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Rheological properties and thermal conductivity of water-based drilling fluid containing SiO_2 and Al_2O_3 nanoparticles

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A B S T R A C T

In this research, enhanced WBMs (water-based muds) was prepared by using SiO_2 and Al_2O_3 nanofluids (size 15-20 nm) in aqueous solution of bentonite and investigated on thermal conductivity, filtration and rheological properties at three temperatures of 27, 50, and 80 °C. Nanofluids were prepared in different concentrations of 0.01, 0.03, 0.05, 0.1, 0.5, and 1 wt% in base fluid. Experimental data with flow curves for different nano water-based drilling fluid (NWBDF) are fitted to rheological drilling fluid models (Herschel-Bulkley, Bingham plastic, and power law models). According to the results, NWBDF follow Herschel Bulkley's model for rheological behavior. All samples exhibit shear-thinning behavior because the shear rate decreases as the apparent viscosity increases. After adding 1 wt% of SiO_2 nanoparticles, the plastic viscosity (PV) increased to 14 ± 0.02 cP. Comparing the permeability of clay cakes according to Darcy's law showed that nanofluids are more impermeable cakes than the base fluid. Thermal conductivity was dramatically improved in the presence of both samples at 80 °C.

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1. Introduction

Rheological properties, fluid loss, yield stress, mud cake thickness, gel strength, pH, formation pressure control, and thermal conductivity are some of the factors that are measured for the performance and evaluation of the drilling system [1, 2]. Of course, not controlling any of these can cause serious problems such as wellbore instability, lost circulation, slowing down of the hole, eruption of the hole, and stuck the pipe events, which in turn leads to a loss of time and money [3]. In a general classification, drilling fluids are divided into liquid fluids (water and oil), gas (air), and liquid-gas mixture (foam) and their derivative. The major fluids used in the drilling industry are water-based fluids in which water is added as the main phase due to easy access, lower operational efficiencies, cheapness and compatibility with the environment and other solids as additives [4-6]. The use of oil-based muds is limited to high-temperature formations and water-incompatible formations in which oil is a continuous phase and water dissolves as an emulsion. Using this type of fluid is costly and has environmental problems. The application of gas fluid is in impermeable formations. Air drilling mud is effective in improving drilling speed and minimizing hole damage. Mixed liquids and gases with complex behavior can also be used in the presence of low-pressure formations [7, 8]. Viscosity is an important feature of WBDFs, and the cheapest and most widespread method of controlling it is using hydrophilic clay minerals such as bentonite [9]. On the other hand, excessive use of bentonite can have disadvantages such as reduced drilling speed, thick filter cake, improper dispersion at high temperatures, and differential pipe sticking [10]. Meanwhile, with the recent development in nanotechnology, the use of nanoparticles (NPs) with bentonite can eliminate these defects and enhance the rheological properties of the fluid [11]. For example nano silica [11], graphene oxide [12], zinc oxide [13], and aluminum oxide/graphene nanocomposite [14], each as a nanoscale additive can have good control over some properties. Ghanbari et al evaluated the performance of SiO_2 nanoparticles in WBDFs. According to their results, the addition of SiO_2 nanoparticles increases the yield point and viscosity [15]. Hassani et al. observed a significant effect on the rheological properties of muds by adding 0.2 wt% of carbon nanotubes (CNT), SiO_2, and ZnO nanoparticles with a size of 20 nm. The greatest improvement was achieved from SiO_2 nanoparticles. Also, by adding 0.2 wt% of SiO_2 nanoparticles and CNT in WBF, they observed a 16.9% and 12% improvement in thermal conductivity, respectively [16]. Al-Yasiri et al. investigated the performance of silicon dioxide (SiO_2) of 20 and 30 nm and xanthan in controlling the loss of WBDF at 25 °C. According to the results obtained from the mixture of polymers and nanoparticles, they are suitable for improving the base fluid function and increasing the rheological properties of waste and lubrication. However, the combination of SiO_2 and polymer nanoparticles shows a better reduction in fluid volume [14]. William et al investigated the effect of CuO and ZnO nanoparticles with

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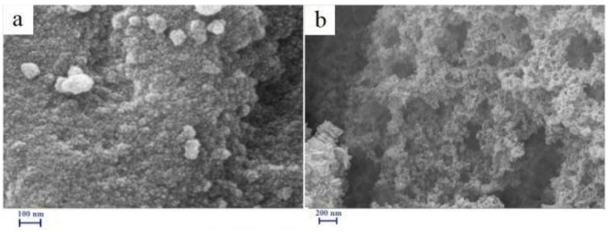

Fig. 1. FESEM images of (a) SiO_2 nanoparticles and (b) Al_2O_3 nanoparticles .

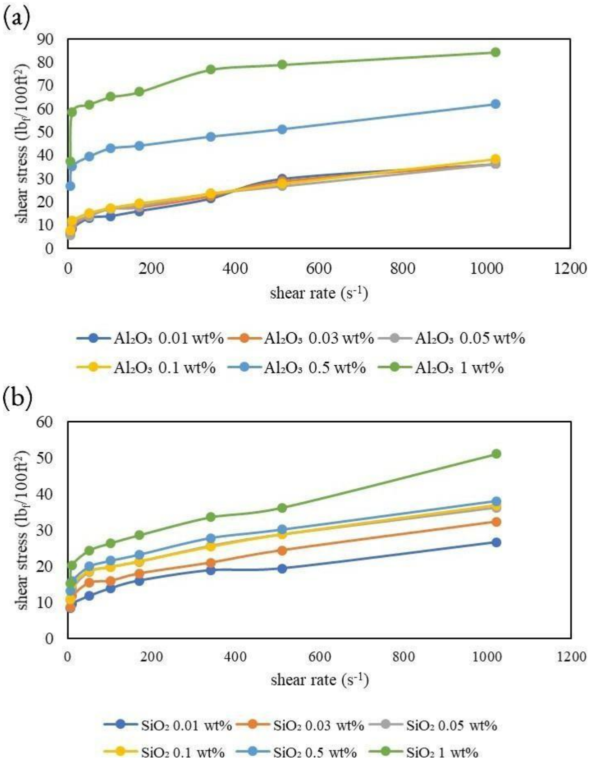

Fig. 2. Shear stress versus shear rate of nano-drilling fluid (0-1 wt%).

a size of about 50 nanometers in concentrations of 1, 0.5, 0.3, and 0.1 wt% on rheological properties of drilling fluids. According to their results, liquid loss and cake thickness are reduced under HPHT and LPLT conditions. In general, ZnO NPs showed better results. The samples containing zinc and copper increased the thermal conductivity by 23% and 53%, respectively [17]. By adding carbon nanoparticles (graphene) to WBDFs in concentrations less than 0.2wt% with xanthan gum, Kosinkin et al showed that this compound can have a significant effect on filtration loss. In their work, a filter cake with a thickness of 20 µm and a loss of about 6 ml of fluid in 30 minutes was obtained [17].

This research reports the effects of SiO_2 and Al_2O_3 nanoparticles on rheological performance and filtration of WBDFs. To measure the properties, nanoparticles were added to bentonite mud with different compositions at concentrations of 0.01, 0.03, 0.05, 0.1, 0.5, and 1 wt%. Thermal conductivity, plastic viscosity (PV), rheological behavior, and yield point (YP) were evaluated in the presence of nanoparticles at three temperatures of 27, 50 and 80 °C [17]. All samples were measured using API standards.

2. Experimental

2.1. Materials and instruments

Sodium bentonite with a purity of 95% was obtained from Iran's National Drilling Company. ($Al(NO_3)_3.9H_2O$), hydrazinium hydrox-

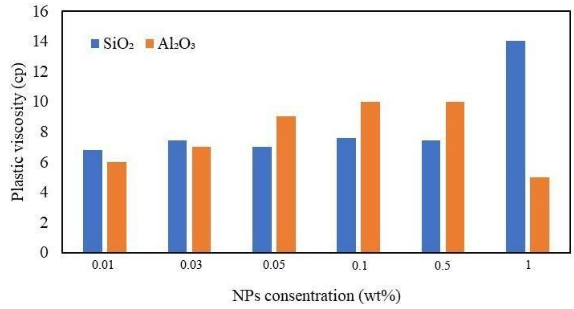

Fig. 3. Plastic viscosity behavior in the presence of SiO_2 and Al_2O_3 nanoparticles with different concentrations.

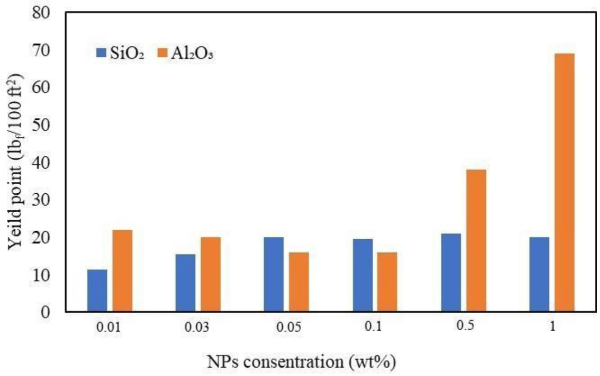

Fig. 4. Yeild point behavior in the presence of SiO_2 and Al_2O_3 nanoparticles with different concentrations.

ide (N_2H_5OH 80%), ethylenediamine, tetraethyl orthosilicate (TEOS), ammonia (NH_4OH), sodium hydroxide (NaOH), and ethanol were purchased from Merck company. MIRA3 FEGSEM was used to prepare FESEM (field emission scanning electron microscope) images.

2.2. Measuring properties

Mixing of drilling fluid additives was done by a mechanical mixer (TAT-2500) [18]. Filter press and rotary viscometer at low temperature and pressure (LPLT 100 psi and 27°C) were used to measure filtration loss and rheological behaviors. The drilling fluid was poured into a 1.4-inch (15 mm) O-Ring with a capacity of 175 ml, the filter paper was placed in place, and then the cell was tightly closed. The time required to measure filter cake thickness and fluid loss was 30 minutes. The filter papers should have a diameter of 6.24-6.34 cm and have a particle holding range of 2-5 µm [15]. KD2 Pro thermal conductivity device with 5% accuracy (with KS-1 sensor) was applied to measure thermal conductivity [20]. For each experiment, the devices were calibrated before use.

2.3. Preparation of Nano Drilling Fluids

Silica nanoparticles were synthesized by sol-gel method [21]. Alumina nanoparticles were synthesized through hydrothermal method and similar to our previous work [22]. Fluid suspension containing tap water, bentonite and SiO_2 and Al_2O_3 nanoparticles were prepared in the prepared fluid samples. 350 ml of water was prepared at 27 °C in the pH range of 9 to 9.5. First, 22.5 grams of bentonite powder was slowly poured to 200 ml of tap water and mixed for 15 minutes in a mixer at 1600 rpm. After complete mixing and before adding nanoparticles, the fluid was stored in a container and aged according to the standard (API 1608) for 16 hours at room temperature (27 °C) to absorb bentonite water. After 16 hours, the bentonite was completely crystallized in the suspension and was placed in a blender for 5 minutes to thoroughly mix the contents of the clay suspension again. Nanofluids prepared in different concentrations of 0.01, 0.03, 0.05, 0.1, 0.5 and 1 wt% were separately ultrasonicated with 150 ml of water and added to the above suspension.

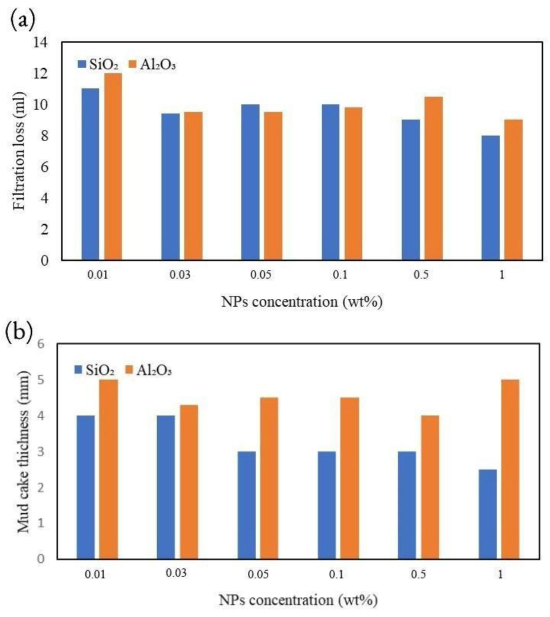

Fig. 5. F Fig. 5. (a) Loss of mud fluid in the presence of different nanoparticles after 30 minutes (b) Mud cake thicknesses in the presence of different nanoparticles at 100 psi and 25 °C.

All the suspensions were prepared in one day and the experiments were performed sequentially. The 13D API standard has been carefully used to perform tests and measure properties. The recorded number for each experiment was the average of its repetition for 5 times.

3. Results and discussion

3.1. SEM images

FESEM images of silica and alumina nanoparticles are presented in Figs. 1a and 1b, respectively. As seen in Fig. 1a, silica nanoparticles are spherical and have a size of about 10 nm. According to Fig. 1b, alumina nanoparticles are in the shape of rice grains with a length of 10-20 nm and a diameter of about 5 nm.

3.2. Measurement of rheological properties and filtration

In order to investigate the rheological behaviors, yield point (YP), FL (filtration less), and plastic viscosity (PV) were measured at 27 °C. API RP 13B-1 standard was used to measure PV and YP parameters. The values obtained from the rotary viscometer at 600 and 300 rpm can be denoted as θ600 and θ300, respectively. YP and PV were calculated based on the equations reported in our previous work [18]. Figs. 2a and 2b show the shear stress against the shear rate of the nanofluids and base drilling fluid in different grades at a temperature of 27 °C. According to the graphs, the shear rate has increased with the increase of shear stress. This shows that the base mud fluid behavior similar to Bingham's quasi-plastic fluids follows the Herschel Buckley model with shear thinning behavior.

Table 1.
Nanofluid formulations used.

NP type	FW (ml)	Bentonite (g)	NaOH (ml)	Concentration of nanoparticles (wt%)
BF	350	22.5	1	-
SiO_2	350	22.5	1	0.01, 0.03, 0.05. 0.1,0.5, 1
Al_2O_3	350	22.5	1	0.01, 0.03, 0.05. 0.1,0.5, 1

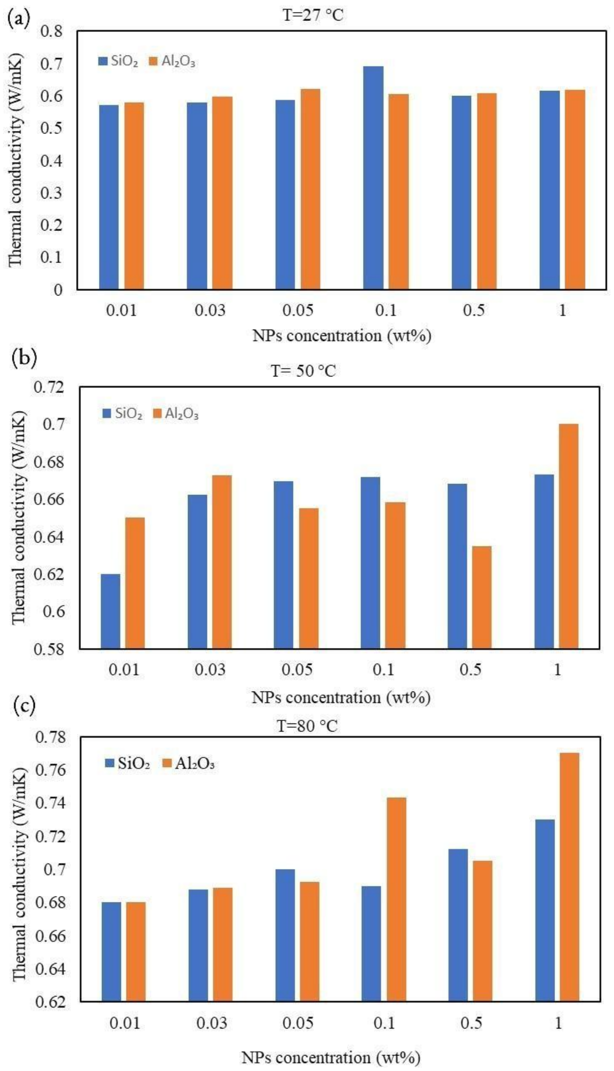

Fig. 6. Thermal conductivity in the presence of different nanoparticles at (a) 27 (b) 50 (c) 80 °C.

Eq. (1) generalizes Herschel Buckley's model:

$$\tau = \tau_0 + k\gamma n \quad (1)$$

τ_0 is the yield point ($lb_f/100\ ft^2$), τ is the shear stress ($lb_f/100\ ft^2$), γ is the shear rate (sec^{-1}), k is the consistency index, and n is the flowbehavior index (dimensionless) that must be less than one for shear-thinning fluids.

3.3. Investigating the effect of nanoparticles (NPs) on PV

Drilling mud with high plastic viscosity (PV) makes pumping in drilling operations difficult. On the other hand, drilling mud with low PV reduces mud density, that is unsuitable for drilling deep reservoirs because it produces little hydrostatic pressure [19]. The PV of the base mud was measured to be 6 $lb_f/100\ ft^2$ ± 0.02 cp. Fig. 3 shows the effects of nanoparticles on the plastic viscosity of mud at 27°C. The plastic viscosity in the presence of SiO_2 nanoparticles was almost the same from 0.01 to 0.5 wt% concentration, but at 1 wt% concentration it changed significantly to 14 $lb_f/100\ ft^2$. On the other hand, Al_2O_3 nanofluid showed a different trend that with the increase of nanoparticle concentration from 0.01 to 0.1 wt%, the PV increased and there was no change in the concentration of 0.1 wt% and 0.5 wt%. Al_2O_3 has a decreasing trend in the concentration of 1 wt%. As a result, nanofluid containing 1 wt% of Al_2O_3 nanoparticles is the best option to increase the yield point in drilling mud.

3.4. Investigating the effect of nanoparticles on YP

Electrochemical forces are fluid resistance to flow. This resistance to fluid flow is called YP (yield point). Base mud YP was measured at 24 $lb_f/100\ ft^2$. Fig. 4 shows the nanoparticles added to WBM at 27 °C. By increasing the concentration of SiO_2 nanoparticles from 0.01 to 1 wt%, the yield stress increased from 11.4 to 20 $lb_f/100\ ft^2$ and had an increasing trend. While this value did not change much as the concentration of Al_2O_3 nanoparticles increased from 0.01 to 0.1 wt%, it changed by 38 $lb_f/100\ ft^2$ at a concentration of 0.5 wt%. Also, the YP changes were more severe at 1 wt% concentration of Al_2O_3 nanoparticles and reached 69 $lb_f/100\ ft^2$, which is an increase of about 81% compared to 0.5 wt%.

3.5. Investigating the effect of nanoparticles on FL (filtration loss)

An increase in filter loss is not desirable because it causes problems such as pore clogging and changing the wettability and stickiness of the pipe. Liquid loss was recorded using a filter press device after 30 minutes under LPLT conditions. Fig. 5 shows the comparison of the functional effect of NWBDF and WBDF with different concentrations. The fluid loss of WBDF after 30 minutes was recorded 12 ml (±0.03 mm). According to Figure 5a, all the nanoparticles used reduced fluid loss compared to the base mud. According to Fig. 5a, nanoparticles reduced fluid loss compared to the base mud. The addition of SiO_2 nanoparticles from 0.01 to 1 wt% reduces the liquid loss from 11 to 8 mL. Al_2O_3 nanoparticles also reduce liquid loss from 12 to 9 ml. The results of the effect of nanoparticles in different concentrations on the thickness of mud cake are presented in Fig. 5b. The thickness of mud cake for base fluid is 5 mm. According to the diagram, the filter cake increases with the increase in the concentration of Al_2O_3 nanoparticles. In the presence of SiO_2 nanoparticles, a decreasing trend is observed with increasing concentration from 0.01 to wt%. The decrease in cake thickness with increasing concentration is also obvious. Also, the cake was thin, relatively impervious and uncracked. In general, by using SiO_2 nanoparticles, good permeability was observed at 1 wt%.

3.6. Investigating the effect of nanoparticles on thermal conductivity

Figs. 6a-c display the thermal conductivity of nanoparticles in different concentrations at temperatures of 27 °C, 50 °C, and 80 °C. The thermal conductivity of the bentonite base fluid was measured as 0.55, 0.57, and 0.61 W/mK at 27 °C, 50 °C, and 80 °C, respectively. As shown in Fig. 6, thermal conductivity for both samples at 27 °C is somewhat the same and no significant change is observed. But with increasing temperature at 50 and 80°C, the changes are clearly visible. In this way, the thermal conductivity in SiO_2 nanofluid at a concentration of 0.01 wt% is 0.62 W/mK and by increasing the concentration to 1 wt%, it has reached 0.67, and an increasing trend is observed in AL_2O_3 nanofluids from 0.67 to 0.7 W/mK. At 80 °C, silica and alumina nanoparticles show an increasing trend, among which alumina nanoparticles at 1 wt% reached 0.77 W/mK and are chosen as the best sample for increasing thermal conductivity.

4. Conclusion

The effect of Al_2O_3 and SiO_2 nanoparticle with a particle size of 15-30 nm and concentrations of 1, 0,5, 0.1, 0.05, 0.03, 0.01 wt% on the rheological behaviors of WBMs was investigated. Shear stress was measured versus shear rate, filtration properties (water loss and filter cake), plastic viscosity, thermal conductivity, and yield point at 27 °C, 50 °C, and 80 °C. Al_2O_3 in all concentrations increased the thermal conductivity so that the thermal conductivity in the presence of 1 wt% of Al_2O_3 nanoparticles increased by about 26% compared to the base fluid at 80 °C. The yield point in Al_2O_3 nanoparticles has an increasing trend in all concentrations, and this value increases with increasing concentration, especially in nanofluids with a concentration of 1 wt%, which has reached the highest value of 69 $lb_f/100\ ft^2$. Plastic viscosity in SiO_2 nanoparticles with 1 wt% concentration shows the best result to increase viscosity. In general, liquid loss in SiO_2 nanofluids worked better and reduced the amount of waste to 8 ml. Nanostructured materials have a significant effect on the rheological behaviors of WBDFs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] J. Abdo, M. Haneef, Nano-enhanced drilling fluids: pioneering approach to overcome uncompromising drilling problems, Journal of Energy Resources Technology 134(1) (2012).
[2] S.I. Reilly, Z. Vryzas, V.C. Kelessidis, D.I. Gerogiorgis, First-principles rheological modelling and parameter estimation for nanoparticle-based smart drilling fluids, Computer Aided Chemical Engineering, Elsevier2016, pp. 1039-1044.
[3] M. Huskić, M. Žigon, M. Ivanković, Comparison of the properties of clay polymer nanocomposites prepared by montmorillonite modified by silane and by quaternary ammonium salts, Applied clay science 85 (2013) 109-115.
[4] M. Sadeghalvaad, S. Sabbaghi, The effect of the TiO_2/polyacrylamide nanocomposite on water-based drilling fluid properties, Powder Technology 272 (2015) 113-119.
[5] G. Cheraghian, Q. Wu, M. Mostofi, M.-C. Li, M. Afrand, J.S. Sangwai, Effect of a novel clay/silica nanocomposite on water-based drilling fluids: Improvements in rheological and filtration properties, Colloids and Surfaces A: Physicochemical and Engineering Aspects 555 (2018) 339-350.
[6] M.-C. Li, Q. Wu, K. Song, S. Lee, C. Jin, S. Ren, T. Lei, Soy protein isolate as fluid loss additive in bentonite–water-based drilling fluids, ACS applied materials & interfaces 7(44) (2015) 24799-24809.
[7] A. Paknejad, J.J. Schubert, M. Amani, Key Parameters in Foam Drilling Operations, IADC/SPE Managed Pressure Drilling and Underbalanced Operations Conference & Exhibition, OnePetro, 2009.
[8] A. Aftab, A.R. Ismail, Z. Ibupoto, H. Akeiber, M. Malghani, Nanoparticles based drilling muds a solution to drill elevated temperature wells: A review, Renewable and Sustainable Energy Reviews 76 (2017) 1301-1313.
[9] A. Benslimane, I.M. Bahlouli, K. Bekkour, D. Hammiche, Thermal gelation properties of carboxymethyl cellulose and bentonite-carboxymethyl cellulose dispersions: Rheological considerations, Applied Clay Science 132 (2016) 702-710.
[10] S. Jilani, H. Menouar, A. Al-Majed, M. Khan, Effect of overbalance pressure on formation damage, Journal of Petroleum Science and Engineering 36(1-2) (2002) 97-109.
[11] M.V. Kök, B. Bal, Effects of silica nanoparticles on the performance of water-based drilling fluids, Journal of Petroleum Science and Engineering 180 (2019) 605-614.
[12] N.M. Taha, S. Lee, Nano graphene application improving drilling fluids performance, International petroleum technology conference, OnePetro, 2015.
[13] P. Dejtaradon, H. Hamidi, M.H. Chuks, D. Wilkinson, R. Rafati, Impact of ZnO and CuO nanoparticles on the rheological and filtration properties of water-based drilling fluid, Colloids and Surfaces A: Physicochemical and Engineering Aspects 570 (2019) 354-367.
[14] M. Al-Yasiri, A. Awad, S. Pervaiz, D. Wen, Influence of silica nanoparticles on the functionality of water-based drilling fluids, Journal of Petroleum Science and Engineering 179 (2019) 504-512.
[15] S. Ghanbari, E. Kazemzadeh, M. Soleymani, A. Naderifar, A facile method for synthesis and dispersion of silica nanoparticles in water-based drilling fluid, Colloid and Polymer Science 294(2) (2016) 381-388.
[16] S.S. Hassani, A. Amrollahi, A. Rashidi, M. Soleymani, S. Rayatdoost, The effect of nanoparticles on the heat transfer properties of drilling fluids, Journal of Petroleum Science and Engineering 146 (2016) 183-190.

[17] J.K.M. William, S. Ponmani, R. Samuel, R. Nagarajan, J.S. Sangwai, Effect of CuO and ZnO nanofluids in xanthan gum on thermal, electrical and high pressure rheology of water-based drilling fluids, Journal of Petroleum Science and Engineering 117 (2014) 15-27.
[18] N. Kalhori, M. Mousavi-Kamazani, F. Hormozi, Effect of $CeVO_4/Al_2O_3$/rGO nanocomposite on rheological properties and thermal conductivity of water-based drilling fluid, Journal of Petroleum Science and Engineering (2022) 111312.
[19] A. Piroozian, I. Ismail, Z. Yaacob, P. Babakhani, A.S.I. Ismail, Impact of drilling fluid viscosity, velocity and hole inclination on cuttings transport in horizontal and highly deviated wells, Journal of Petroleum Exploration and Production Technology 2(3) (2012) 149-156.