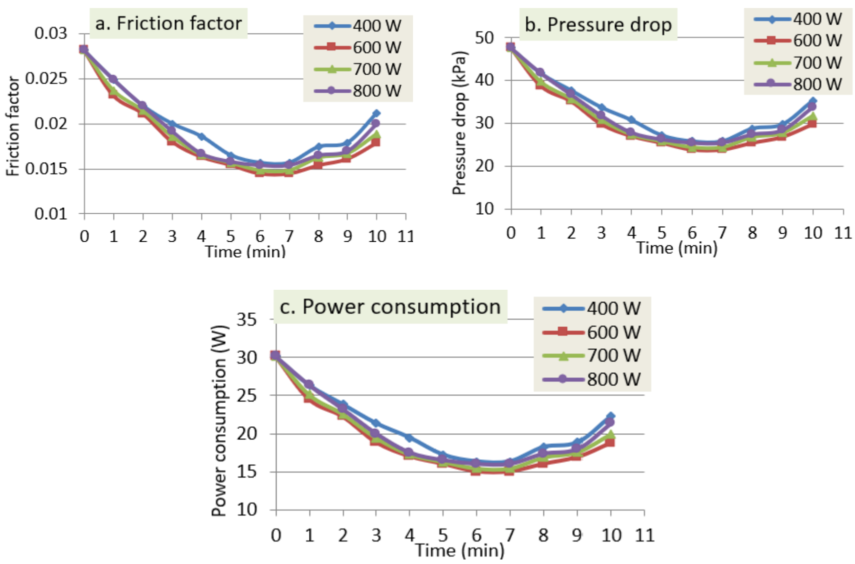

Fig. 6. Effect of ultrasound on measured values of (a) friction factor, (b) pressure drop, and (c) power consumption of crude oil.

4.2. Impact of ultrasonic on heavy fuel oil

Figure 7 illustrates the impact of ultrasonic waves on HFO viscosity and API. It is noticed that the viscosity of the HFO at an irradiation time of 8 min decreases from 620 cp to 154, 120, and 100 cp at power values of 400, 600, and 700 W, respectively. Furthermore, at 800 W effective power and 8 min duration, the viscosity of the HFO decreases to the lowest value of 80 cp. The HFO is more sensitive to the effects of ultrasonic waves than crude oil because a greater percentage of heavier hydrocarbons made up of longer carbon-plus-hydrogen molecule chains make up HFO. After a treatment time of 8 min, the value of viscosity increases rapidly to become 189, 160, 140, and 100 cp at 400, 600, 700, and 800 W, respectively. Additionally, the API gravity increased by 36.3% at 800 W.

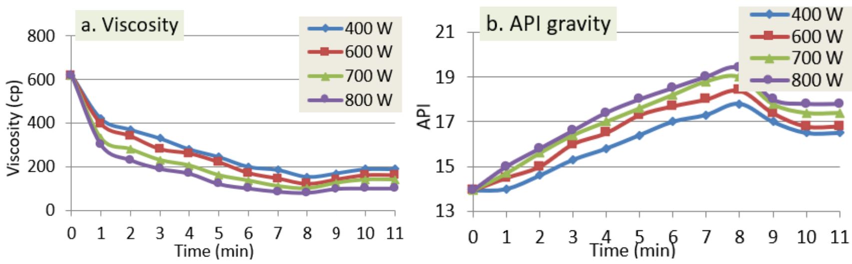

Fig. 7. Effect of ultrasonic wave power on measured values of (a) viscosity, (b) API of heavy fuel oil.

The friction factor, pressure drop, and power consumption of heavy fuel oil are reduced by ultrasonic, as shown in Fig. 8. The friction factor goes from 0.161 to the lowest value of 0.02133 while the pressure drop decreases from 4920.33 kPa to the lowest value of 634.8831 kPa and the power consumption decreases to a minimum value of 1.6084 kW when the oil is treated with ultrasound of 800 W within 8 min.

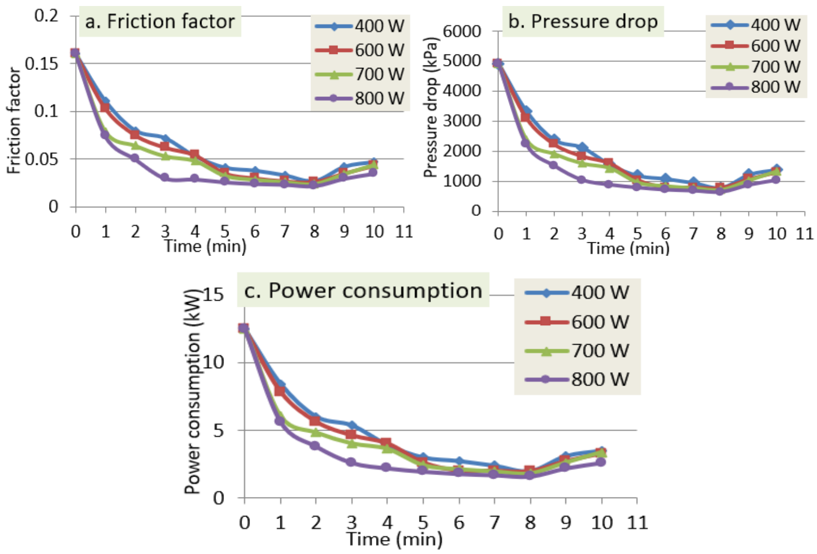

Fig. 8. Impact of ultrasonic on measured values of (a) friction factor, (b) pressure drop, and (c) power consumption of heavy fuel oil.

On the other hand, when the wave power and processing time increase, the friction gradually increases to 0.02644, pressure decreases to 1031.68 kPa, and energy consumption decreases to 2.01 kW along with the viscosity increases to approximately 0.02644, 1031.682 kPa, and 2.01051 kW, respectively at 800 W for 10 min.

4.3. Influence of ultrasonic waves with the addition of 20% ethanol on heavy fuel oil

Figure 9 illustrates the effect of subjecting the HFO to ultrasonic waves with the addition of ethanol, which causes the highest viscosity reduction. The viscosity reduced from 620 cp without any processing to a maximum value of 75 cp at 700 W of power and an 8 min irradiation time. The viscosity reduction rate for the mixed oil sample was significantly greater than that for the heavy oil sample alone, indicating that adding ethanol helped improve the viscosity reduction rate.

In contrast, ethanol acts as an organic solvent by reducing the asphaltene content affected by ultrasonic waves and the action of polar solvents to disperse asphaltene agglomerates. After 8 min, the viscosity gradually increased to reach 113 cp at 800 W. This behaviour may be due to reaggregations of asphaltene particles, which gives the reverse outcomes. Reducing viscosity leads to increasing API gravity by 50.64%.

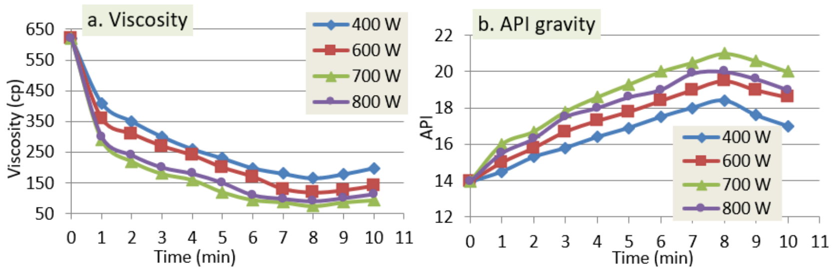

Fig. 9. Impact of ultrasonic waves with 20% addition of ethanol on (a) viscosity, (b) API.

Figure 10 illustrates the effect of subjecting the HFO to ultrasonic waves with the addition of ethanol on the friction factor, pressure drop, and power consumption. It is shown that the value of the friction factor drops from 0.161 with no treatment to 0.020997 as a minimum value, which leads to a decrease in pressure by 87.96% and power consumption by 87.93% at 700 W and 8 min. In contrast, as wave power and time grow, friction, pressure drop, and power consumption progressively rise with rising viscosity to approach 0.03095, 89676, and 2.27 kW, respectively.

4.4. Effect of ultrasonic power and radiation time

When the power of ultrasonic waves in the range of 400, 500, 600, 700, and 800 W is applied to the oil, it needs 2, 3, 4, 5, 6, 7, 8, 9, and10 min to produce the acoustic cavitation bubbles which break long chains and reduce a heavy component along the direction of the flow thus reducing the viscosity to a great extent. Figure 11 shows this relation with dynamic viscosity using STATISTICA 12.0 software. The colour gamut from red to dark green represents a gradual decrease in the dynamic viscosity. The dark green colour represents the least viscosity, and the dark red colour represents the highest dynamic viscosity values.

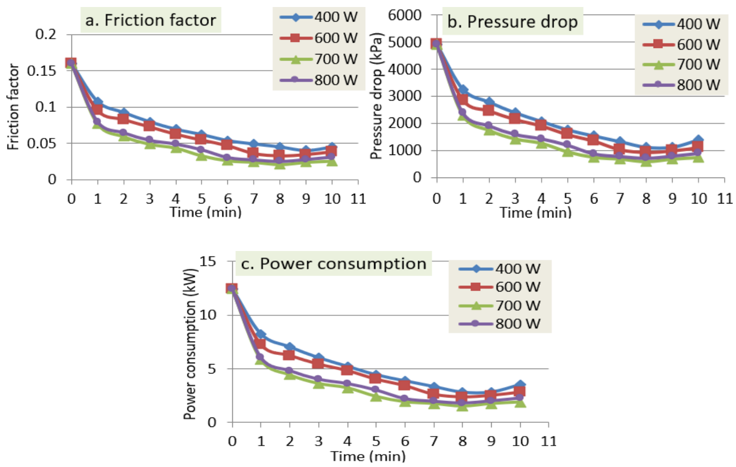

Fig. 10. Effect of ultrasound with 20% addition of ethanol on (a) friction factor, (b) pressure drop, and (c) power consumption by the pump.

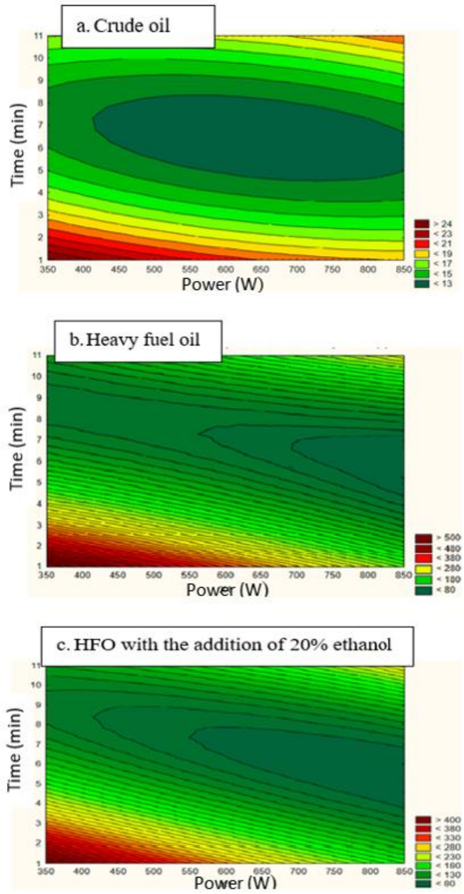

Fig. 11. Contour plot of dynamic viscosity vs. power and time for (a) crude oil, (b) HFO, and (c) HFO with the addition of 20% ethanol.

5. Conclusions

When 500 W of ultrasonic radiation is applied to crude oil over six min, the viscosity is reduced by 50%, the API is increased by 15.7%, and the pressure drop is reduced by 50%, all of which reduce pumping power consumption by 50.24%. Additionally, projecting 800 W of ultrasonic energy over 8 min on heavy fuel oil results in an 87% reduction in viscosity and a 39.16% increase in API gravity. Also, the pressure drop decreased by 87%, which led to an 87.14% reduction in power consumption. After 8 min of exposure to 700 W of processing power, the API gravity of the mixture of HFO and Ethanol increased by 81%, and the viscosity decreased by 88%, resulting in a reduction in power consumption by 87.98%.

It was discovered that the optimum value of crude oil viscosity is 12 cp at ultrasonic power of 600 W for 6 min, and for heavy fuel oil, the viscosity is found to be 80 cp at 750 W for 8 min, while the optimum viscosity of heavy fuel oil with 20% ethanol added is 78 cp at 650 W for 7 min treatment time. It can be concluded from the above results that the ultrasonic treatment is proven to be an effective and cost-effective technique to reduce viscosity and improve the flow ability of heavy oil.

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Nomenclatures

A	Area of plate, m^2
D	Diameter of tube, m
f	Friction factor
L	Pipe length m
l	Tube length from the start to the slide, m
p	Pressure, Pa, kPa
P_E	Power consumption, W
Q	Volumetric flow rate, m^3/s
SG	Specific gravity
u	Fluid speed, m/s
Greek Symbols	
Δp	Pressure drops
μ	Dynamic viscosity, N.s/m^2
ν	Kinematic viscosity, cst
ρ	Mass density, kg/m^3
Abbreviations	
API	American Petroleum Institute
R_e	Reynolds number
RFO	Residual fuel oil
UOT	University of technology

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