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Experimental Study on viscosity reduction of East Baghdad's heavy oil system

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ABSTRACT

East Baghdad's heavy oil is difficult to transport in the pipeline system due to its high viscosity. This work involved studying the viscosity reduction in the east Baghdad crude oil (EBCO) using surface-modified silica particles. Different operating variables were investigated, such as average particle sizes of (5, 10, and 15µm), particle loading of (0, 200, 400, and 500 ppm), and temperatures (10, 30, and 50 ^{o}C), for their effect on viscosity reduction. FTIR and contact angle (WCA) techniques were utilized to identify the particle's surface morphology and degree of wettability before and after surface modification, respectively, while the Brookfield viscometer was used to evaluate variation in the oil viscosity. Experimental results showed that hydrophobic particles were more feasible for use in viscosity reduction, hydrophobic silica particle loading of 400 ppm has the optimum reduction of viscosity of 31% at 30 ^{o}C; increasing the loading beyond the optimum particle size has a negative effect on the viscosity reduction. The ambient temperature has a positive impact on the level of viscosity reduction in the existence of hydrophobic silica particles. A power law equation was developed with a correlation factor of 0.995 to evaluate the crude oil viscosity as a function of hydrophobic particle loading and temperature.

Keywords: Viscosity reduction; heavy oil; silica particles; hydrophobicity; FTIR; contact angle

1. INTRODUCTION

Heavy oil transportation suffers severe issues, especially in cold environments where sediments of waxes and asphaltenes on the inner sides of the piping system decrease the functional pipe size of the flow and finally block them, generating a large pressure difference along the pipeline [1]. The existence of heteroatoms and metals brings asphaltene as the main polar polycyclic aromatic hydrocarbon, resulting in the creation of a viscoelastic grid of nanogroups in growth in viscosity [2-3]. For the handling of heavy oil, different techniques have been suggested and utilized by the petroleum industries, such as mixing with organic solvents, creating heavy crude oil emulsions in water (O/W), warming heavy oil and pipelines, and the usage of viscosity-decreasing additives. All these techniques have been presented in several articles [4]. [3] examined the influence of SiO2 and Al2O3 nanoparticles (Nps) (SiO_2 and Al_2O_3) on the rheological manner of two different crude oil samples in a temperature domain of 30-60 ^{0}C. Rheological evaluations with or without the insertion of Nps to the crude oil indicated that Nps participate in upgrading the rheology characteristics by adjusting the viscoelastic grid. The viscosity of (O/W) emulsion is at most below the phase reversal point. Above this critical phase, emulsions of (W/O) lead to robust growth in emulsion viscosity, and thus the phase reversal point of the (O/W) emulsion could be obviated [5]. [6] studied experimentally various operating variables such as water volume fraction, shear rate, temperatures, and loadings of solid Nps for their influence on decreasing the viscosity of Arabian crude oil in (O/W) emulsions.

Iraq has proven reserves of crude oil amounting to 112 billion barrels, and it is thus considered the second country in terms of quantity of oil reserves after Saudi Arabia. Oil experts expect it to exceed the reserves in Iraq. His counterpart in the Arabian Gulf states completed the research and exploration in the Iraqi lands that did not receive a complete geological survey [7]. Figure 1 shows oil and gas fields in Iraq.

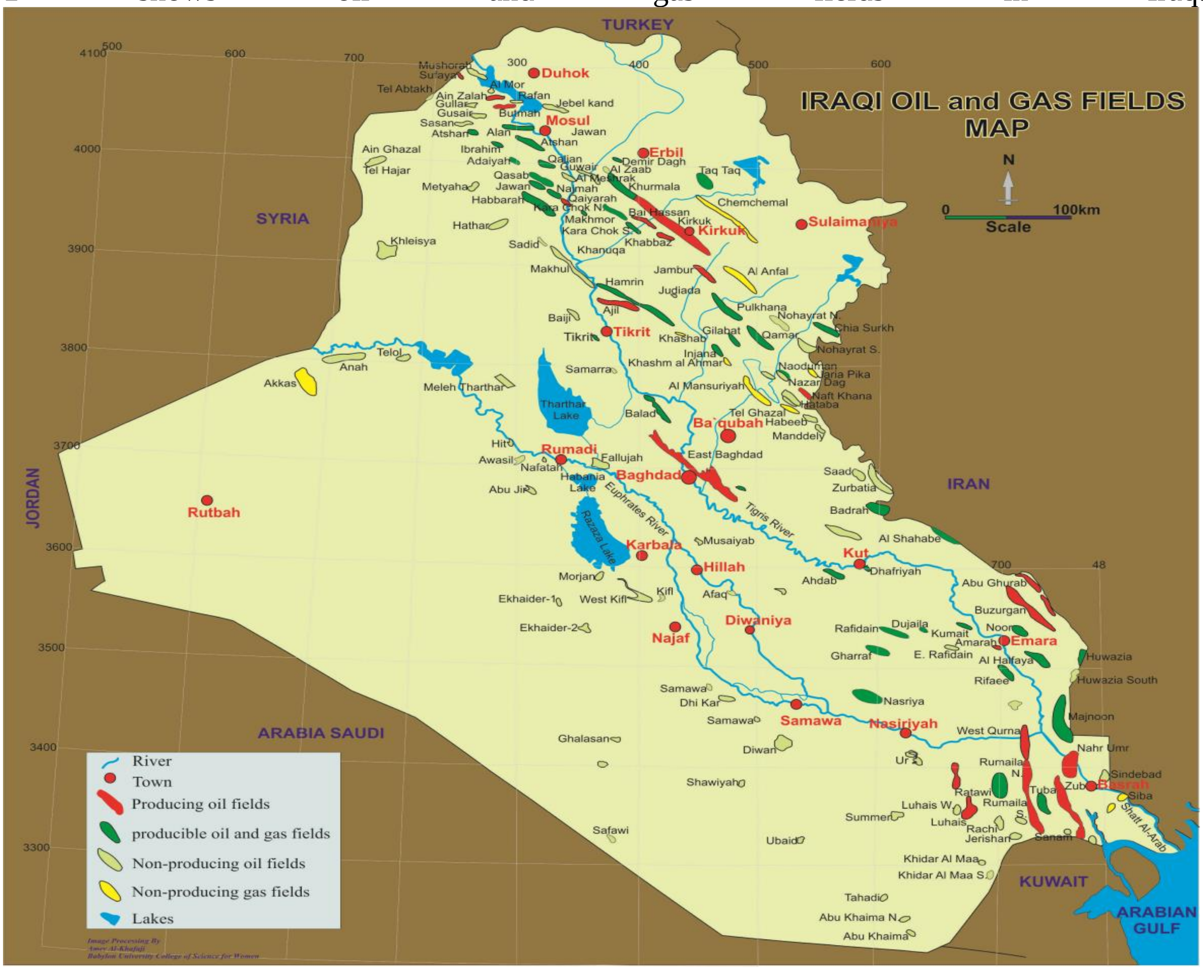


Fig. 1: Oil and Gas Fields in Iraq [8]

Some oil fields (e.g., East Baghdad and Qayara) produce heavy oil and extra-heavy oil, respectively. Products from these fields are used nowadays to supply power generation plants via pipelines and for export. East Baghdad's (EB) heavy oil fields comprise many wells having total oil in place of 6.5 x108 barrels [9-10]. Table 1 lists the crude oil properties of the East Baghdad oil reserve.

Table 1: Crude oil properties of east Baghdad oil reserve obtained from Baghdad east oil fields

Thus, the adjustment of rheological characteristics has turned into a major action to upgrade the flow capability of heavy oil and to attain economic production. The present study aims to minimize the crude oil viscosity for transportation along pipelines. Hydrophilic silica particles have been converted into hydrophobic silica particles tested with different particle loadings and temperatures for their effect on minimizing viscosity.

2. MATERIAL AND METHODS

2.1 MATERIAL

Property	Value
API @ 60 ^oF	16.8
Viscosity (cP) @20 ^oC	42.0
Total sulfur (wt%)	5.0
Wax (wt%)	2.1
Asphaltenes (wt%)	7.10
Naphthene compounds (wt%)	23.8

Samples of heavy crude oil were supplied by the Petroleum Center of Development, Ministry of Oil. The physical properties of the heavy oil sample used are given in Table 1. The silica sands of composition (0.7% max. Fe_2O_3, 96% min. SiO_2, and 1% max. Al_2O_3) were supplied by the state company for mining industries in Iraq. 1-propanol (≥99%) was supplied by Sigma-Aldrich, India. Deionized water was purchased from Mansoor Co., Iraq.

2.2 METHODS

2.2.1 Particle size distribution

500 g of sand was washed several times with hot demineralized water to remove salts and impurities. Then it dried in an electric oven (model Hmg, indiamart Co, India) at 80 ^oC for 6 hours. The dry sands were ground using a ball mill (Model: TOB-DSP-LBPBM05A, China) for 24 hours. The cumulative size distribution of the particles has been acquired by the following procedure: The 500-gram dry sample of sand is put over a screening column (Glenammer Laboratory Test Sieve Shaker model GEM 200 3D, Scotland, UK), with additional sieves supplied by lab alpha sieves. The column has eight sieves; at the top, a sieve with larger holes was installed. The column is shaken mechanically, and then particles held onto each sieve are weighted.

2.2.2 Surface modification

Hydrophilic sands were turned into hydrophobic sands utilizing the technique of Maloney and Oakes [11]. [11] revealed that H-bonds created from interactions of hydrophobic alcohols with surface silanol content seem to be more steady at a high working temperature that is identical to the working temperature of the hydroconversion reactor. In the current study, 1-propanol was employed as the bulk medium for the silica particles. The prepared suspension was warmed under the boiling point of octanol (i.e., 178 ^oC) for 4 hours, which was enough to make the SiO2 interact with the large hydrophobic alcohol. Additionally, the influence of surface modification on the silica particles was investigated. The meter of contact angle model (CAM 110-Taiwan) was employed to quantify the contact angle of water (WCA); a 5 µL DI water was trickled on the silica particle. Fig. 3 (a, and b) depicts the computer photos of contact angles acquired for water.

2.2.3 Viscosity monitoring procedure

The mixtures of crude oil with different loadings of silica particles (0, 100, 200, 300, and 400 ppm) were poured into a 250-mL closed beaker. The beaker was put on a hotplate magnetic stirrer (model: CSL Hotplate, Cleaver Scientific Ltd., UK) for one hour. The viscosity evaluations were performed in a shear rate range of 4–10 10 s^{-1} using a Brookfield CAP 2000+ viscometer (Labomat, Franceas) seen in Fig. 2).

Figure 2 : Brookfield CAP 2000+ viscometer (Labomat, France).

The rheological variables were first evaluated at 5°C. The above procedure was conducted for crude oil viscosity reduction at different temperatures (15, 30, and 50 ^{o}C. The viscosity reduction (Vred.%) is calculated by equation (1) [12]for heavy oil.

$$\text{Viscosity reduction } \% = \frac{\mu_i - \mu_f}{\mu_i} \text{ x } 100 \qquad (1)$$

Where μ_i and μ_f are the initial and final viscosities of crude oil in Cp. An additional test to investigate the degree of hydrophobicity of modified-surface particles, an easy technique proposed by Mata and Joseph [13], was used to confirm the particle's affinity for the 1 wt% glycerin in water. They identified the utilized particles through easy visual monitoring. If common sand is spilled into a vat with water, it will easily, particle by particle, drop to the vat base. If the same thing was done with hydrophobic sand, a dissimilar trend occurs: some of the particles remain at the surface, but large quantity of them drop to the base in big clusters enfolded with tiny bubbles of air.

RESULTS AND DISCUSSION

3.1 Particle size distribution

Figure 3 depicts the micro-size distribution of silica particles. As can be seen in Fig., particles of 7 µm size consist of 50% of the lump, while particles of 12 and 15 µm size consist of 5%.

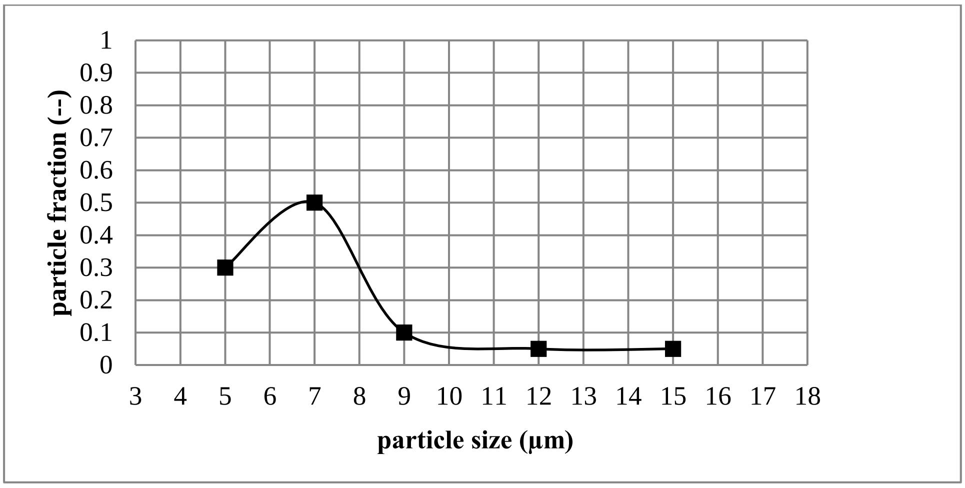
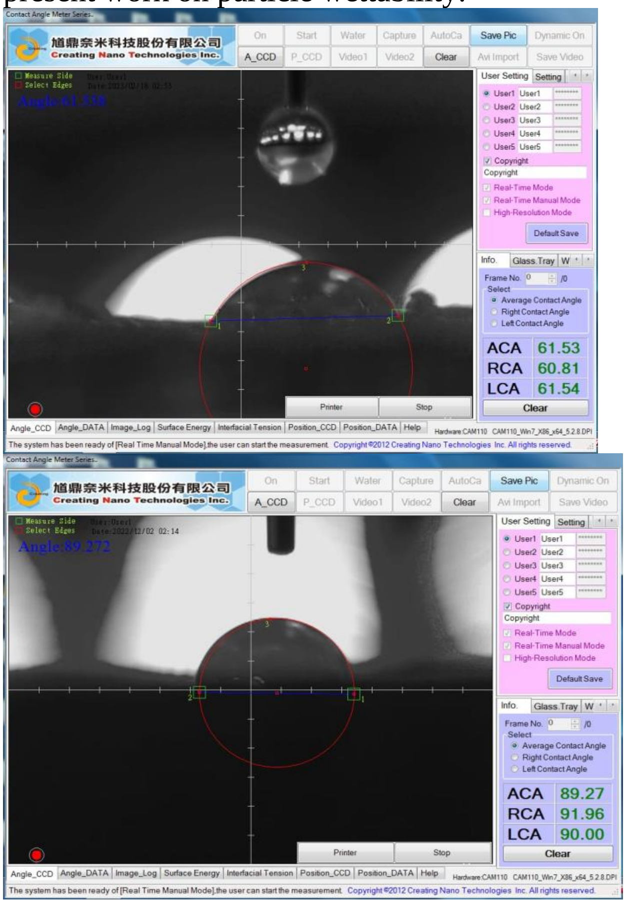


Figure 3: Normal particle distribution against % weight particles holding on a sieve hole

3.2 Surface modification of silica

Figure 4 (a, and b) displays the effect of the surface modification technique used in the the present work on particle wettability.

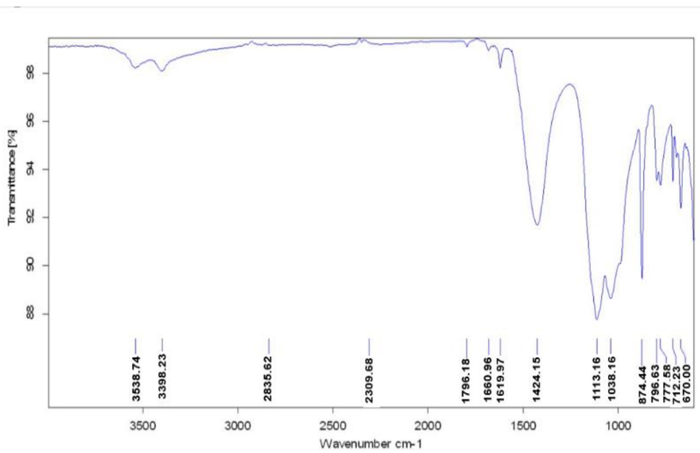


(a) (b)

Figure 4: Water contact angle of Iraqi Silica used (a) before surface modification; (b) after surface modification

Betancur et al. [14] revealed that the surface morphology of the SiO2 Nps has a major influence on the Np−asphaltenes interaction, which resulted in viscosity reduction [15]. On a certain path, siloxane and silanol classes are significant for controlling the adsorption process. Figure 4 plots the common silanol and other Si−O functional classes characterized on the surface of the silica Nps. To investigate the influence of the chemical characteristics of microparticles on heavy oil viscosity decreasing, the surface microparticles were satisfactorily identified using Fourier transform infrared (FTIR) for evaluating composition variations, and the existence of both functional species. The FTIR images of the untreated and treated silica microparticles are shown in Figure 5 (a and b), respectively. As can be seen in Figure 5b, the common oscillations of the siloxane and silanol groups could be noticed in all of the microsubstances. The bands at around 740 and 820 cm^{-1} represent the Si−O bond flection, and the wide band between 845 and 955 cm^{-1} corresponds to the O−Si−O stretching oscillations. Additionally, the neighboring confronting band between 1100 and 1350 cm^{-1} exhibits identical bonds as asymmetric stretching [16]. Furthermore, the existence of silanol groups is linked to the band between 2550 and 3850 cm^{-1} formed by the O−H bond oscillations. The band at 1650 cm^{-1} demonstrates OH scissoring [17].

(a)



(b)

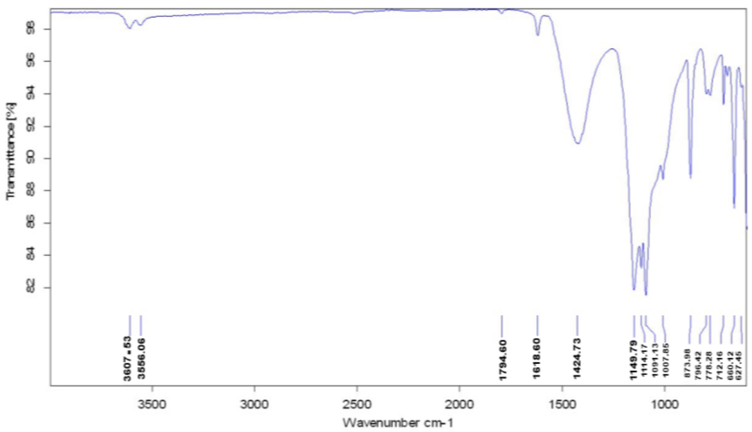


Figure 5. FTIR spectra for silica particles (a) before surface modification; (b) after surface modification

3.3 Effect of operating variables

3.3.1 Effect of particle wettability

Our assessments have been performed at the same loading of hydrophilic and hydrophobic particles with the same crude oil to monitor the rheology attitude for the current work. In Fig. 6, each type of particle creates viscosity reductions, as predicted. Nevertheless, the silica microparticles show the same trend of making changes in viscosity for the loading measured. Note: hydrophobic silica microparticles (SMPs) at 400 mg/L showed a major reduction in the same amounts as hydrophilic silica microparticles. Moreover, it may not be difficult to use silica microparticles again by separating them from the oil using filtration or centrifuging. Hence, the hydrophobic SMP sample exhibited feasibility for being used in oil and gas technology, decreasing costs in the dilution operation for the handling of highly viscous oil. This observation could be recognized from Fig. 7, showing the outcomes quantitatively. Fig. 7 displays that the reduction in viscosity of the hydrophobic SiO2 particles is 31%, higher than the 12% produced by hydrophilic SiO2 microparticles (evaluated at 7.1 s^{-1}) and particle loading of 400 ppm. Moreover, the benefit of utilizing SMP particles is the re-usage they can have, this markedly decreases the consumption of additional silica particles. This can affect the economic side of the operation. This phenomenon (reduction of viscosity) is attributed to the interaction between SMPs and asphaltene aggregates in the heavy oil structure. The asphaltene sorption onto the hydrophobic SMPs enhances the collapse of the viscoelastic framework, which recommends decreasing their viscosity. The demonstration of this situation is quite demonstrated in published data [18-19].

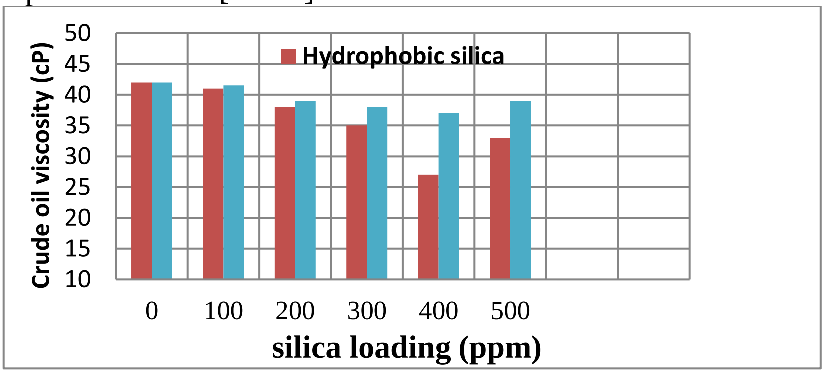


Figure 6: Effect of particle wettability on viscosity reduction for EBCO at different silica loading, and 30^{o}C

3.3.2 Effect of Solid Loading

It is shown in Fig. 7 that when the solid loading increases by more than 400 ppm, the influence on viscosity reduction is of no account, and viscosity may grow in the suspension of oil/ particles. This may be attributed to the clustering influence of the microparticles themselves in the high-viscous oil. The clustering makes the particles work as a lump of solids, decreasing the reaction with asphaltenes and enhancing a rise in viscosity, as stated in Einstein’s theory of viscosity [24] [20]. Moreover, Fig. 7 illustrates the percentage reduction of viscosity for all silica loadings estimated in crude oil [25][21]. Remarkably, at 400 ppm and 30 ^{o}C, a viscosity reduction of 33% was achieved, indicating the better achievement of silica particles over a broad range of loadings estimated. This is an optimistic outcome in the seeking for a hydrophobic particle\ crude oil suspension model that has the potential to promote handling operations. Furthermore, the operation may finally decrease the use of diluents, thereby economizing energy.

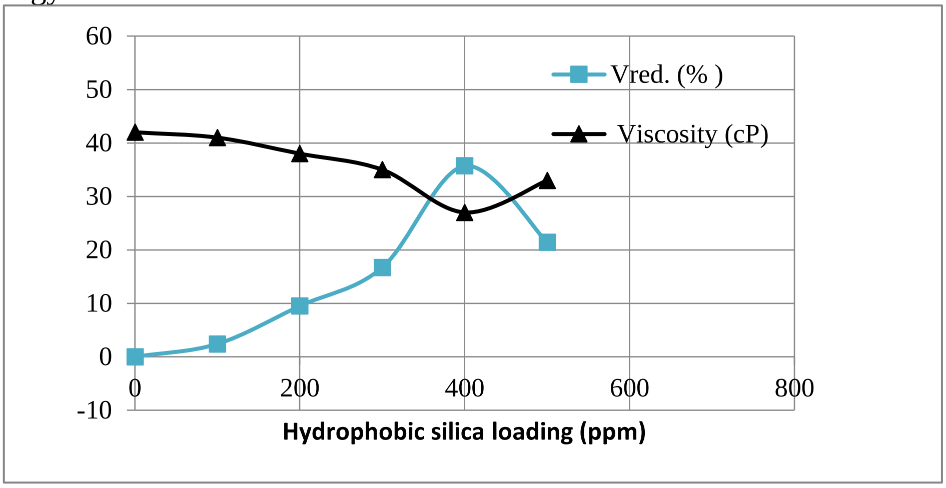


Figure 7: Effect of Hydrophobic silica loading (ppm) on % Vred and crude oil viscosity (cP) at
30 ^{o}C.

3.3.3 Influence of temperature

The influence of temperature on viscosity relies mainly on the source or constituents of the oil. However, it also depends on other parameters, like volatility [26][22]. Nevertheless, for complex setups, like crude oil, a rise in temperature acts mostly on the heavy oil macromolecular frameworks, enhancing aggregate disturbance and maintaining monomer units dispersed. The fluid flow characteristics of the dispersed system could be preferable over those of the arranged macrostructures [27][23], making oil flow resistance better. Analyzing the data in Figure 8, the crude oil without hydrophobic particles was investigated at the studied range of temperature (i.e., 10 to 50 ^{o}C) and has a linear reduction rate in viscosity of 0.25 cP/^{o}C. On the other hand, crude oil with hydrophobic particles has two trends of viscosity reduction rate with temperature. The first trend is linear and has a reduction rate of 0.70 cP/^{o}C in a temperature range of 10 to 30. While a different image from 30 to 50 ^{o}C shows a nonlinear viscosity reduction rate, which can be approximated by linearization to be 0.18 cP/^{o}C. The reduction in viscosity (i.e., 0.25 cP/^{o}C) of crude oil without hydrophobic particles was mainly due to increased temperature from 10 to 50 ^{o}C. A synergetic effect of temperature and hydrophobic particles is shown in the operating range of Fig. 8. The effect of hydrophobic particles on viscosity is dominant, as seen in Fig. 8, with a viscosity reduction rate of 0.45 cP/^{o}C in the temperature range of 10 to 30 ^{o}C . This was attributed to the high adsorption rate of asphalt aggregates onto hydrophobic particles. This effect was minimized as the particles were saturated by asphalting aggregates, as shown in the temperature range of 30 to 50 ^{o}C.

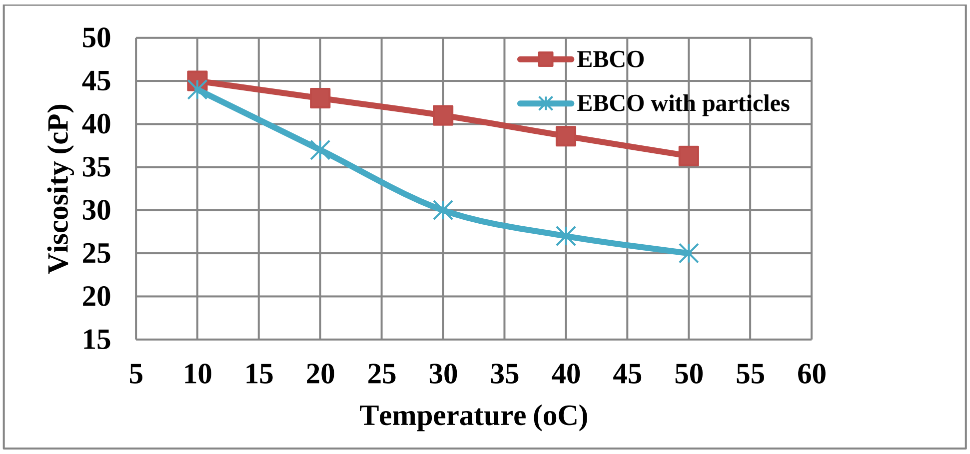


Fig. 8: Variation of viscosity of the east Baghdad crude oil (EBCO) against temperature with or without hydrophobic particles (at constant particle loading of 400 ppm),

4. Mathematical Correlation

A power law equation was suggested (Eqn. 2) to relate the operating variables (i.e., hydrophobic particle concentration and applied temperature) with the objective function (i.e., viscosity of East Baghdad crude oil). The coefficients were estimated using the regression analysis technique.

$\mu\ (cP) = a_0\, C_P{}^{a_1}\, T^{a_2}$ (2)

Where a1 and a2 are constants, indicating the magnitudes of the influence of hydrophobic particle concentration (C_P), and applied temperature (T), respectively, on the objective function, while a_o is a constant that relies on the nature of the system setup. The regression analysis technique using STAISTICA ver. 7.2 software was employed to match the experimental outcomes with the suggested model, giving the Eqn. 3:

$\mu\ (cP) = 60.07\, C_P{}^{-0.028}\, T^{-0.179}$ (3)

Correlation coefficient (R2) = 0.995

Standard deviation = 2.25

Squared error = 3.51

The statistical analysis of equation 3 confirms the validity of this relation to be utilized as a model to forecast the trend of the viscosity reduction over the studied operating variables.

Conclusion

The main goal of this work is to enhance the flow of heavy crude oil from East Baghdad through the piping system using surface-modified silica microparticles. The experimental outcomes reveal that:

Natural silica can be surface-modified to gain hydrophobic characteristics using a simple surface-treatment method. Contact angle measurement and FTIR techniques confirmed the validity of the treatment method. Different operating parameters (e.g., surface wettability, microparticle loading, and temperature) were investigated for their effect on crude oil viscosity reduction. Experimental results showed that hydrophobic particles were more feasible for use in viscosity reduction; hydrophobic silica-particle loading of 400 ppm has the optimum reduction of viscosity of 35%; increasing the loading beyond the optimum particle size has a negative effect on the viscosity reduction. It was observed that at 25, 30, and 50 ^oC, the percentage reduction of viscosity was 19.5, 32, and 34%, respectively, using hydrophobic silica microparticles.

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References

[1] Kumar, R., Banerjee, S., Mandal, A., Naiya, T.K. (2017) Flow improvement of heavy crude oil through pipelines using surfactant extracted from soapnuts. J. Petrol. Sci. Eng. 152, 353e360. https://doi.org/10.1016/j.petrol.2017.02.010

[2] Montes, D., Taborda, E.A., Minale, M., Cortes, F.B., Franco, C.A. (2019) Effect of the NiO/SiO2 nanoparticles-assisted ultrasound cavitation process on the rheological properties of heavy crude oil: steady state rheometry and oscillatory tests. Energy Fuels 33 (10), 9671e9680. https://doi.org/10.1021/ acs.energyfuels.9b02288

[3] Anto, R., Deshmukh, S., Sanyal, S., Bhui, U.K., 2020. Nanoparticles as flow improver of petroleum crudes: study on temperature-dependent steady-state and dynamic rheological behavior of crude oils. Fuel 275, 117873. https://doi.org/ 10.1016/j.fuel.2020.117873

[4] Santos, I.C.V.M., Oliveira, P.F., Mansur, C.R.E., 2017. Factors that affect crude oil viscosity and techniques to reduce it: a review. Braz. J. Pet. Gas 11 (2), 115e130. https://doi.org/10.5419/bjpg2017-0010

[5] Al-Hashmi, A.R., Al-Wahaibi, T.K., Al-Wahaibi, Y.M., Mjalli, F., Al-Omairi, R. (2017) Transportation of heavy oils using polymer-stabilized oil-in-water emulsions. J. Petrol. Explor. Prod. Technol 7 (3), 881e890. https://doi.org/10.1007/s13202- 016-0298-7

[6] Al-Wahaibi, T., Al-Wahaibi, Y., Al-Hashmi, A.A.R., Mjalli, F.S., Al-Hatmi, S. (2015) Experimental investigation of the effects of various parameters on viscosity reduction of heavy crude by oilewater emulsion. Pet Sci. 12 (1), 170e176. https://doi.org/10.1007/s12182-014-0009-2

[7] https://www.brookings.edu/articles/how-much-oil-does-iraq-have/

[8] Oil and Gas Fields in Iraq (doi:10.13140/RG.2.1.2662.5763)

[9] Janan Al-Asady (2019) Iraq’s oil and gas industry: The legal and contractual framework, Routledge Press, Oxfordshire, UK

[10] Kamil Al-Mehaidi (2006) Geographical distribution of Iraqi oil fields and its relation with the new constitution, Revinue Watch Institute, https://resourcegovernance.org/sites/default/files/052706.pdf

[11] James E. Maloney and Thomas R. Oakes “Hydrophobic silica or silicate, compositions containing the same and methods for making and using the same” for making patent number US4443357A in Apr. 17, 1984

[12] H. Quan, and L. Xing, “The effect of hydrogen bonds between flow improvers with asphaltene for heavy crude oil, “Fuel, vol. 237, pp. 276–282, 2019

[13] Mata and D.D. Joseph, Foam control using a fluidized bed of hydrophobic particles. Submitted for publication to Int. J. Multiphase Flow, Vol.25, No.1, PP. 63-85.1997

[14] Betancur, S.; Carmona, J. C.; Nassar, N. N.; Franco, C. A.; Cortés, F. B. Role of particle size and surface acidity of silica gel nanoparticles in inhibition of formation damage by asphaltene in oil reservoirs. Ind. Eng. Chem. Res. 2016, 55, 6122−6132

[15] Taborda, E. A.; Franco, C. A.; Lopera, S. H.; Alvarado, V.; Cortes, F. B. Effect of nanoparticles/Nanofluids on the rheology of́ heavy crude oil and its mobility on porous media at reservoir conditions. Fuel 2016, 184, 222−232
[16] Al-Oweini, R.; El-Rassy, H. Synthesis and characterization by FTIR spectroscopy of silica aerogels prepared using several Si (OR) 4 and R″ Si (OR′) 3 precursors. J. Mol. Struct. 2009, 919, 140−145
[17] Brinker, C. J.; Scherer, G. W. Sol−Gel Science: The Physics and Chemistry of Sol−Gel Processing; Academic Press, 2013
[18] Taborda, E.A.; Alvarado, V.; Cortés, F.B. Effect of SiO 2 -based nanofluids in the reduction of naphtha consumption for heavy and extra-heavy oils transport: Economic impacts on the Colombian market. Energy Convers. Manag. **2017**, 148, 30–42
[19] Yang, X.; Czarnecki, J. Tracing sodium naphthenate in asphaltenes precipitated from athabasca bitumen. Energy Fuels **2005**, 19, 2455–2459
[20] Einstein, A. Eine neue bestimmung der moleküldimensionen. Ann. Phys. **1906**, 324, 289–306
[21] García, R.H.C.; Toro, G.A.M.; Diaz, R.J.; Perez, H.I.Q.; Guardia, V.M.D.; Vargas, K.M.C.; Bustamante, J.M.P.; Aya, C.L.D.; Romero, R.A.P. Polymer flooding to improve volumetric sweep efficiency in waterflooding processes. CTF—Ciencia Tecnología Futuro **2016**, 6, 71–90

[22] Speight, J. G., The Chemistry and Technology of Petroleum. Marcel Dekker, Inc. (1991)

[23] Szilas, A. P., Production and Transport of Oil and Gas. Gathering and Transportation. Elsevier, New York (1986)

دراسة عملية لتخفيض لزوجة النفط الخام الثقيل في حقول شرق بغداد

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من الصعب نقل النفط الثقيل في حقول شرق بغداد عبر شبكة الأنابيب بسبب لزوجته العالية ويستعاض عن ذلك بالسيارات الحوضية مما يؤدي الى زيادة في مشاكل النقل و انخفاض طاقة الانتاج. تضمن هذا العمل دراسة عملية لتخفيض اللزوجة في نفط خام شرق بغداد (EBCO) باستخدام جزيئات السيليكا المعدلة سطحيا لتحويلها الى جزيئات كارهة للماء. تم دراسة متغيرات التشغيل المختلفة، مثل متوسط أحجام الجسيمات (5، 10، 15 ميكرومتر)، تحميل الجسيمات (0، 200، 400، 500 جزء في المليون)، ودرجات الحرارة (10، 30، و 50 درجة مئوية)، لبيان تأثيرها على تقليل اللزوجة. تم استخدام تقنيات FTIR و EDXوزاوية التلامس لتوصيف شكل سطح الجسيم ودرجة قابلية البلل قبل وبعد تعديل السطح، على التوالي، بينما تم استخدام مقياس اللزوجة Brookfield لتقييم التغير في لزوجة النفط الثقيل. أظهرت النتائج التجريبية أن الجسيمات الكارهة للماء كانت أكثر كفائة للاستخدام في تقليل اللزوجة، وأن تحميل جسيمات السيليكا الكارهة للماء بمقدار 400 جزء في المليون ادى الى التخفيض الأمثل للزوجة بنسبة 31٪ عند 30 درجة مئوية؛ كما اضهرت النتائج العملية إن زيادة التحميل بما يتجاوز حجم الجسيمات الأمثل له تأثير سلبي على تقليل اللزوجة. كما درجة الحرارة المحيطة لها تأثير إيجابي على درجة انخفاض اللزوجة في وجود جزيئات السيليكا الكارهة للماء. تم تطوير معادلة بمعامل ارتباط قدره 0.995 لتقييم لزوجة النفط الخام الثقيل كدالة لتحميل الجسيمات الكارهة للماء ودرجة الحرارة.