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Impact of surface-modified silica and magnesium oxide nanoparticles on the flow behaviour of East Baghdad crude oil and emulsion

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HIGHLIGHTS

- As oil wells age, water content rises, creating stable emulsions at 50% water cut.
- 3% modified Nanosilica enhances flow and reduces viscosity.
- 3% MgO addition significantly alters fluid behavior at high water cuts.
- Power consumption decreases with SiO_2-added emulsions.

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ABSTRACT

The transportation of crude oil naturally, including emulsion from the wellhead to the processing facility, presents a challenge in the oil industry, particularly as wells age and the production of associated water increases. To improve the flowability of the emulsified oil, traditional methods for reducing the viscosity, such as dilution and heating, are costly and energy-intensive. However, nanotechnology offers a potential solution to improve flowability and crude oil behavior. This paper examines how adding 3% wt of surface-modified silicon dioxide (SiO_2) and magnesium oxide (MgO) nanoparticles impacts the flow properties of an emulsion containing East Baghdad crude oil. The investigation is conducted across different water cut levels (5%, 35%, 50%, and 75% v/v) within a horizontal pipe 0.0145 m inner diameter and 13m in length. The effect of these nanoparticles on emulsion stability, rheology, viscosity, pressure drop, and energy consumption was studied. The rheology study found that the best results were achieved by adding surface-modified nano silica at 3%, which significantly reduced viscosity with shear thinning behavior. Adding 3% nano-silica obtained a highly stable emulsion and a higher reduction of 69% in power consumption for pumping the fluid. In comparison, a 25% increase in power consumption was achieved by adding the same concentration of MgO.

1. Introduction

The transportation of crude oil, including emulsion, in East Baghdad's oil field from the wellhead to the processing facility presents a significant challenge due to its low mobility. While various aspects of oil production have been researched, few have studied the crude oil emulsion rheology and the expected impact of water content on crude oil viscosity, which is an essential impact to consider, given the potential for increased water content over time in aging wells. The popularly reported types of emulsions encountered in the petroleum industry include the binary-component water-in-oil (W/O) and oil-in-water (O/W) emulsions [1-10]. The addition of nanoparticles to various base fluids allows the creation of diverse nanofluids. The stability and dispersion of nanoparticles in solutions rely on the functionality or surface activity of the nanoparticles. It was pointed out that the most interesting feature of nanosilica-stabilized emulsions is their very high viscosity at relatively low particle concentrations [11]. Experimental findings have shown that increasing the water fraction, asphaltene content, and shearing energy form a tightly bound emulsion [12]. Extensive investigations have confirmed that asphaltenes, highly polar fractions of crude oil, can be adsorbed on various types of nanoparticles [13,14]. Other researches revealed that the aggregation of asphaltenes can be reduced by changing the physicochemical conditions with silica and alumina nanoparticles [15-19]. Also, similar experiments indicated that silica nanoparticles effectively decreased crude oil's viscosity by decreasing the average size of asphaltene aggregates [20]. The asphaltene is dispersed due to the presence of nanoparticles, which has proven to be an essential factor in their application as flow improvers [21]. Another experiment showed that when nanoparticles are added to crude oil, their viscosity increases, but their presence does not affect the Newtonian flow behavior of oil [22]. Another study examined how energy dissipation affects

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pressure drops in oil-water emulsion lines. The findings were that, as the water cut ratio increased, more water in the oil emulsion was formed, leading to a higher pressure drop [23]. Other researchers found that variations in the properties of emulsions are significantly affected by the presence of solid particles and surfactants in water-oil emulsions. Produced emulsions with nanoparticles had lower viscosity than crude oil, reducing the system's viscosity and making it more suitable for pumping out [24]. In similar work through rheological experiments conducted on crude oil with and without nanoparticles, it became evident that including nanoparticles enhanced the flow properties by modifying the viscoelastic network. As a particular example, crude oil with silica nanoparticles (0.3 wt%) exhibited a much larger decrease in viscosity than when alumina nanoparticles treated the oil sample. It also manifested different effects on the behavior of both crude oil samples.

The produced oil and water are transported in the shape of crude oil, free water, and emulsions from the wellhead to the process facilities in the East Baghdad field. However, the transport of the emulsion in pipelines is challenging due to the occurrence of pressure drops. Estimating pressure drops of a given pipeline considers the flow frictional losses of crude and water, but there is no consideration of the effect of emulsions. To contribute more understanding to flow assurance research, the relationship between emulsion formation, pressure drop, and the energy consumption is further discussed and studied in this research. Hence, this work aims to study the impact of adding two types of nano-particles of SiO_2 and MgO on the flow behavior index, viscosity, pressure drop, and power consumption of the water-oil emulsion flow in the pipeline with different water-to-oil ratios.

2. Experimental work

2.1 Material

2.1.1 Crude oil

The fresh, untreated crude oil sample was collected from the east Baghdad field. The oil sample was collected carefully after flushing the line for a long time to ensure a representative sample would be taken for this study. East Baghdad crude oil is classified as a low API for medium crude oil, as proposed by Rendon et al., [25]. Table 1 represents the laboratory test to identify the crude oil's physical properties.

Table 1: East Baghdad crude oil specification

Test	Unit of Measurement	ASTM	Result
Density at 15 C	g/cm^3	D5002	0.9133
API	-	D5002	23.4
Salt Content	PTB	D3230	2410
Pour Point	C	D 97	-27
H2S Content	PPM	D7621	5
BS&W	Vol.%	D4007	2
Water Cut	Vol.%	-	2
Sediment	Vol.%	-	0
Wax Content	Wt.%	UOP46-85	1.9
Carbon Residue	Wt.%	D4530	8.186
Sulfur Content	Wt.%	D4294	3.8766
Asphaltene Content	Wt.%	D6307	5.8

2.1.2 Water

The water used in this study was tap water. The tap water source used for this investigation was local municipal tap water. This approach was similar to the work done by Sen et al., [26].

2.1.3 Magnesium oxide

Hydrophilic Magnesium Oxide (MgO) is metal oxide at 20 nanometer sizes. The material was supplied by US Research Nanomaterials, Inc.. The product specification is illustrated in Table 2.

Table 2: Magnesium Oxide physical properties

Magnesium Oxide	Water insoluble
Purity	99+ %
Average Particle Size (APS)	20 nm
SSA	>60 m^2/g
Color	White
Density Bulk	0.145 g/cm^3
True Density	3.58 g/cm^3

2.1.4 Surface modified SiO_2

US Research Nanomaterial Incorporated manufactures hydrophilic surface-modified silicon dioxide (Silica). 3-4% KH570 coats its surface with particle sizes ranging from 20-30 nm. Table 3 represents the physical properties of surface-modified silicon dioxide.

Table 3: Surface-modified Silicon Dioxide physical properties

Silicon Dioxide	Hydrophilic
Purity	95.9+ %
Average Particle Size (APS)	20-30 nm
SSA	130 – 600 m^2/g
Color	White
Bulk Density	<0.1 g/cm^3
True Density	2.4 g/cm^3
CAS NO	7631-86-9

2.2 Sample preparation

The emulsion preparation process started by adding MgO / SiO_2 to water at 3% wt of total tap water. This step expressed particle concentrations in weight percentages relative to the water phase (5, 35, 50, and 75) vol%. The sample was mixed at high speed (2000 rpm) using a Heidolph mixer (RZR 2020 module, Heidolph Instruments GmbH & Co., Schwabach, Germany) for 10-15 minutes.

Next, water/nanoparticle samples were added to the oil and sti stirred for 10 minutes. The last step is homogenizing the sample for 3 minutes using a Crown Professional homogenizer device.

2.3 Experimental setup

One of the main objectives of this study is to investigate the pressure drop over the pipeline for emulsion samples prepared in the previous section. A lab-scale loop is specifically designed and fabricated for this purpose. The flow loop consists of 13 meters pipeline length with an inside diameter of 0.014 m, two pressure gages that are far from each other by 5.5 m, a sampling line, calibration pot, 0.016 m^3 conical tank, and gear pump for pumping the fluid through the loop at a constant volumetric flowrate of 1.052×10^{-5} m^3/sec. The schematic of the experimental flow loop is presented in Figure 1.

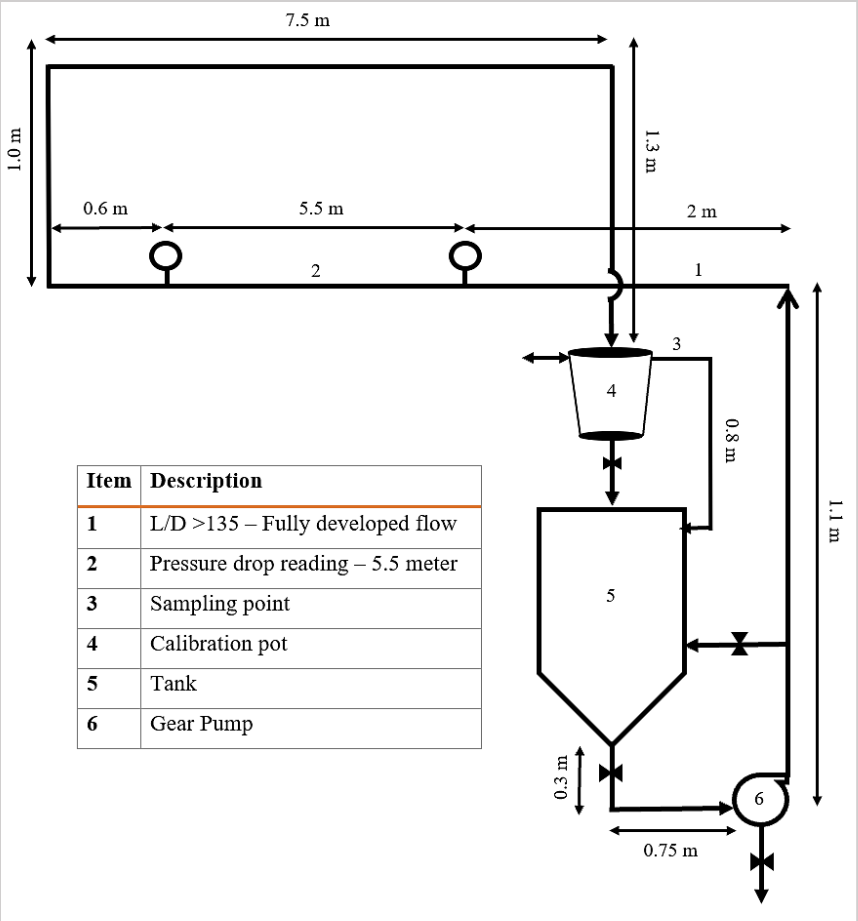

Figure 1: Experimental flow loop scheme

2.4 Measurements and tests

This study will monitor stability using the general Basic Sediment and Water (BS&W) test following the ASTM method D4007. The rheology study will be carried out using a Brookfield rheometer (DV3T module). The test will be conducted at a constant temperature using a jacketed holder with water recirculation to mimic the field condition of 45 ℃.

In addition to the above tests, the flow loop system will be used to investigate the pressure drop over the 5.5-meter-long tube for the advanced prepared emulsion stated in section 2.2.

3. Results and discussion

3.1 Stability test

The emulsion volume that remains after conducting the BS&W test is presented in Figure 2. In 0% nano additives, the 5% water cut illustrated lower stable emulsion volume. This trend was true for all other emulsions, even those in which the nano additives were used with a 5% water cut. This might be because a less dispersant volume of water results in a lower volume of stable emulsion. The emulsion appeared when no nanoparticle was added, which could be justified by other emulsifier agents that are naturally present in the oil.

The different water cuts represent different ages of the well, showing different values for the created stable emulsion for blank samples (no nanoparticle was added). At the point where, as illustrated by Figure 2, the water cut reaches 50%, the highest volume of stable emulsion will be formed as both oils and water come together in their best proportion to form the maximum amount possible. Further increases in water cut without adding nanoparticles will reduce the volume of a stable emulsion. Once the nanoparticles were added, it was found that all water cuts treated by 3% surface-modified nano silica formed a higher volume of stable emulsion compared to blank samples. The highest stable emulsion volume obtained was 50% water cut and 3% nano-silica. Studies have shown that the excess of non-adsorbed particles contributes to stabilizing the emulsions by forming a three-dimensional network of flocculated particles. This improves the stability by interfering with the mutual contact of the droplets [27,28].

A more stable emulsion at a higher volume was gained when the MgO nanoparticle was examined in this study. This can be attributed to the fact that the magnesium oxide employed in preparing the emulsion was a powder with a strongly basic character, which helped increase the emulsion's basicity, giving it more stability. The comparison of the emulsion volume and stability after conducting the BS&W test for both MgO and SiO_2 is shown in Figure 2. A higher and more stable emulsion for MgO than surface-modified SiO_2 can be seen in that Figure.

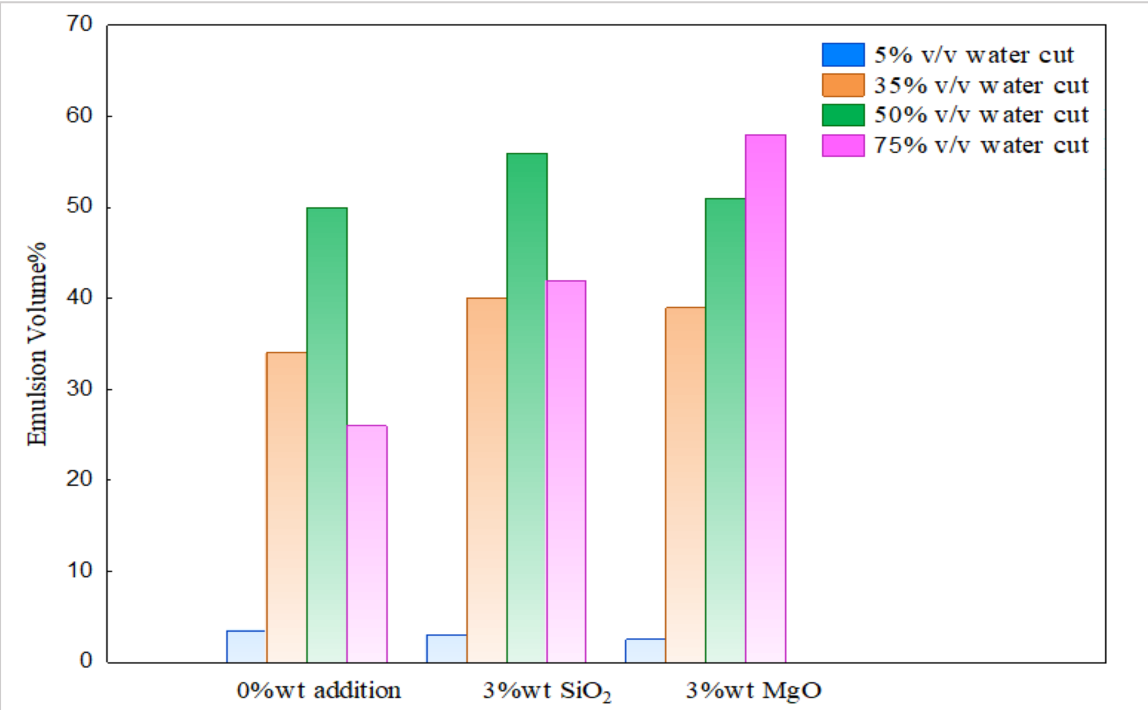

Figure 2: Stable emulsion volume with/without nano additives

3.2 Rheology test

The experimental data of shear stress and shear rate were plotted to examine the flow behavior model using the best curve fitting. The obtained data shows a shear-thinning behavior following the power law model Equation 1.

$$\tau = K(\gamma)^n \quad (1)$$

In which τ is shear stress, γ shear rate, K (consistency index), and power index (n). Table 4 shows the prepared emulsions' power index and consistency index values.

Table 4: Fluid behavior data for the emulsion prepared with/ without the addition of nanoparticles

Nanoparticle Type		Water Cut%				
		0%	**5%**	**35%**	**50%**	**75%**
0%	K	0.03	0.03	0.38	0.55	0.49
	n	0.93	0.98	0.50	0.50	0.57
	R^2	0.99	1.00	1.00	1.00	1.00
	Var	0.99	1.00	1.00	1.00	0.99
3%wt SiO_2	K		0.05	0.19	0.11	0.02
	n		1.01	0.64	0.96	1.15
	R^2		1.00	1.00	1.00	1.00
	Var		1.00	1.00	0.99	1.00
3%wt MgO	K		0.02	0.26	0.20	0.06
	n		1.07	0.78	1.15	2.50
	R^2		1.00	0.94	1.00	1.00
	Var		1.00	0.89	1.00	1.00

Table 4 shows that an increase in water cut from 0-75% leads to shear thinning behavior when no nanoparticle is added to the sample. In the 5% water cut, all nano additions kept the flow index at a very narrow range of 0.98- 1.07 with almost Newtonian flow characteristics. When SiO_2 was added, the power index showed a shear thinning behavior, except for a 75%v/v water cut, which went up to 1.15. On the other hand, MgO addition showed a significant rise in power index significantly in 75% water cut when the fluid behavior showed shear thickening behavior with a power index of 2.5. In further detail, the study of viscosities vs. the applied shear rates for the prepared samples is presented in Figures 3 to 5.

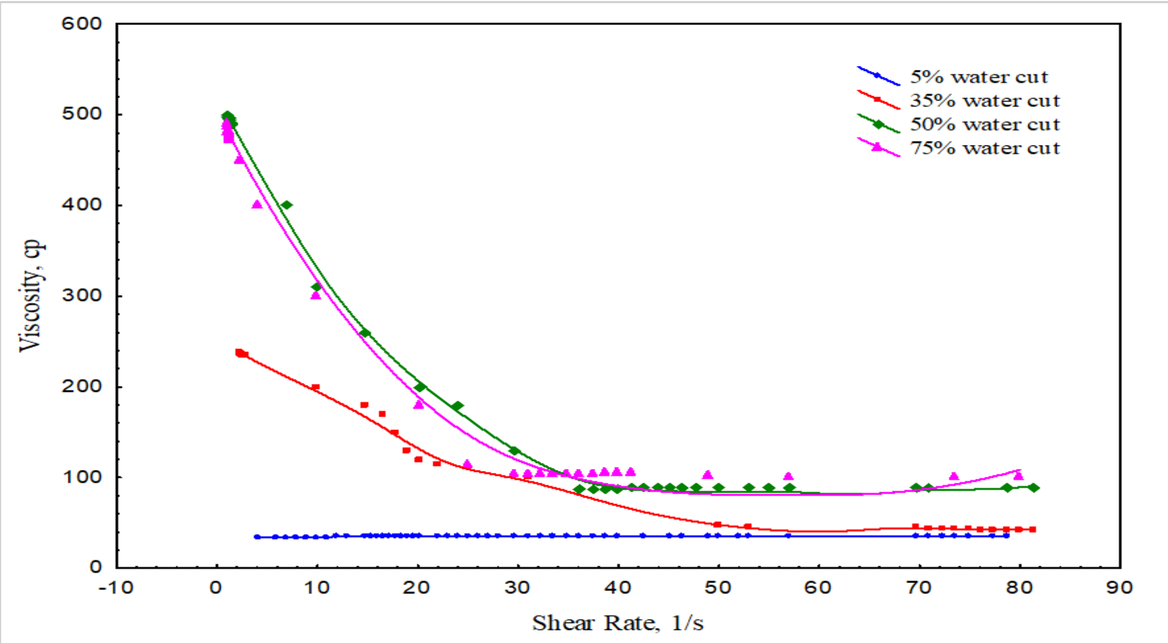

Figure 3: 0% nano silicon dioxide particle at different water: oil ratios at 45 °C

From the first glance at Figure 3, it is obvious that the viscosity is decreasing with increasing share rate values. It is also noticeable that at the higher water cut, the viscosity trend shows a steeper reduction in viscosity with respect to applied shear rates. Furthermore, the 5% water-to-oil ratio sample could be considered a Newtonian behavior with almost a 0.98 power index. However, the rheometer was able to sense a very low margin reduction in viscosity over the range of studied shear rates. In contrast, the viscosity values and the fluid behavior were more obvious at higher water ratios, and most behaved as a shear-thinning fluid. At the highest water ratio (75% water content), the viscosity showed a much lower value compared to a 50% water cut sample, and this can be explained by the fact that part of the water content was partially dispersed in oil as an emulsion. The rest of that volume was settled out of the sample. Overall, sample viscosity was impacted by the nondispersed part. This more severe reduction in viscosity is explained by the fact that in emulsions with high water content, the possibility of droplets deforming significantly is higher due to greater collisions brought about by the applied shear force. Such deformation can lead to the droplets sliding over each other, thereby making the emulsion less resistant (less viscous) to the applied shear and resulting in a higher drop in viscosity values [29].

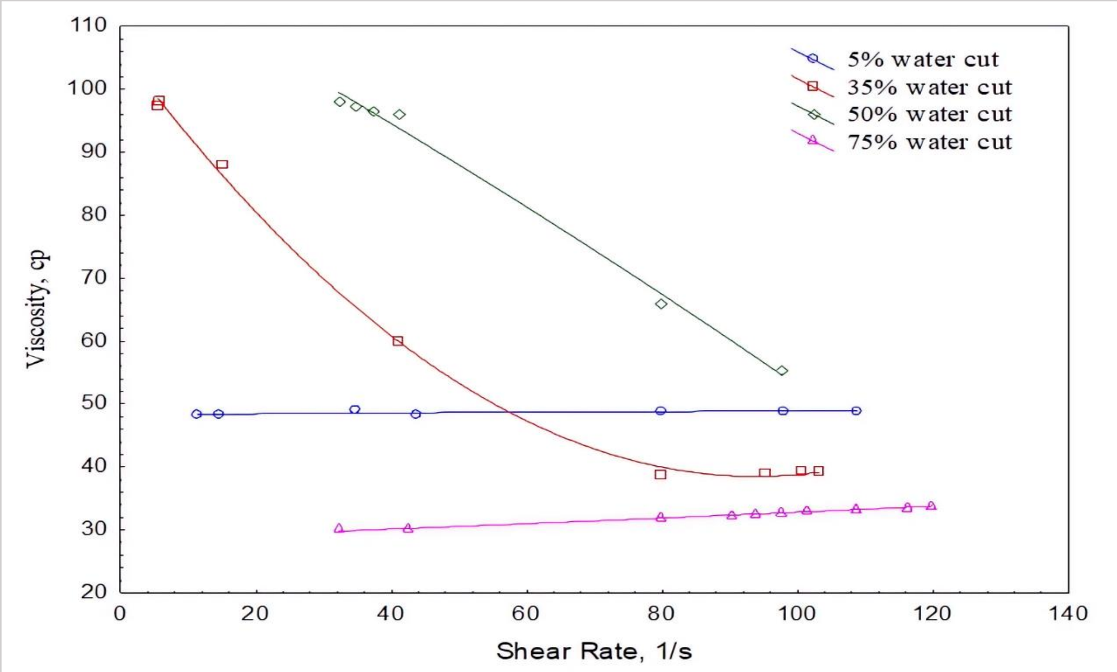

Figure 4: 3% nano silicon dioxide particle at different water: oil ratios at 45 °C

Adding nano silicon dioxide to the 5% water cut sample slightly increased viscosity readings. The viscosity raised to 48 cP, and it seems the nanoparticles increased the resistance between the crude oil layers when the sample was subjected to a shear force. However, the sample still exerts Newtonian behavior. The 35% water cut sample showed a shear thinning behavior and reduction in viscosity reading ranges compared to the 35% without SiO_2 nano addition. The 50% water content sample showed a lower viscosity than the blank sample in Figure 2. The viscosity started at 100 cP for a 3% dosage rate of nano silica, while the viscosity was 200 cP at the same shear rate of $7.5s^{-1}$. In the higher water cut, 75%, the viscosity dropped significantly due to the water phase being a continuous phase and showing lower resistance to the movement of the fluid layers. The results were similar to the one achieved by the study of Umer et al. [30] when 20-50% water cut samples were studied, and the emulsion viscosities for the higher water cuts (50%) decreased more significantly than those with lower water cuts.

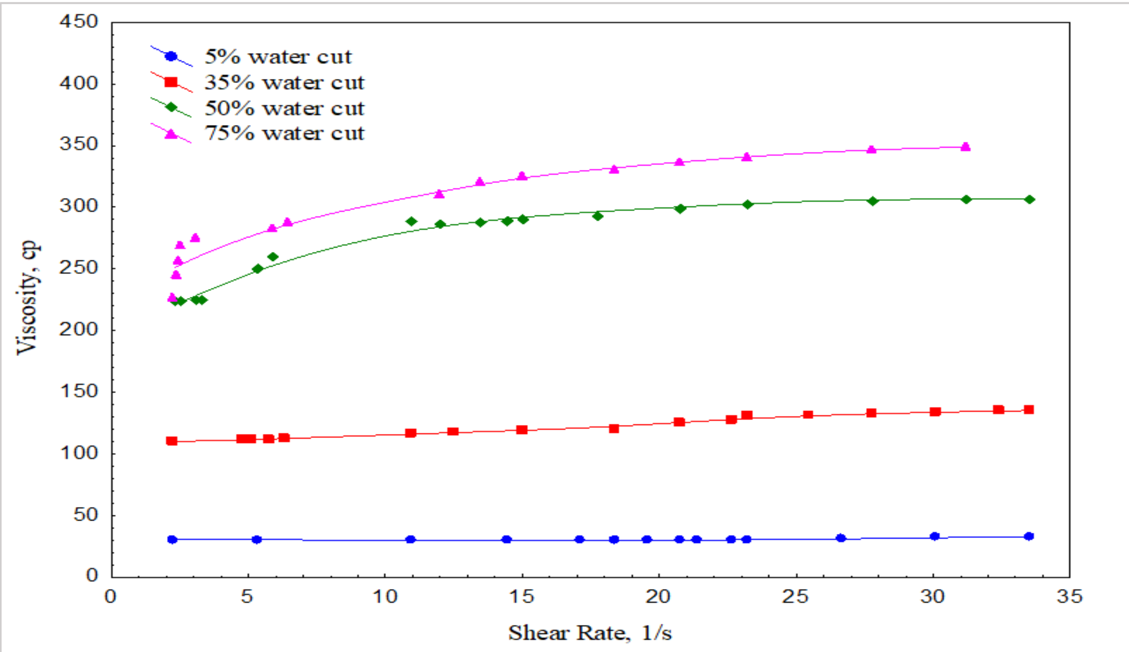

Figure 5: 3% nano Magnesium Oxide particle at different water: oil ratios at 45 °C

In Figure 5, the overall fluid behavior after adding MgO has become different from the blank sample. The rheology of the 75% water cut shows a clear shear thickening behavior at 3% MgO addition. This was also confirmed by the values obtained for the power index, which was 2.5. An increase of nanoparticles from 0 to 3% has generally resulted in a more viscous fluid. The power index for zero addition was 0.57 with a viscosity range of 500-100 cP, while it turns to a lower viscosity range of 250-

350 cP but at a higher power index of 2.5 at the same share rate range of 0-30 s^{-1}. Very similar to the 75% water cut, the 50% water cut showed the same trend in viscosity reading. The power index for 50% water cut and zero MgO addition showed 0.5 at the viscosity reading range of 500-90 cP then it decreased to 220-280 cP with a rise in power index to 1.15 with shear thickening behavior. These two treatment ratios (75%+3% and 50%+3%) are unfavorable regarding flowability as the shear thickening behavior will require more energy at higher shear rates. On the other hand, the viscosity of 35% water cut and 3% MgO imposed the shear thinning behavior at a power index of 0.78. Similar to the results achieved by Sy et al. [31], the increase in MgO concentration increased the viscosity of the emulsion. A similar conclusion was found in the study of Torres et al. [32] when clay nanoparticles were employed.

3.3 Pressure drop

The pressure drop of all prepared emulsions was measured at a constant flow rate ($1.05x10^{-5}$ (m^3/sec)) conditions. All measurement conditions were conducted at a steady state and constant ambient temperature. The results are presented in Figure 6. As per Figure 6, the pressure drops for 0% nano addition resulted in interesting results. The pressure drop was increased for a 5%- 50% water cut and then reduced gradually when a 75% water cut was employed. This part of the graph comprehensively shows the well’s future behavior when the water cuts start increasing from 0-75%. The results show that the pressure drop is increasing up to 50% water cut, which is proportional to the obtained values for both power index values and the rheology studies. The 75% water cut has resulted in a lower pressure drop (5 KPa/ 5.5 m) because water became the continuous phase in this system instead of oil, which was the continuous phase for 0-50% water cut cases. Once the surface-modified nano silicon was added to the system, a significant reduction in pressure drop was achieved in this study. The impact of nano-silica on the pressure drop is more obvious at higher water cuts as this material is more effective at higher water cut systems. Due to that, the 75% water cut showed a very low-pressure drop reading.

This study concluded that more MgO additives resulted in higher pressure drops for all studied water cuts. This is not favorable for adding a nanoparticle, which might lead to a higher pressure drop. In this study, the highest recorded pressure drop value was 25 KPa / 5.5 meters pipe length, and it was for the emulsion prepared by 50% water cut with 3% MgO.

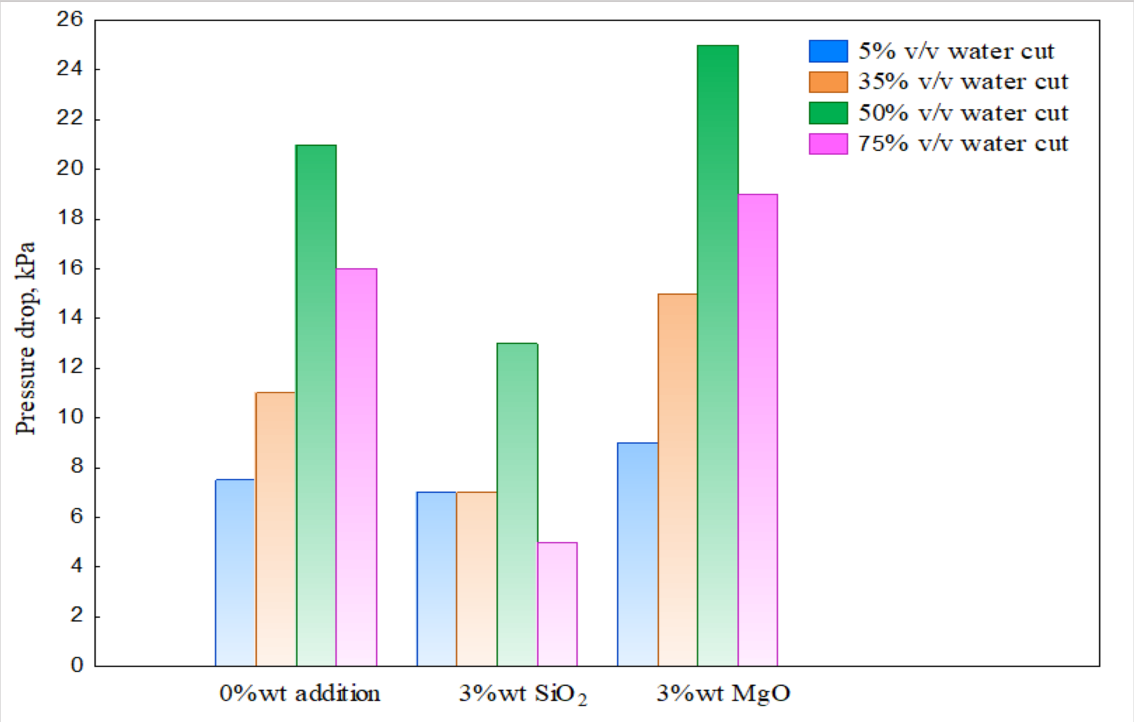

Figure 6: The pressure drop values over 5.5 m pipe length

3.4 Energy consumption

Considering the cost associated with pumping the fluid, it becomes very important to determine the power required to transfer the oil from the point of production down to the central process facilities. In this section, the power (W) will be calculated using Equation 2, which is cited in [33].

$$W = Q \cdot \Delta p \quad (2)$$

when Q represents the volumetric flow rate m^3/min, Δp is the pressure drop over the pipeline (KPa). The power consumption rates are represented in Table 5.

Table 5: Energy consumption with and without Nano additives

Nanoparticle Type	Nanoparticle (wt.%)	Water cut%	Q (m^3/sec)	Δp (KPa)	Re. no	Friction factor, (f)	Power (W)
Blank	0	5	1.053E-05	7.5	28.78	0.56	0.0789
	0	35	1.053E-05	11	13.30	1.2	0.115
	0	50	1.053E-05	20	9.06	1.77	0.210
	0	75	1.053E-05	16	8.02	2.00	0.168
SiO_2	3	5	1.053E-05	7	18.52	0.86	0.073
	3	35	1.053E-05	7	16.02	1.0	0.0736
	3	50	1.053E-05	13	9.24	1.7	0.136
	3	75	1.053E-05	5	33.01	0.48	0.052
MgO	3	5	1.053E-05	9	29.79	0.54	0.094
	3	35	1.053E-05	15	7.59	2.11	0.157
	3	50	1.053E-05	25	2.82	5.68	0.263
	3	75	1.053E-05	19	10	1.6	0.2

As per the results presented in Table 5, the pretreated oil with 50% water without nano material represents the highest energy consumption over those treated by surface-modified SiO_2 or MgO. This agrees with the results obtained for the viscosity and pressure drop. It is worth mentioning that once the wells age and the water cuts increase, more power will be needed to pump the fluid over the same pipe length. The pressure drop has been reduced by adding SiO_2 compared to blank samples. Despite the fluid behavior, the presence of SiO_2 has shown more drag reduction over the tested pipeline, and as a result, a lower pressure drop along the pipe was recorded.

The data from the experimental pressure drop can be used to get the fanning friction factor (f). The f factor in laminar flow is defined in Equation 3.

$$f = \frac{16}{Re_g} \tag{3}$$

Re_g is the generalized Reynolds number of the non-Newtonian fluid obeying power-law fluid. It can be obtained by Equation 4.

$$Re_g = \frac{\rho D^n u^{2-n}}{K.8^{n-1}} \left(\frac{4n}{3n+1}\right)^n \tag{4}$$

The lowest energy consumption was for 75% water cut and 3% surface-modified SiO_2 emulsion. Likewise, the highest energy dissipation was found for the emulsions treated by MgO nano additives. As an example, a 50% water content with 3% MgO represents the highest energy consumption over all the studied samples. In comparison, the last one was found to be for the case when the emulsion was created with a 5% water content and 0% nano additives concentration.

4. Conclusion

In conclusion of this study, once the water cut increases with the well's life, the energy required for pumping the fluids increases, as does the viscosity. Then, adding nanoparticles at different water cuts improved the flow characteristics. No significant improvement was seen for MgO-treated samples.

1) If the well's water cut increases by up to 5%, as per the studied nanomaterials, the best nano addition for reducing the viscosity would be treating the oil with 3% wt SiO_2.
2) As the well's water cut reached 35% over time, the most notable reduction in viscosity could be achieved by adding only 3% wt of SiO_2.
3) Moreover, when the well's water cut reached 50%, 3% SiO_2 was the most effective treatment for improving fluid flowability and reducing viscosity.
4) The concentration of 3% SiO_2 proved to be the most effective ratio in reducing the viscosity of an oil well-producing emulsion with a 75% water cut.

Author contributions

Conceptualization, A. Alwasiti, R. Almukhtar and M. Naser ; data curation, M. Naser and M. Shibeeb; formal analysis, A. Alwasiti, R. Almukhtar and M. Naser.; investigation, A. Alwasiti, R. Almukhtar.; methodology, A. Alwasiti, R. Almukhtar.; project administration, M. Naser, resources, A. Alwasiti, M. Naser; software, A. Alwasiti, M. Naser supervision, A. Alwasiti, R. Almukhtar; validation, A. Alwasiti, R. Almukhtar and M. Naser; visualization, M. Naser; writing— M.Naser, A. Alwasiti, All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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