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Application of Copper Oxide Nanoparticles in Improving Filtration and Rheological Properties of Water-based Drilling Fluid

Mohamad Esmaiel Naderi[1], Maryam Khavarpour[2], Reza Fazaeli[3*], and Arezoo Ghadi[4]

[1] Ph.D. Candidate, Department of Chemical Engineering, Ayatollah Amoli Branch, Islamic Azad University, Amol, Iran

[2] Associate Professor, Department of Chemical Engineering, Ayatollah Amoli Branch, Islamic Azad University, Amol, Iran

[3] Assistant Professor, Department of Chemical Engineering, Faculty of Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran

[4] Assistant Professor, Department of Chemical Engineering, Ayatollah Amoli Branch, Islamic Azad University, Amol, Iran

Highlights

- Developing an effective solution to improving the rheological and fluid loss properties of drilling fluids by adding nanoparticles;
- Synthesizing CuO nanoparticles with wire morphology and preparing a long-time stabilized nanofluid as a drilling fluid additive;
- The improvement in the yield point, apparent viscosity, 10 s and 10 min gel strengths of the drilling fluid, and the fluid loss;
- Investigating the effect of the pH level of the nanofluid on the improvement in the water-based drilling fluid properties;
- Comparing the performance of the water-based drilling fluid containing nanoparticles with conventional water-based drilling fluids in the Iranian drilling industry;

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Abstract

A successful drilling operation requires an effective drilling fluid system. This work aims to provide an effective solution for improving the rheological and filtration properties of a water-based drilling fluid using a CuO nanofluid additive. CuO nanoparticles were synthesized by a hydrothermal method using an autoclave, which can control the temperature and pressure. Then, a CuO nanofluid (eco-friendly ethylene glycol based) was produced as a drilling fluid additive. X-ray diffraction, Fourier-transformed infrared spectroscopy, and scanning electron microscopy were used to characterize the nanoparticles. The results confirmed the formation of the high-purity CuO nanoparticles forming a wire shape structure. The experimental design method optimized the operating parameters, and two long-time stabilized nanofluids were prepared to improve the rheological properties and the fluid loss of a polymeric water-based drilling fluid based on the optimal results. Xanthan, polyanionic cellulose, and starch are commonly used to improve rheological and fluid loss properties in drilling fluids. Further, the effect of the pH level of the nanofluids on the improvement in the water-based drilling fluid properties was investigated. The results showed that the nanofluid with a pH of 8.0 could be used as the best additive to improve the drilling fluid properties. The yield point, apparent viscosity, 10 s and 10 min

[*] Corresponding author
Email: r_fazaeli@azad.ac.ir

gel strengths of the drilling fluid, and the fluid loss improved by 45%, 33%, 200%, 100%, and 44%, respectively.

Keywords: Nanoparticle, CuO, Drilling Fluid, Fluid loss, Rheology

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1. Introduction

Drilling fluids (DFs) or drilling muds are an essential element of the drilling process used for onshore and offshore drilling. Drilling fluids control the formation pore pressure and carry drilled cuttings from the bottom of the well to the surface, where they are recycled. A successful drilling operation depends heavily on the proper performance of the DF (Asgari Pirbalouti, 2021). With recent advances in nanoparticle (NP) technology, several studies have evaluated the feasibility of using NPs in the oil and gas industry (Cheraghian, 2017; Li et al., 2016; Hassanzadeh et al., 2021). In particular, the experimental results showed that NPs could be used as an additive to improve the properties of DFs (Muhsan et al., 2017; Zhong et al., 2021; Beg et al., 2021). There are different types of NPs to make nanofluids (NFs) (Guo et al., 2018) and improve the rheological characteristics of DFs. Metal oxide NPs are among the most applicable NPs used in various base fluids due to their high surface area-to-volume ratio (Esfahani et al., 2018; Kamali et al., 2021; Prakash et al., 2021). CuO NPs can improve the rheological characteristics of water-based drilling fluids (WBDFs) (William et al., 2014; Akinyemi et al., 2020; Alsaba et al., 2020; Esfandyari Bayat et al., 2018; Medhi et al., 2020) .

In addition to the rheological properties, which play a crucial role in successful drilling operations, fluid loss (FL) of DFs must be reduced during all critical well operations. The invasion of DF filtrate into the formation is the most common cause of formation damage, leading to the increased costs of well stimulation and even loss of production. The researchers have shown that NPs could effectively reduce FL (Al-Malki et al., 2016; Ponmani et al., 2016; Mahmoud et al., 2021). Many studies have been performed on the effect of NPs on the filtration and rheological properties of DFs during drilling operations (Al-Yasiri et al., 2019; Dejtaradon et al., 2019; Saboori et al., 2019). Long-time stabilized NF can improve the dispersion of NPs in the DF. In some studies, CuO NF was used as an additive to improve the properties of DF (Saboori et al., 2017). Therefore, the improvement in the rheological properties and fluid loss of WBDF was investigated using aloe vera-based CuO NF as a novel additive (Ahmed Mansoor et al., 2021). Further, the effect of stabilized CuO/clay nanofluid on the rheological properties of DF was assessed (Kumar et al., 2020).

This study uses long-time stabilized CuO NFs (eco-friendly ethylene glycol based) to improve the rheological and filtration characteristics of a DF. The operating parameters are optimized by the experimental design method. Forty-three NF samples are prepared, and their stability time is monitored. Based on the optimal results, two long-time stabilized CuO NFs are prepared and added to a polymeric WBDF as a DF additive to improve the rheological and filtration properties. NF1 with a pH of 8.0 improves the yield point, apparent viscosity, and 10 s and 10 min gel strengths of the WBDF by 45%, 33%, 200%, and 100%, respectively. Moreover, NF1 enhances the fluid loss of the WBDF by 44%.

2. Materials and methods

2.1. Materials

The chemicals used to synthesize the CuO nanoparticles included ammonia (NH_3 25%), potassium

hydroxide (KOH ≥ 99.99%), and copper sulfate ($CuSO_4 \cdot 5H_2O$ ≥ 98%). Further, the materials used to make the NF were distilled water, ethylene glycol ($C_2H_6O_2$ ≥ 99.5%), sodium dodecyl sulfate ($NaC_{12}H_{25}SO_4$ ≥ 98.5%), and sodium hydroxide (NaOH ≥ 98%). The chemicals used in this research were purchased from Merck.

2.2. Synthesis method

This research used a hydrothermal method to synthesize copper oxide NPs with nanowire morphology. For hydrothermal synthesis on a laboratory scale, the autoclave was mainly used, with different types depending on the type of process (Yang and Park, 2019). Hydrothermal technology is a powerful method in the production of nanomaterials. Essential features of this method include high efficiency, optimal control, and biocompatibility. Furthermore, this synthesis method produces a wide range of nanostructures with the desired quality and dimensions.

To synthesize the CuO NPs using the hydrothermal method, initially, 0.19 g of $CuSO_4 \cdot 5H_2O$ ≥ 98% was added to 30 ml of distilled water (I) under stirring. Further, 0.26 g of KOH ≥ 99.99% was added to 10 ml of distilled water (II), and then the solution (II) was added dropwise to the copper sulfate solution (III). Next, 9 ml of NH_3 was added to solution III dropwise, and solution III was exposed to 80 °C for 2 h in the autoclave chamber. Then, the residue was washed, and NPs were heated in an oven at 60 °C for 2 h.

2.3. Characterization of nanoparticles

Synthesized CuO NPs were characterized by scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transformed infrared (FTIR) spectroscopy. The crystal structure of the CuO NPs was determined using a Philips X-ray diffractometer (model PW1730). The FTIR spectra of CuO NPs were recorded using a Thermo-Nicolet Avatar model. Additionally, the morphology of the CuO NPs was detected using scanning electron microscopy (model Mira 3-XMU, Tescan Co., Brno, The Czech Republic).

2.4. Preparation of nanofluids

The main challenges of NFs are their stability and operational performance. Due to the difference in density, NPs tend to settle with time. Further, due to the attraction between NPs, such as van der Waals forces and chemical bonds, the NPs tend to aggregate and agglomerate. Each of these phenomena, in turn, causes the suspension to become unstable. In recent years, much research has been done on the impact of this issue on the properties and applications of nanofluids. For example, the nonuniform distribution of NPs in the base fluid and their aggregation decreases the effect of nanofluid on the properties of the drilling fluid. Therefore, it is necessary to study and analyze the factors affecting the stability of NFs. This study used the response surface methodology and Box-Behnken design (BBD) to optimize and prepare long-time stabilized NFs containing CuO NPs. The response surface methodology is an effective method for optimizing process parameters. Five independent variables, including CuO concentration (wt %), sodium dodecyl sulfate (SDS) concentration (wt %), ultrasound time duration (h), ethylene glycol/water ratio, and the pH value, were evaluated at three levels (Table 1). The general answer surface equation is defined as Equation (1). Based on the design of the experiment, 43 NF samples were prepared, and their stability time was monitored (Table 2).

Table 1

Independent variables and experimental levels

Variables	Factor	Unit	Range and level		
			Low (–1)	Middle (0)	High (+1)

The concentration of copper oxide nanoparticles	A	wt %	0.1	0.2	0.3
The concentration of sodium dodecyl sulfate	B	wt %	0.1	0.2	0.3
Ultrasound time duration	C	h	3	6	9
Ethylene glycol/water ratio	D	-	0.25	0.5	0.75
pH value	E	-	6	7	8

Table 2

Experiments designed with the response surface methodology

STD order	RUN order	A	B	C	D	E	Stability experimental (day)
1	44	0.1	0.1	3. 6	50	7	40
2	27	0.3	0.1	6	50	7	51
3	37	0.1	0.3	6	50	7	58
4	15	0.3	0.3	6	50	7	73
5	24	0.2	0.2	3	25	7	61
6	16	0.2	0.2	9	25	7	73
7	25	0.2	0.2	3	75	7	70
8	43	0.2	0.2	9	75	7	86
9	10	0.2	0.1	6	50	6	3
10	13	0.2	0.3	6	50	6	8
11	42	0.2	0.1	6	50	8	74
12	39	0.2	0.3	6	50	8	90
13	6	0.1	0.2	3	50	7	60
14	9	0.3	0.2	3	50	7	67
15	41	0.1	0.2	9	50	7	57
16	19	0.3	0.2	9	50	7	81
17	22	0.2	0.2	6	25	6	7
18	5	0.2	0.2	6	75	6	7
19	36	0.2	0.2	6	25	8	81
20	28	0.2	0.2	6	75	8	100
21	7	0.2	0.1	3	50	7	54
22	32	0.2	0.3	3	50	7	71
23	14	0.2	0.1	9	50	7	61
24	33	0.2	0.3	9	50	7	75
25	11	0.1	0.2	6	25	7	48
26	30	0.3	0.2	6	25	7	54
27	20	0.1	0.2	6	75	7	54
28	17	0.3	0.2	6	75	7	79
29	21	0.2	0.2	3	50	6	5
30	34	0.2	0.2	9	50	6	8
31	18	0.2	0.2	3	50	8	91
32	2	0.2	0.2	9	50	8	93
33	40	0.1	0.2	6	50	6	4
34	31	0.3	0.2	6	50	6	8
35	12	0.1	0.2	6	50	8	76
36	35	0.3	0.2	6	50	8	85
37	23	0.2	0.1	6	25	7	46
38	8	0.2	0.3	6	25	7	59
39	3	0.2	0.1	6	75	7	73
40	1	0.2	0.3	6	75	7	65
41	26	0.2	0.2	6	50	7	67
42	38	0.2	0.2	6	50	7	68
43	29	0.2	0.2	6	50	7	68

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_{i} \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i \quad (1)$$

where β_0 is a constant, β_j indicates the linear effect, β_{jj} represents the quadratic effect, β_{ij} denotes the coefficient of the interaction factor, Y is the response, X represents the variable, and e_i is the error (Hashemi et al., 2018).

2.5. Preparation of nano-drilling fluids

A WBDF was formulated and prepared using salt, polyanionic cellulose low viscosity (PAC-LV), xanthan gum, potato starch, lime, and limestone. The concentration of the mud materials was kept constant for all experiments reported in Table 3. Then, NFs were added to the WBDF at different concentrations of 1% to 6% (V/V). Then, the rheological and filtration characteristics of the WBDF were examined.

Table 3

Formulation of the WBDF

Item	Product	Amount
1	Water, ml	350
2	Salt (g)	125
3	Polyanionic Cellulose Low Viscosity (g)	2
4	Xanthan (g)	1.3
5	Potato Starch (g)	4
6	Limestone (g)	10
7	Lime (g)	0.2

2.6. Measurement of rheological properties and fluid loss

The rheological properties of DFs measured using a rotational viscometer (VG meter model 35A, Fann. Instrument Co., Houston, Texas) at standard atmospheric pressure (0.1 MPa) and room temperature (25 °C). The apparent viscosity (AV), plastic viscosity (PV), and yield point (Yp) were calculated using the following formulas according to the American Petroleum Institute (API) statistical method for testing WBDFs.

$$AV = \theta_{600}/2 \tag{2}$$

$$PV = \theta_{600} - \theta_{300} \tag{3}$$

$$Yp = \theta_{600} - PV \tag{4}$$

$$GS = \theta_3 \tag{5}$$

where θ_{600}, θ_{300}, and θ_3 read at 300, 600, and 3 rpm, respectively, by dial reading. DFs were mixed for 10 min before rheological measurement to achieve steady-state conditions.

Low-temperature and low-pressure (LT/LP) static filtration tests were performed using a Standard Filter Press (Model 300, Fann Instrument Co., LPLT API Filter Press) with pressure assembly, regulator, and qualitative filter paper. The filtration test was performed in the standard condition recommended by API. The filtrate volume was measured with a graduated cylinder.

3. Results and discussion

3.1. XRD, FTIR, and SEM analysis

The X-ray diffraction pattern of the synthesized CuO NPs is shown in Figure 1a. The interplanar spacing obtained from the XRD patterns confirms a monoclinic crystal structure. These values match standard diffraction data (JCPDS card no 45-0937) (Joint Committee on Powder Diffraction Standards, 1991).

The functional groups present in the synthesized CuO NPs were identified by FTIR analysis. The spectrum is represented in Figure 1b. The absorption bands at 422.03, 500.40, and 615.79 cm^{-1} correspond to the stretching vibrations of the Cu–O bond (Manyasree et al., 2017), confirming the formation of high purity in CuO NPs. In addition, the absorption bands at 1644.23 and 3430.30 cm^{-1} are related to the O–H bending (Manyasree et al., 2017) and stretching (Halder et al., 2017) vibrations that refer to water as moisture in the sample. The Infrared (IR) bands in the regions mentioned above confirmed the formation of CuO NPs (Umar et al., 2016).

The morphology of the synthesized CuO NPs was investigated by SEM analysis, as shown in Figure 1c. The SEM analysis shows that the powders are composed of uniform NPs, which tend to aggregate to form a wire shape structure. The SEM images indicated an agglomeration of particles with homogeneous and uniform sizes with a diameter of about 20 nm.

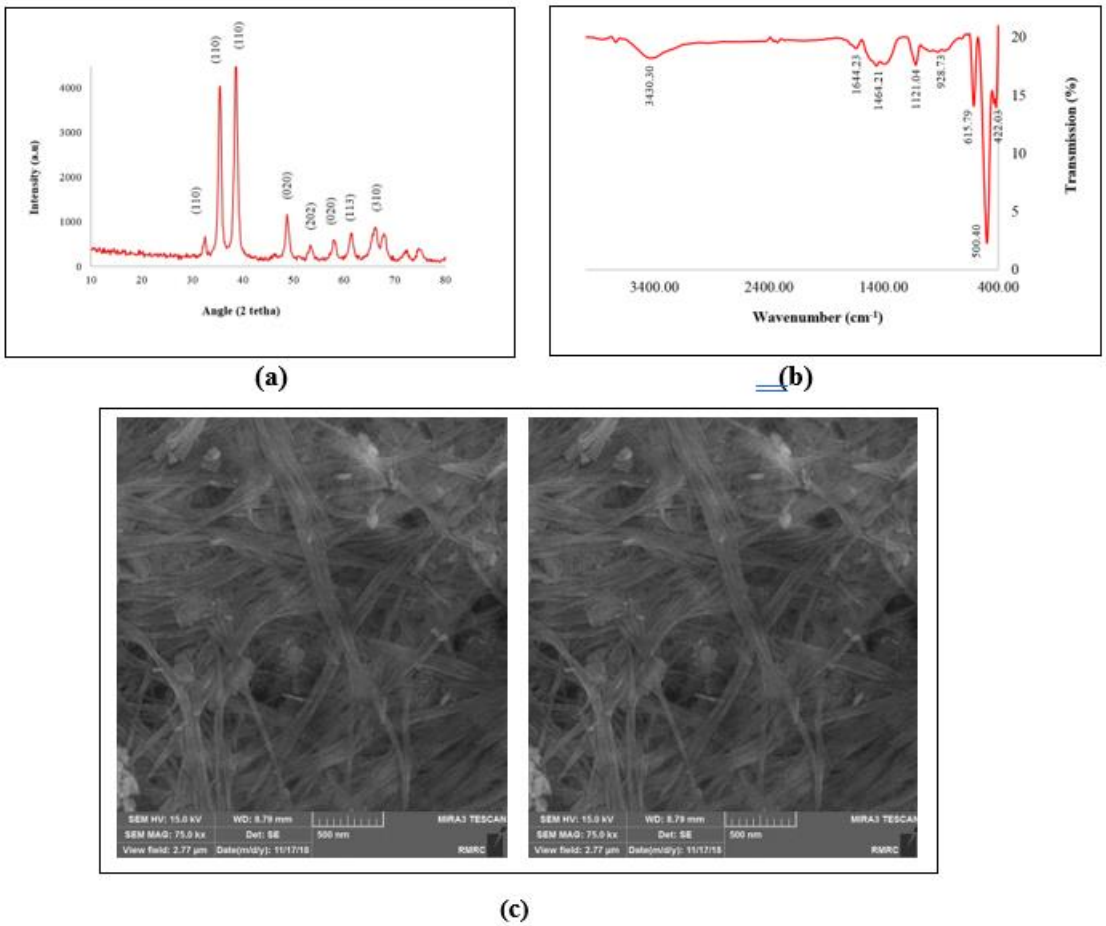

Figure 1

(a) The X-ray diffraction pattern of CuO NPs with wire morphology, (b) the FTIR of CuO NPs with wire morphology, and (c) The SEM results of synthesized CuO NPs with wire morphology.

3.2. Design of experiment

The normal probability plot of the residuals versus the response is shown in Figure 2. A perfect correlation exists between the results obtained with the experimental method and the values predicted with the statistical method. According to the analysis of variance, the values of R-squared and Adj R-squared are approximately 0.9847 and 0.9707, respectively, indicating the accuracy of the model. The results of the analysis of variance for the quadratic response level model on the experimental data are presented in Table 4.

Table 4

The results of the analysis of variance for the quadratic response level model.

Source	Sum of squares	DF	Mean square	F-value	P-value Prob >F	Remark
Model	31995.93	20	1599.80	70.59	< 0.0001	Significant
A-CuO	637.56	1	637.56	28.13	< 0.0001	
B-SDS	588.06	1	588.06	25.95	< 0.0001	
C-Time	189.06	1	189.06	8.34	0.0085	
D-EG/water	689.06	1	689.06	30.40	< 0.0001	
E-pH	25600.00	1	25600.00	1129.60	< 0.0001	
AB	4.00	1	4.00	0.18	0.6785	
AC	72.25	1	72.25	3.19	0.0880	
AD	90.25	1	90.25	3.98	0.0585	
AE	6.25	1	6.25	0.28	0.6047	
BC	2.25	1	2.25	0.099	0.7557	
BD	110.25	1	110.25	4.86	0.0382	
BE	30.25	1	30.25	1.33	0.2604	
CD	4.00	1	4.00	0.18	0.6785	
CE	0.25	1	0.25	0.011	0.9173	
DE	90.25	1	90.25	3.98	0.0585	
A^2	250.00	1	250.00	11.03	0.0031	
B^2	211.60	1	211.60	9.34	0.0058	
C^2	82.18	1	82.18	3.63	0.0700	
D^2	2.18	1	2.18	0.096	0.7595	
E^2	2351.11	1	2351.11	103.74	< 0.0001	
Residual	498.58	22	22.66			
Lack of Fit	497.92	20	24.90	74.69	0.0133	Significant
Pure Error	0.67	2	0.33			
Cor Total	32494.51	42				

Note: R^2 = 0.9847; Adjusted R^2 = 0.9707; CV = 8.32%, and PRESS = 1993.17.

The effect of the independent variables on the stability time of the NFs as three-dimensional response surface plots are plotted in Figure 3. The effect of CuO concentration and SDS concentration on the stability time of the NF is shown in Figure 3a. The results show that increasing the CuO and SDS concentrations increases the stability time of the NF. Figure 3b reveals the effect of CuO concentration and the ultrasound time duration on the stability time of the NF. According to the results, the stability time of the NF increases by increasing the CuO concentration and ultrasound time duration. In addition, Figure 3c displays the effect of the concentration of CuO and the ethylene glycol/water ratio on the stability time of the NF. According to the results, the stability time of the NF increases with increasing the CuO concentration and the ethylene glycol/water ratio. Figure 3d indicates the effect of the concentration of CuO and pH value on the stability time of the NF. The results show that the stability time of NF increases by raising the concentration of CuO and elevation of the pH value. According to the results, it can be concluded that the influential factors affecting the stability time of the NF (based on their effect size) are the pH value, the ethylene glycol/water ratio, the CuO concentration, the SDS concentration, and the ultrasound time duration, respectively .

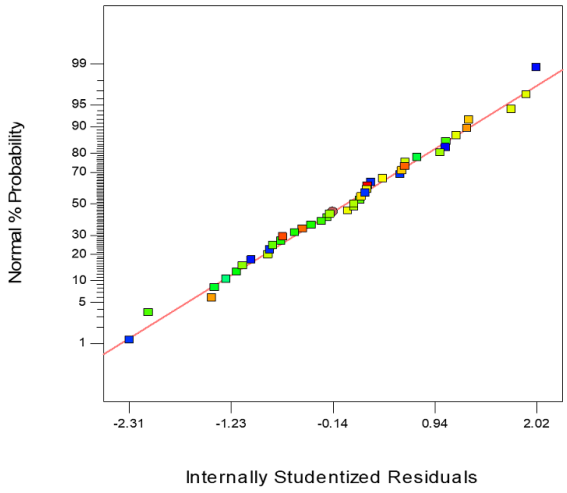

Figure 2

The normal plot of residuals.

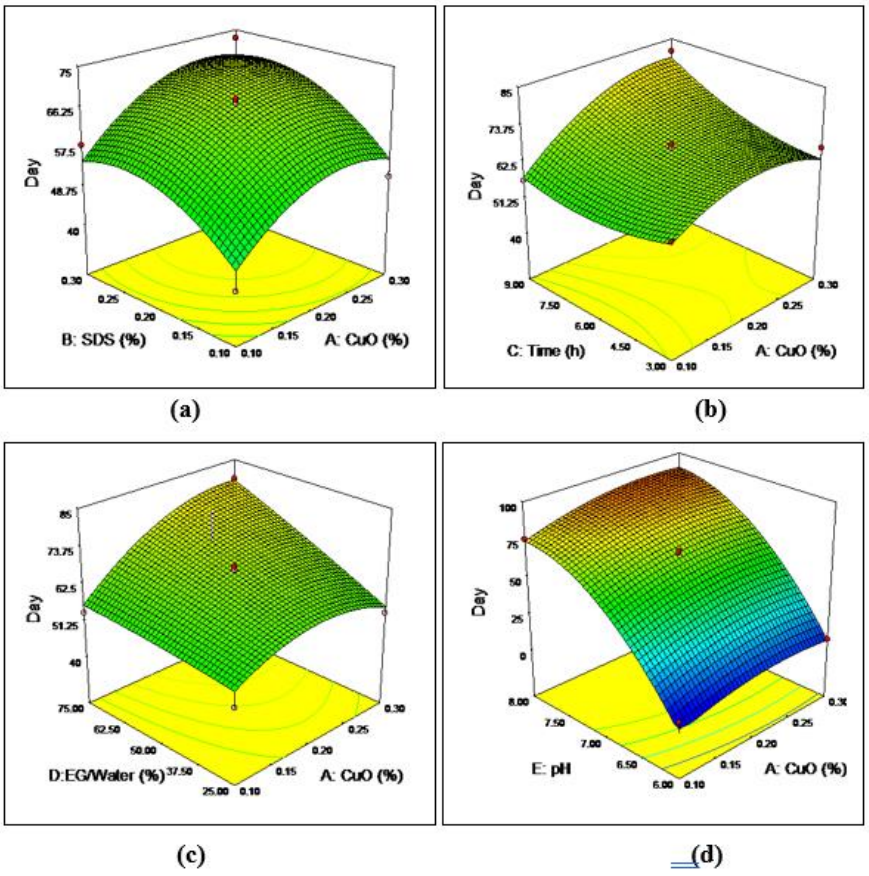

Figure 3

Three-dimensional response surface plots for the stability time of the NF versus independent variables: (a) CuO weight percentage and SDS weight percentage; (b) CuO weight percentage and ultrasound time duration; (c) CuO weight percentage and ethylene glycol/water ratio; (d) CuO weight percentage and pH value.

Finally, the software determined that the best point to achieve the longest stability time of NFs was 100.02 days. The optimum values of the independent variables are shown in Figure 4.

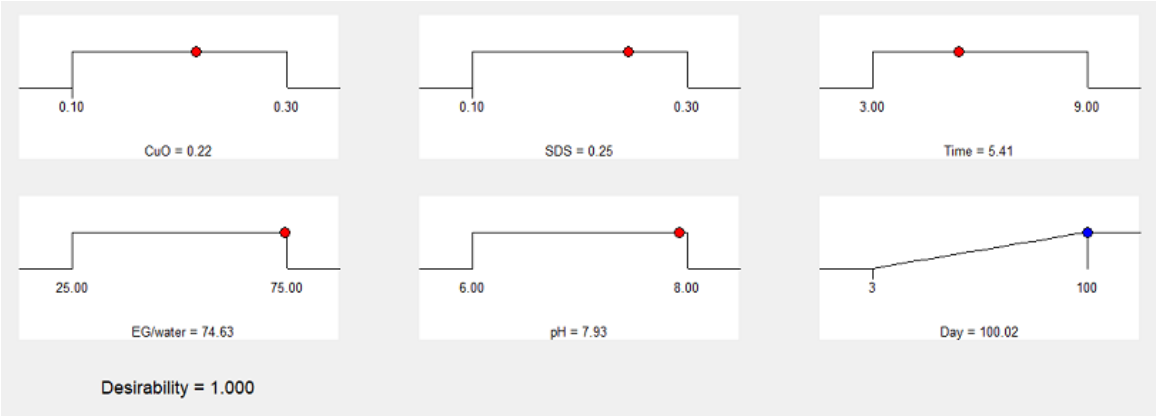

Figure 4

The optimization of the operational parameters.

3.3. Measurement of drilling fluid properties

Based on the optimal results in Figure 4, two long-time stabilized NFs were prepared with specifications mentioned in Table 5 to improve the DF properties and to investigate the effect of the pH of the NF on the DF properties. Monitoring two NF samples recorded a stability time of more than 180 days.

The results of scientific research showed that some properties of NFs, such as viscosity (Wang et al., 2009), depend on their pH. Adding two NFs with different pH values to the DF also leads to different changes in the pH of the DF. The fluid loss and rheological properties of the DF depend on its pH (Gamal et al., 2019). Therefore, adding two NFs with different pH values to the DF leads to different possible improvements in the properties of the DF.

Table 5

Specifications of the selected NFs for subsequent experiments

	Morphology of nanoparticles	Ethylene glycol/water ratio (%)	Ultrasound Time (h)	Copper oxide (wt %)	sodium dodecyl sulfate (wt %)	pH
Nanofluid No. 1	Nano wire	75	6	0.22	0.25	8
Nanofluid No. 2	Nano wire	75	6	0.22	0.25	7

3.4. Zeta potential

The zeta potential is an essential measurable indicator of the stability of colloidal dispersions. The NPs with a zeta potential of more than +30 mV or less than –30 mV are considered a stable colloidal suspension system (Ravichandran et al., 2014). The zeta potential refers to the surface charge of the colloidal particles, and charge formation by adsorption strongly depends on the pH value of the colloidal system. The measured zeta potential of CuO NPs at different pH values is reported in Table 6 .

Table 6

The zeta potential values for the CuO NPs at different pHs.

NP	pH = 3	pH = 6	pH = 7	pH = 8	pH = 13
CuO	–1.79 mV	–17.9 mV	–25.6 mV	–29.8 mV	–19.7 mV

3.5. The rheological properties of the drilling fluids

The next stage of the experiment focused on improving the rheological properties of the WBDF as the base fluid. The two long-time stabilized NFs were added to the WBDF at different concentrations (1 to 6 vol %). The composition of the nano-drilling fluids is reported in Tables 7 and 8.

After testing and calculation, the rheological properties of the nano DFs were reported in accordance with Figure 5a and 5b. According to data in Figure 5a, the maximum value of the rheological properties is related to the DF containing 1% V/V NF1. The maximum value of Yp, AV, Gel 10 s, Gel 10 min, and PV were 6.2 Pa, 20.5 mPa·s, 1.4 Pa, 1.9 Pa, and 14 mPa·s, respectively.

Further, according to Figure 5b, the maximum value of the rheological properties is related to the DF containing 1% V/V NF2. The maximum values of Yp, AV, Gel 10 s, Gel 10 min, and PV were 6.2 Pa, 19.5 mPa·s, 1.4 Pa, 1.9 Pa, and 13 mPa·s, respectively.

The research results by Salih and Bilgesu (2017) revealed that adding 0.5 to 1.5 pound per barrel (ppb) nanosilica to the DF decreased the PV value from 28 to 24 cP, respectively. They claimed that the NPs increased the distances between the DF particles, working as lubricants or "ball bearings", facilitating the movement and decreasing the PV value of the DF. However, Esfandyari Bayat et al. (2018) showed that the PV value increased by adding CuO and Al_2O_3 NPs to the WBDF. They also confirmed that adding TiO2 to the DF decreased the PV value. In contrast, Perween et al. (2018) showed that the PV value increased by adding zinc titanate NPs to the WBDF.

The results show that by increasing the concentration of NF1 up to 1 vol%, the amount of AV, Yp, Gel 10 s, and Gel 10 min properties have an increasing trend due to the creation of more connections between the particles in the drilling fluid. By increasing the concentration of NF1 up to 6 vol %, the changes of the mentioned properties have a decreasing trend due to the breaking of the created bonds.

Therefore, both NF1 and NF2 can be used as an additive (at 1 vol %) to improve the rheological properties of the WBDF during drilling operations. NF1 improved Yp, AV, Gel 10 s, and Gel 10 min properties of the WBDF by 45%, 33%, 200%, and 100%, respectively. Moreover, adding NF2 to the WBDF improved these properties by 45%, 26%, 200%, and 100%, respectively.

The results show that the effects of NF1 (pH = 8) and NF2 (pH = 7) on improving the Yp, Gel 10 s, and Gel 10 min of the base fluid are the same. Nevertheless, the effect of NF1 on the improvement in AV is more than that of NF2. Therefore, NF1 can be used as an additive (at 1 vol %) to improve the rheological properties of the WBDF during drilling operations.

Table 7
Composition of the nano water-based drilling fluid containing the base fluid and nanofluid 1

Item	Product	Sample 1 (Base fluid)	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
1	Water (ml)	350	350	350	350	350	350
2	Salt (g)	125	125	125	125	125	125
3	Polyanionic cellulose low viscosity (g)	2	2	2	2	2	2
4	Xanthan (g)	1.3	1.3	1.3	1.3	1.3	1.3
5	Potato Starch (g)	4	4	4	4	4	4
6	Limestone (g)	10	10	10	10	10	10

Item	Product	Sample 1 (Base fluid)	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
7	Lime (g)	0.2	0.2	0.2	0.2	0.2	0.2
8	Nanofluid 1 (vol %)	0	1	2	3	4	6

Table 8

The composition of the nano water-based drilling fluid containing the base fluid and nanofluid 2

Item	Product	Sample 1 (Base fluid)	Sample 7	Sample8	Sample 9	Sample 10	Sample 11
1	Water (ml)	350	350	350	350	350	350
2	Salt (g)	125	125	125	125	125	125
3	Polyanionic cellulose low viscosity (g)	2	2	2	2	2	2
4	Xanthan (g)	1.3	1.3	1.3	1.3	1.3	1.3
5	Potato Starch (g)	4	4	4	4	4	4
6	Limestone (g)	10	10	10	10	10	10
7	Lime (g)	0.2	0.2	0.2	0.2	0.2	0.2
8	Nanofluid 2 (vol %)	0	1	2	3	4	6

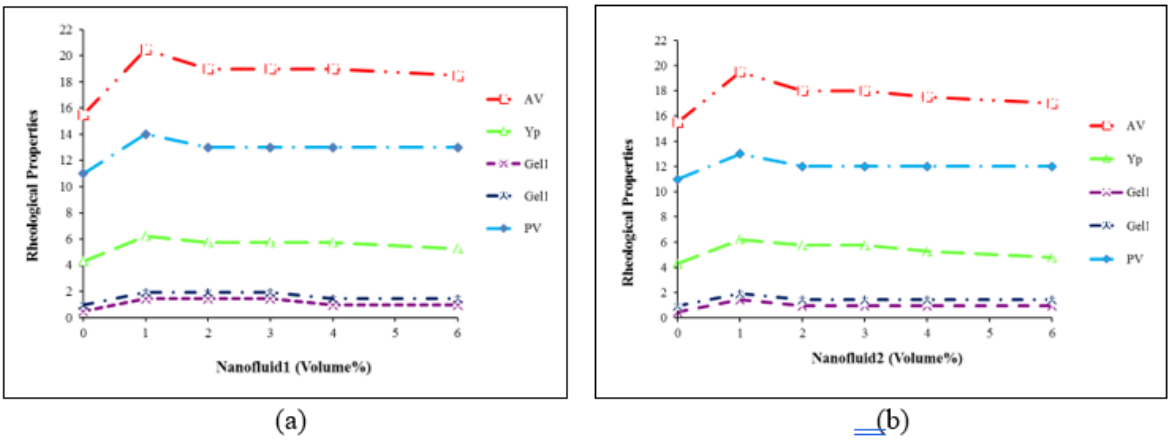

Figure 5

(a) The rheological properties of the samples composed of the base fluid and NF1 and (b) the rheological properties of the samples composed of the base fluid and NF2.

3.6. Measurement of fluid loss property

As the last part of the experiment, the FL tests were performed on the DF samples (containing NF1 and NF2), and the filtrate volumes were measured. The results of the experiments are shown in Figure 6a and 6b. According to the results, the minimum FL volumes of the DFs are 3.8 and 4.1 ml, which are related to the DFs containing 4% V/V NF1 and NF2, respectively. NF1 and NF2 (as an additive) improve the fluid loss of the WBDF by 44% and 39%, respectively. The results show that the effect of NF1 (pH = 8) on the FL of the base fluid is greater than that of NF2 (pH = 7). Therefore, NF1 can be used as an additive (at 4 vol %) to improve the FL of the WBDF during drilling operations. Al-Saba et al. (2019) showed that adding CuO NPs to bentonite mud with two concentrations increased YP and gel strength by 231% and 95%, respectively. Further, Esfandyari Bayat et al. (2018) showed that by

adding CuO NPs to bentonite mud and increasing the NPs concentration from 0.01 to 1.0 wt%, the amount of Yp, Gel 10 s, and Gel 10 min decreased. The fluid loss value also has a decreasing trend as the CuO concentration rose from 0.01 to 1.0 wt %. Nevertheless, increasing the CuO concentration to 1.0 wt % increased the fluid loss value.

By making nanofluids with a range of concentrations of CuO and ZnO NPs from 0.1 to 1.0 wt% and adding them to the water-based drilling fluid, Dejtaradon et al. (2019) showed that the amount of AV, Gel 10 s, and Gel 10 min decreased compared to the base fluid. However, the amount of gel property was constant. Further, the fluid loss property of the nano drilling fluid containing 0.8 wt % of CuO NPs, compared to the base fluid, had the highest reduction of 30%.

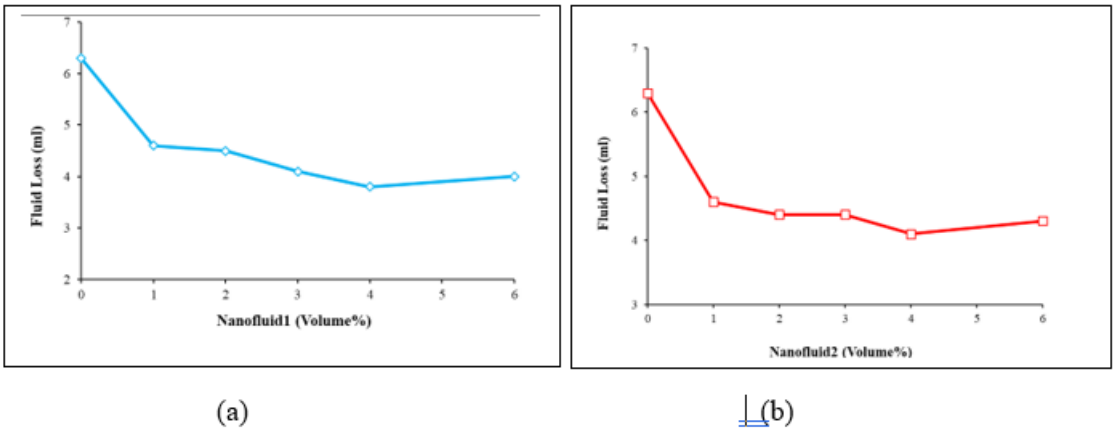

Figure 6

(a) The fluid loss of the samples composed of the base fluid and NF1 and (b) the fluid loss of the samples composed of the base fluid and NF2.

4. Conclusions

In this study, CuO NPs were synthesized to improve the rheological and filtration properties of DFs, and CuO NFs (eco-friendly ethylene glycol based) were produced as a drilling fluid additive. The experimental design method optimized the operating conditions of the experiment. Then, two long-time stabilized NFs (with different pH values) were prepared according to the optimal results to improve the rheological and filtration properties. The effect of the pH of the NFs on the improvement in the DF properties was also investigated. The results showed that NF1 (pH = 8) and NF2 (pH = 7) improved the properties of Yp, Gel 10 s, and Gel 10 min similarly by 45%, 200%, and 100%, respectively.

Nevertheless, NF1 and NF2 improved the AV by 33% and 26%, respectively. Moreover, NF1 and NF2 enhanced the fluid loss by 44% and 39%, respectively. Therefore, NF1 could be used as an additive to improve the rheological properties (at 1 vol %) and fluid loss (at 4 vol %) of the WBDF during drilling operations. It was confirmed that using CuO NPs combined with eco-friendly ethylene glycol as suitable additives could enhance the rheological and filtration properties of the DF for drilling operations.

Nomenclatures

cP	Centipoise
FTIR	Fourier-transformed infrared
h	Hours
ml	Milliliter

mPa·s	Millipascal-Second
mv	Millivolt
Pa	Pascal
SEM	Scanning electron microscopy
V/V	Volume per volume
vol	Volume
wt	Weight
XRD	X-ray diffraction

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