Tikrit Journal of Engineering Sciences (2025); 32(1): 1783

DOI: http://doi.org/10.25130/tjes.32.1.16

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Impact of Integrating Nanoparticles with Hydrocarbon Solvent on Enhanced Heavy Oil Recovery

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Keywords:

An organic solvent; Degree of viscosity reduction (DVR); Nanomaterials; Solvent concentration; Xylene weight fraction.

Highlights:

- *Effect of integrating nano-silica (SiO_2) with solvent.*
- *Large reduction in the oil viscosity to improve oil production.*
- *Different concentrations of the solvent were combined with various concentrations of nanoparticles to increase oil recovery.*

ARTICLE INFO

Article history:

Received	13 Oct. 2023
Received in revised form	12 Dec. 2023
Accepted	22 Jan. 2024
Final Proofreading	05 Dec. 2024
Available online	21 Mar. 2025

Citation: Hasan MM, Al-Zuhairi FK, Sadeq AH, Azeez RA, Al-Jadir T, Rigby SP. **Impact of Integrating Nanoparticles with Hydrocarbon Solvent on Enhanced Heavy Oil Recovery**. *Tikrit Journal of Engineering Sciences* 2025; **32**(1): 1783.
http://doi.org/10.25130/tjes.32.1.16

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Abstract: Solvent-based enhanced oil recovery has received greater attention lately. Besides solvents, nanoparticles, due to their unique characteristics have also been widely used for enhanced oil recovery techniques to help extract the trapped oil left underneath the surface. This work investigated the effects of nano-silica (SiO_2) and xylene, as a nanoparticle (NP) and solvent, respectively, on the viscosity of heavy crude oil. Several variables were considered to obtain a large reduction in the oil viscosity to improve oil production, including temperature, shear rate, the weight fraction of xylene as a diluent, and concentration of SiO_2 NPs. A Brookfield viscometer was applied to assess the viscosity of crude oil, and it was found that integrating NPs with solvent significantly reduced the total viscosity of the oil to 32 cP when NPs were used vs. 65 cP when the solvent was added alone.

تأثير دمج الجسيمات النانوية مع المذيبات الهيدروكربونية على تحسين استخلاص النفط الثقيل

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الخلاصة

قد حظي الاستخلاص المعزز للنفط المعتمد على المذيبات باهتمام أكبر في الآونة الأخيرة. إلى جانب المذيبات، تُستخدم الجسيمات النانوية، نظرًا لخصائصها الفريدة، على نطاق واسع أيضًا في تقنيات الاستخلاص المعزز للنفط للمساعدة في استخراج النفط المحتجز المتبقي تحت السطح. هذا العمل بحث في تأثيرات النانو سيليكا (SiO_2) والزايلين، كجسيمات متناهية الصغر (NP) ومذيب، على التوالي، على لزوجة النفط الخام الثقيل. للحصول على انخفاض كبير في لزوجة النفط وتحسين إنتاجه، تم أخذ العديد من المتغيرات في الاعتبار، بما في ذلك درجة الحرارة ومعدل القص وجزء الوزن من الزايلين كمخفف وتركيز SiO_2 NPs. تم استخدام مقياس اللزوجة Brookfield لتقييم لزوجة النفط الخام، وقد وجد أن دمج NPs مع المذيب قلل بشكل كبير من اللزوجة الإجمالية للنفط إلى ٣٢ سنتي بويز عند استخدام NPs مقابل ٦٥ سنتي بويز عند إضافة المذيب وحده.

الكلمات الدالة: مذيب عضوي، درجة تخفيض اللزوجة (DVR)، المواد النانوية، تركيز المذيب، الكسر الوزني للزايلين.

1.INTRODUCTION

With the advancement of technology and the exponential population growth, the demand for energy worldwide has been constantly increasing. In recent years, the petroleum industry has become an important foundation for the economic survival of countries, which has led to a decline in petroleum resources from conventional oil reserves. Hence, many petroleum companies are interested in researching unconventional reserves to use them as an alternative energy supply. Most of the world's heavy and extra-heavy oil reserves are considered unconventional [1]. As is well known, petroleum can be produced via the primary recovery stage in which, hydrocarbons using the pressure present in the reservoir are naturally extracted. Then, the secondary recovery stage starts, during which water and gas are introduced into the well to force oil to the surface while providing extra energy to support the reservoir's capacity to keep producing. After that, 60 to 80 % of the oil is still inside the well. Thus, by applying some techniques to change the rock fluid system, the application of the tertiary recovery (Enhanced Oil Recovery, or "EOR"), which represents the final stage, might contribute up to 70% of the initial oil in place (IOIP) to be retrieved [2-7]. Heavy oil represents most of the world's oil reserves, ranging from nine to thirteen trillion barrels. It is an appropriate alternative to conventional oil (extracted by the reservoir's natural pressure). These types of oil also contain a large amount of asphaltenes and other chemical components, including sodium, nitrogen, and others, as well as higher viscosity and density [8]. High viscosity is one of the main characteristics of heavy oil that makes it more difficult to explore and transport than light oil. The high viscosity of heavy crude oil is closely related to its chemical composition and molecular structure due to the presence of a large proportion of high-molecular-weight components, leading to low mobility in porous rocks [9]. Therefore, it is essential to find practical technical techniques to enhance their characteristics and increase oil recovery. Reducing the viscosity using various methods has become the main philosophy in searching for economically viable options to enhance production, mobility, and transportation, thus meeting the market's expected production volumes by Demirbas et al. [10] and Aristizábal-Fontal et al. [11]. Furthermore, only three mechanisms dominate retrieving oil from reservoir rocks instead of using water alone. The methods are divided into those that (a) depend on a drop in oil viscosity, (b) depend on the employment of a solvent for oil extraction, and (c) depend on an alteration in the capillary pressure and viscous forces between the crude oil, displaced fluid, and the rock surface. The EOR techniques are divided into the following three groups: Chemical techniques, which include injecting chemicals or surfactants; thermal techniques, which involve injecting heat; and miscible gas injection techniques, which involve injecting a solvent [12].

1.1.Solvents

Recently, more attention has been paid to solvents as a good scenario to reduce crude oil viscosity for enhanced oil recovery [13, 14]. The crucial benefit of viscosity reduction is that it prevents pressure drop rises, lowers pumping costs, and assists the downstream treatment process steps of desalination and hydration [15]. Experimentally, many types of solvents, such as hydrocarbons, flue gas, and CO_2, can be applied to enhance oil recovery processes [16, 17]. In addition, another study conducted by Mukhamatdinov et al. [18] employed aromatic compounds such as toluene, benzene, and Solvesso-150 (a blend of aromatic composition) as solvents for enhanced heavy oil recovery. The study found that adding aromatic compounds to the oil resulted in the lowest viscosity compared to the original oil. The effect of light oil as a solvent on the viscosity reduction of the heavy crude at room temperature has been studied. It was found that adding 20 vol.% of light crude oil lowered the viscosity of the heavy oil by about 90 %. According to Nourozieh et al. [19], adding a minimal n-hexane to Athabasca bitumen at various pressures and temperatures enhances its mobility and significantly reduces viscosity. Al-Zuhairi et al. [20] used toluene, normal heptane, and a combination of various toluene/n-heptane ratios as solvents to examine their impact on the viscosity decrease in crude oil. The findings revealed that when a certain percentage of (5, 10, and 20 wt.% n-heptane, toluene, and a mixture of different ratios of toluene/n-heptane) were mixed, the viscosity of crude oil reduced from 135.6 to 26.33 cP. Moreover, gas condensate has been blended with various types of Brazilian heavy crude oil with the API ranging from (13.7^o to 21.6^o) to illustrate its impact on the crude oil viscosity. It was observed that a higher viscosity reduction was obtained by adding 32 vol % of solvent [21]. Additionally, the solvent can be used with steam in the increased oil recovery technique known as Steam-Assisted Gravity Drainage (SAGD). The results showed that introducing steam into the solvent in higher oil recovery is achieved with the SAGD technology than the traditional SAGD approach [22].

1.2.Nanomaterials

Nanotechnology is another technology that greatly attracted researchers for application to improving oil production. Several laboratory tests have shown that the addition of nanofluid improves oil recovery by altering the properties of the fluid and rock/fluid, including wettability, viscosity, and interfacial tension (IFT). The nanoparticles have a very large specific surface area, which increases exponentially as the particle diameter decreases [3, 23]. Among several types of nanoparticles selected as heavy oil viscosity reducers, including Fe_3O_4, Fe_2O_3, Al_2O_3, NiO, CuO, ZnO, and their derivatives, silica nanoparticles have received the most attention recently and have shown good results [24, 25]. The effects of silica nanoparticles (SiO_2 NPs) on rock surfactant adsorption were studied by Yining Wu. The findings indicated that the injection of SNP-surfactant solution increased oil recovery by 4.68% compared to the standard surfactant solution. His study also proved that SNP is a cost-effective method for enhanced oil recovery [26]. According to research conducted by Alberto Bila, experimental results indicated that different polymer-coated silica nanoparticles (PSiNPs) could increase the effectiveness of flood oil recovery when used as saltwater injection additives for enhanced oil recovery (EOR). Compared with the 56% OOIP attained by the reference water flood, between 60% and 72% of the initial oil in place (IOIP) was recovered as secondary nanofluid processes. The tertiary recovery method increased the additional oil production from 2.6% to 5.2% of the OOIP [27]. An experimental study was conducted by Ngouangna [28] et al. 2020 to investigate the effect of SiO2 NPs modified by (3 –Aminopropyl) triethoxysilane (APTES) on EOR applications. The performance of the modified nanoparticles in changing the rock wettability into the water-wet sandstone core was evaluated by utilizing the Sessile Drop method. The findings revealed that the oil recovery was enhanced to 75% [28]. Another experimental research flooded four various types of silica nanoparticles (which mainly consist of silicon dioxide, aluminum oxide (Al_2O_3), and mixed oxides (MOX)) that were coated by methacrylate-based polymer molecules into seawater. These results have a significant role in understanding the mechanisms of the polymer-coated NPs injection in porous media through the EOR processes. [29]. In the present study, various concentrations of nano-silica (SiO_2) NPs were combined with different weight fractions of xylene as a solvent to illustrate the effects of several parameters, such as temperature, shear rate, and the weight fraction of xylene. A high reduction in the heavy oil viscosity was obtained due to integrating NPs with solvent compared with using solvent alone.

2.EXPERIMENTAL

2.1.Materials

The Amara oil field in southern Iraq provided this study with a heavy crude oil sample. The physical properties of the Amara oil are presented in Table 1. The heavy oil supplied by the local store was diluted using xylene, and the characteristics of this solvent are listed in Table 2. Additionally, in this experiment, silicon dioxide (SiO_2) (also known as silica) nanoparticles were acquired from local markets (Trading Company, Jiangsu, China), which were integrated with solvent (supplied from Al-Doura refinery) and have the physical characteristics shown in Table 3. The nanoparticles were selected for this study due to their substantial specific surface area, high porosity, and favorable surface activity compared to other NPs. Silicon dioxide is acid- and water-resistant, in addition, to its economic reason of being low cost. Furthermore, nano-silica can be used effectively because it is inert and does not chemically react with rocks [30].

Table 1 Physical Properties of the Amara Oil.

API^o	Density (gm/cm^3)	Viscosity (cP)
16	0.979	135.6

Table 2 Characteristics of the Solvent Xylene.

Molecular weight (gm/mole)	Density (gm/cm^3)	Viscosity (cP)	Boiling point K	Melting point K	Flash point K
106.17	0.68	0.812	410.91	225.75	302.15

Table 3 Physical Properties of Nano-Silica.

Chemical formula	Molecular weight (gm/mole)	Density (gm/cm^3)	Particle size (nm)	Boiling point (K)	Melting point (K)	Surface area (m^2/gm)
SiO_2	60.08	2.196	20	3223.15	1986.15	122.17

2.2.Sample Preparation

Several samples were used, starting with crude heavy oil alone. Then, the heavy oil was combined with various xylene concentrations (5, 10, and 20 wt %). The crude oil and 20 wt % xylene combination were then mixed with different quantities of silica nanoparticles (10, 100, 500, and 1000 ppm). A 125 ml beaker-sized sample was prepared for each processing step. The sample was then agitated on a magnetic stirrer for an hour to achieve a homogenous mixing. Using a viscometer of type Brookfield (USA) model DV-11, which is a programmable viscometer equipped with a temperature sensor and connected to the computer, the viscosity of the samples was measured under a wide range of shear rates of (2 to 42 s^{-1}). The magnetic stirrer and the viscometer used in the experiments are presented in Fig. 1. The rheological parameters were measured at a temperature of 298.15 K prior to the tests. Additionally, several temperatures of 298.15, 308.15, and 318.15 K were considered to see how they affected the crude oil viscosity.

Fig. 1 The Magnetic Stirrer and the Viscometer of Type Brookfield Used in the Experiments.

3.RESULTS AND DISCUSSION

Because of the high viscosity of heavy crude oil, extracting such oil from reservoirs faces plenty of challenges. Under typical reservoir conditions, one of the major difficulties is that oil does not readily come out to the surface. Therefore, the primary target of decreasing viscosity is to improve heavy oil production. In this study, the oil sample was combined with nano-silica particles and treated with various solvent concentrations at varying temperatures to investigate these parameters' effect on the enhanced recovery of heavy oil. Integrating nano-silica particles with solvent may enhance several variables, including interfacial tension and rock wettability, and significantly decrease crude oil viscosity, increasing oil recovery. The findings of these experiments are discussed below:

3.1.Effect of Xylene Weight Fraction

Figure 2 shows the behavior of heavy oil viscosity after blending xylene as a diluent in various concentrations at a temperature of 298.15 K. It can be seen that the viscosity of heavy oil without a diluent was decreased slightly with the increase in shear rate, the viscosity decreased from about 132.6 to 110 cP, while blending organic solvent of various concentrations has assisted in reducing the viscosity of the oil, showing that viscosity reduction increases with increasing diluent concentration and shear rate. Figure 2 also illustrates that the crude viscosity decreased from about 132.6 to 102.3 cP when mixed with 5 wt% xylene, while the viscosity lowered to 89.2 cP when blended with 10 wt% xylene. Furthermore, when 20 wt % of xylene was integrated with crude oil, the oil viscosity reduced to approximately 65.5 cP, indicating a 48% drop in viscosity. Most high molecular weight materials in heavy crude oil, such as waxes, asphaltenes, and resins, are responsible for its high viscosity. Because of the dilution caused by adding solvent to the heavy oil, the viscosity of the heavy crude oil is reduced. The results obtained are consistent with the findings reported by Al-Zuhairi [20] and his colleagues. Figure 3 displays the behavior of crude oil viscosity regarding the relationship between the degree of viscosity reduction (DVR%) and shear rate. It has been observed that the viscosity reduction increased with the increase in weight fractions of solvent. The findings revealed that 24.56 DVR % was obtained by blending 5 wt % xylene with heavy oil at a rate of 42 s^{-1}, while this value was raised to 34.22 DVR % when crude oil was mixed with

10 wt% xylene at the same shear rate. The greatest viscosity reduction occurred at the maximum xylene value of 20 wt% for all shear rate values. Structure formation within the diluents at a specific shear rate is believed to cause the viscosity reduction.

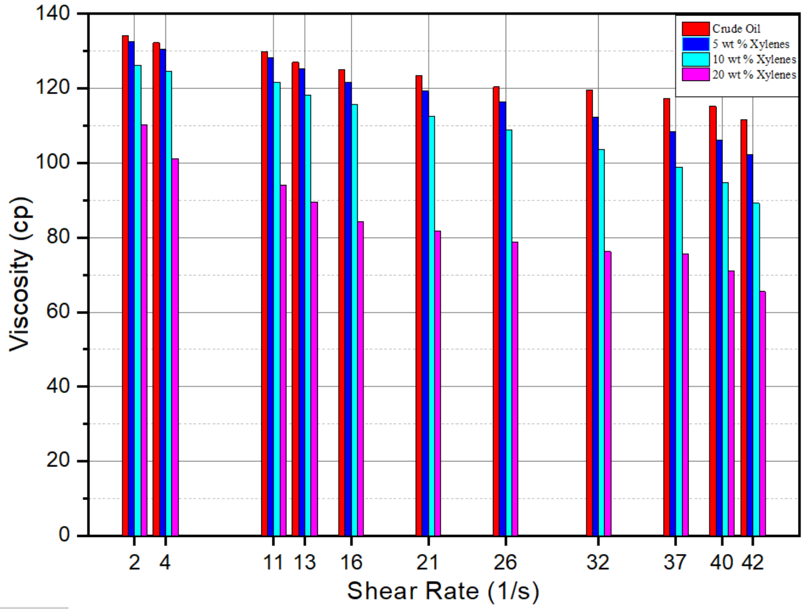

Fig. 2 The Behavior of Heavy Oil at Various Xylene Weight Fractions.

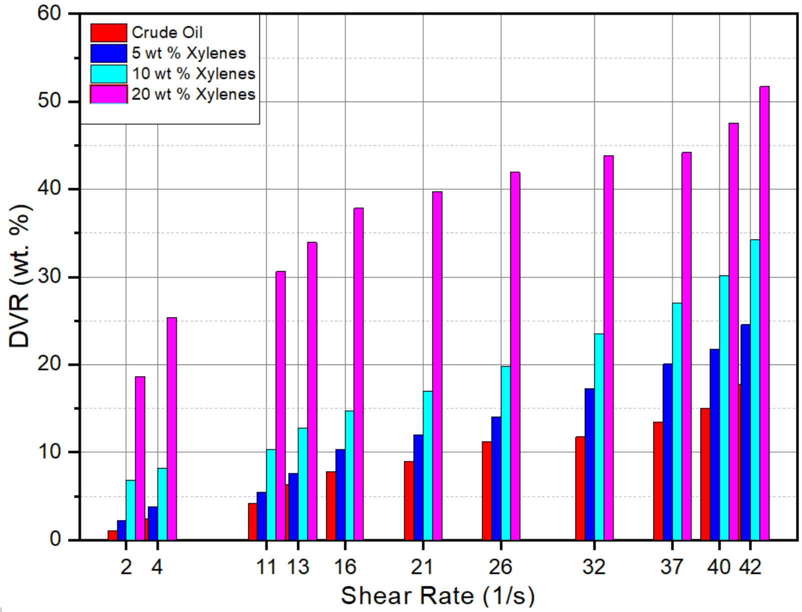

Fig. 3 Reduction in Viscosity of Heavy Oil at Different Xylene Weight Fractions.

3.2.Effect of Nanoparticle Concentrations

Moreover, since the results obtained from Figs. 2 and 3 revealed that blending 20 wt % of xylene with crude oil resulted in the highest viscosity reduction; therefore, this percentage was taken and combined with different nanomaterials concentrations in the form of silica nanoparticles (SiO_2) NPs. This integration aims to investigate the impact of Nanoparticle-Enriched solvents on enhanced oil recovery. In the present study, four nano-silica samples were blended with 20 wt % xylene to analyze the crude oil viscosity behavior and compare it with pure heavy crude oil. Figure 4 presents the effect of different concentrations of SiO_2 NPs dispersed in 20 wt % xylene as a diluent on decreasing the viscosity of heavy oil. From Figure 4, it is distinctly observed that increasing the concentrations of SiO_2 NPs in xylene led to a decrease in the viscosity of the crude oil. This behavior can be explained by the adsorption ability of SiO_2 NPs towards asphaltene; thus, the interaction between asphaltene and NPs is better than between asphaltene and asphaltene in crude oil [11]. The dispersion of NPs in the oil phase occupies a larger area, which weakens electrostatic bonds among the asphaltene atoms, decreasing the viscosity of the crude oil [31]. It can also be noticed from Figure 4 that the viscosity decreased from 106.5 cP to a range from 53.5 to 43.79 cP after blending heavy oil with 20 wt % xylene and 10, 100, and 500 ppm, respectively. An even greater lowering in the oil viscosity reached 31.9 cP by adding 1000 ppm SiO_2 NPs to 20 wt % of xylene mixing with pure oil. Figure 5 shows how improvements in the percentage of viscosity reduction (DVR) were made by altering the concentration of the nanoparticles inside a specific weight percent of solvent as well as shear rates. According to the experimental findings, at the highest concentration of silica NPs, the reduction in oil viscosity was maximized. In contrast to crude oil alone, the heavy hydrocarbon viscosity was drastically reduced at 1000 ppm of nanomaterials. Additionally, an oil sample treated with 20 wt % xylene and 1000 ppm SiO2 NPs was examined using a range of shearing rates from (2 to 42 s^{-1}). The viscosity of the heavy oil was found to be considerably impacted by temperature, as seen in Figure 6, which illustrates the relationship between shear rate and temperature. Specifically, a considerable decrease in viscosity was observed upon increasing the temperature from 298.15 K to 318.15 K. Moreover, when the molecules in a solvent move more quickly, they interact with the solute molecules more frequently and with greater force, which usually leads to more dissolution. However, since different substances are composed of different atoms, ions, or molecules, increased temperature will affect their solubility to varying degrees. On the other hand, as seen in Figure 7, the DVR% considerably increased as the temperature rose. Figure 6 shows that with 20 weight percent xylene and 1000 ppm, the viscosity DVR% decreased from about 42.8% at 298.15 K to about 82.01% at 318.15 K. As stated by Bera and Kumar [32], heavy oil thermal cracking in the presence of nanoparticles enhances the characteristics of crude oil by reducing oil viscosity, upgrading heavy oil, and eliminating contaminants present in the oil.

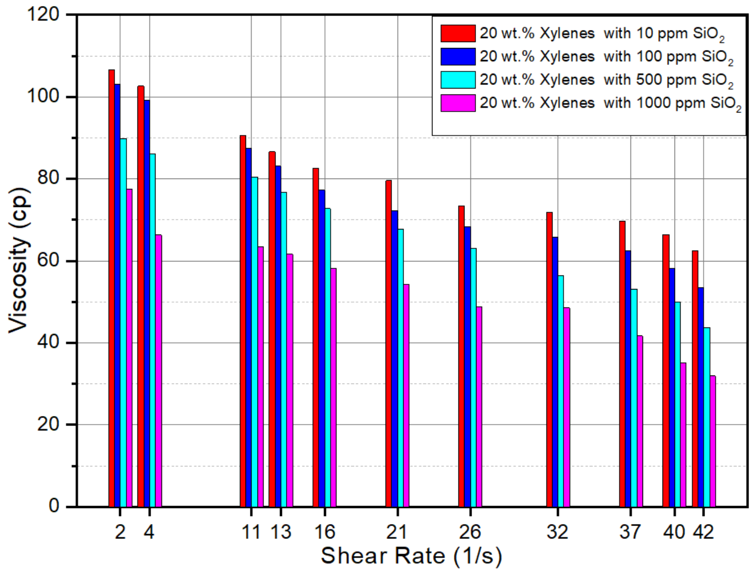

Fig. 4 Viscosity Reduction of Crude Oil Including 20% Xylene at Various Concentrations of Solvent.

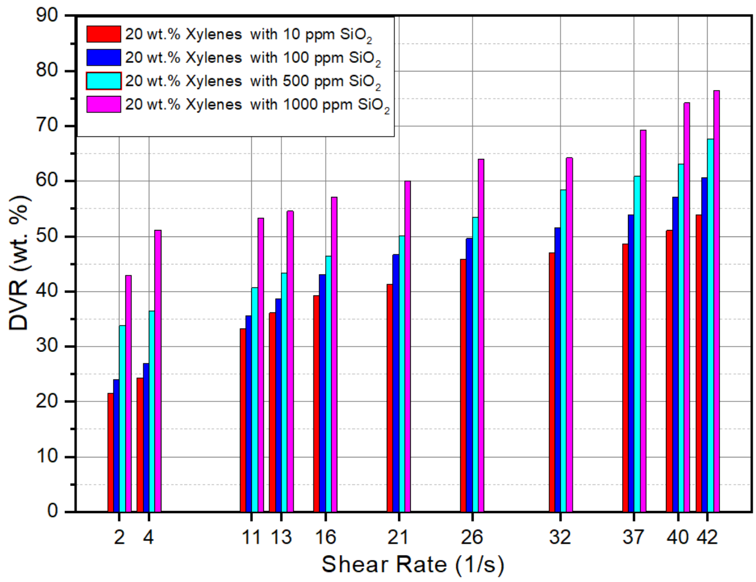

Fig. 5 The Reduction Degree in the Viscosity of Heavy Oil Treated with 20% Xylene at Different Concentrations of Solvent.

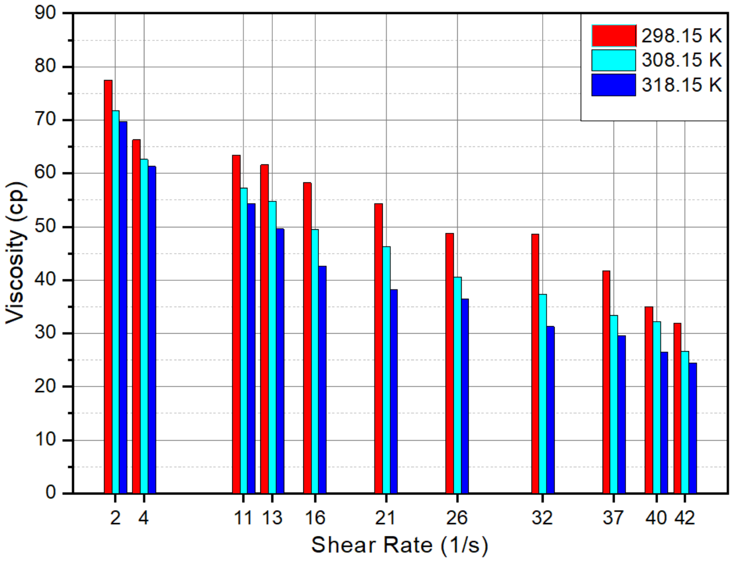

Fig. 6 The Oil Viscosity Behavior Treated with 20% Xylene and 1000 ppm Nanoparticles Concentrations.

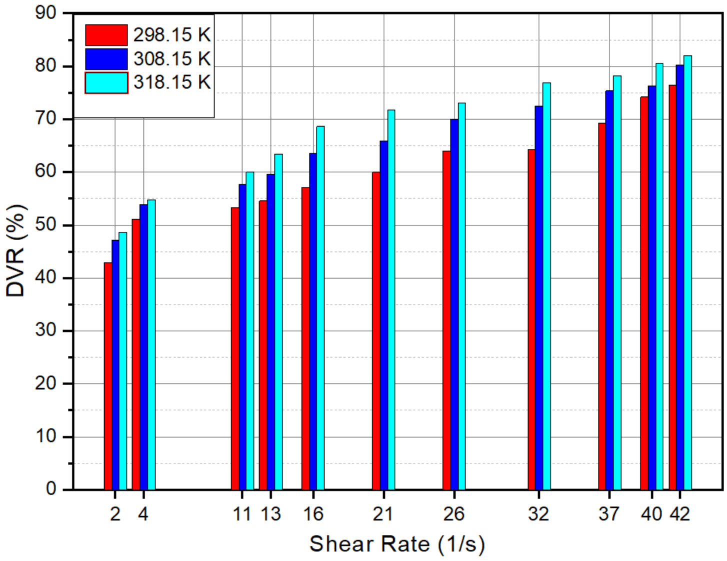

Fig. 7 The Weight Percent of Oil Viscosity Reduction Processed with 20% Xylene and 1000 ppm Concentration of Nano-Silica.

4.CONCLUSIONS

This work employed many experimental tests to analyze and comprehend the effects of silica nanoparticles (NPs) on the viscosity reduction of heavy crude oil when combined with different xylene concentrations as a solvent to improve oil recovery. This study has considered the impact of various parameters such as temperature, shear rate, and concentration for solvent and nanomaterial. The findings detected that the crude viscosity was reduced to about 63 cP when different concentrations of just solvent were used to dilute the crude oil. Compared to the solvent alone, the lowering of the heavy oil's viscosity significantly increased when different concentrations of the solvent were combined with various concentrations of nanoparticles. An even greater reduction in oil viscosity was achieved by adding 1000 ppm SiO_2 NPs to 20 wt % xylene mixed with pure oil, resulting in a viscosity of around 32 cP.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the staff of the Oil and Gas Engineering Department, University of Technology-Iraq, for supporting this work.

NOMENCLATURE

Acronym	Meaning
DVR	Degree of Viscosity Reduction
EOR	Enhanced Oil Recovery
IFT	Interfacial Tension
IOIP	Initial Oil in Place
NPs	Nanoparticles
OOIP	Original Oil in Place
PSiNPs	Polymer-Coated Silica Nanoparticles
SAGD	Steam-Assisted Gravity Drainage
SNP	Silica Nanoparticles

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