

Experimental investigation of the effect of TiO₂ nanofluid and KCl salt on polymeric water-based drilling fluid properties

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Abstract. In petroleum industries, nanofluids have the potential to improve the characteristics of the fluids used in drilling wells or Enhanced Oil Recovery (EOR) processes. In this study, a water based mud containing polymer was considered as the base fluid. Different concentrations of TiO₂ nanoparticle (0, 0.5 and 0.75 wt%) and different concentrations of KCl salt (0, 0.5, 1.5, and 3 wt%) were added to the base fluid and exposed to different temperatures (30, 50, 70 and 90 °C) with 19 different shear rates for investigating the effects of nanoparticle concentration, salt concentration, temperature and shear rate on viscosity of the base mud. Presence of TiO₂ particles enhanced not only the rheological behavior but also electrical and thermal conductivity of fluid up to 25% and 43%, respectively. Furthermore, the stability of the fluid containing salt and nanoparticle was investigated in these temperatures owing to the fact that the temperature could cause degradation of the fluid. For the purpose of investigating this phenomenon, the after cooling experiment was conducted. In addition, the data gathered in this investigation were examined by using three famous rheological models (Power law, Herschel-Bulkley and Herschel-Bulkley-Papanastasiou models) and the rheological parameters of each model were determined.

1 Introduction

In the recent years, nanoparticles have been introduced in many of the science and engineering branches and they have improved the required properties in them. Nanoparticles are the materials that are usually smaller than 100 nm and they have a very high Specific Surface Area (SSA) and surface to volume ratio which cause their specific properties (Anoop *et al.*, 2009; Choi and Eastman, 1995; Nguyen *et al.*, 2007). Nanoparticles usually alter the thermal conductivity, electrical conductivity and viscosity of the containing fluids and consequently ameliorate the performance of the fluids (Choi and Eastman, 1995; Karimi *et al.*, 2011).

Nanoparticles have been introduced and developed in medicine, health care and chemistry for many years. One of the recently focused applications of nanoparticles is their usage in petroleum engineering for recovery improvement in Enhanced Oil Recovery (EOR) processes and drilling processes (Friedheim *et al.*, 2012; Hoelscher *et al.*, 2012; Song *et al.*, 2016; Torsater *et al.*, 2013; William *et al.*, 2014).

Utilizing nanoparticles in EOR processes is usually due to their capability in viscosity increasing of the used fluid for EOR processes whereas in drilling processes, they are

under consideration for torque, drag, filter cake, wellbore stability, viscosity, thermal and electrical conductivity improvements and pipe sticking preventions (Abdo and Haneef, 2011; Agarwal *et al.*, 2011; Amani *et al.*, 2012; Hassani and Ghazanfari, 2017; Javeri *et al.*, 2011; Paiaman and Al-Anazi, 2009; Zakaria *et al.*, 2012; Zoveidavianpoor and Samsuri, 2016).

Drilling process is nearly the most expensive stage of oil well construction and production. Nowadays, drilling of oil wells is going to be more complicated, expensive and problematic since the drilling of conventional reservoirs have been decreased because they have been depleted and the focuses are given on the drilling of deep and unconventional reservoirs in which more complicated and undesirable situations occur (William *et al.*, 2014).

Drilling mud is a crucial portion of drilling processes and its properties determine the efficiency of drilling operation to some degree (Tehrani *et al.*, 2009). Also most of the drilling problems like kicks, blowouts, mud loss and stuck pipes which induce additional time delays and costs to the drilling operation, are related to the wrong mud selection and inadequate design of its properties (Li *et al.*, 2012; Tehrani *et al.*, 2009). To overcome the mud related problems, different types of drilling muds have been introduced and are used in drilling engineering (Arabloo and

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Shahri, 2014; Hoelscher *et al.*, 2012; Tehrani *et al.*, 2009; William *et al.*, 2014). In addition, different methods and additives have been developed for appropriate design of mud properties.

Water-Based Mud (WBM) and Oil-Based Mud (OBM) are two most using categories of drilling muds. OBM is usually utilized in drilling of the reservoir section of the well to reduce the drilling induced formation damage while for drilling of other sections of the well, WBM is more desirable owing to its lower cost, more flexibility, more compatibility with environment and low damaging (Tehrani *et al.*, 2009; William *et al.*, 2014).

Well cleaning is one of the main duties of drilling mud during drilling operations. Drilling mud must effectively remove the cuttings, clean the bore hole and prevent them from deposition during the circulation stops. If this process was not conducted efficiently enough, all the cuttings might not be removed from the bottom of the well or they would be deposited during circulation stops and this phenomenon would lead to inability of the bit to drill the fresh formation. Consequently, the significant time of drilling will be expended to re-drill the previously drilled cuttings deposited at the bottom of the well. In case of weak cleaning capability of the mud, more cuttings will be deposited at the bottom or at the angle point of the well and this may lead to the bit burial or suction of the pipes which their fishing treatments are very time consuming and expensive (Arabloo and Shahri, 2014). To overcome these problems, the rheological properties of the mud must be properly designed. In drilling mud, rheological property (Barnes *et al.*, 1989; Ezeakacha and Salehi, 2018; Rao and Cooley, 1983) are controlled with dynamic and static viscosities which represent rheological states of the mud during mud circulation and circulation stops.

Another duty of the drilling mud is to keep the bit cool. Generally, the mud must have the ability to remove the heat from the bit (which has been heated during its cutting action) and transfer this heat to the surface. If the heat removal is not implemented properly by the drilling mud, the performance of the bit will be decreased and ultimately it will be damaged and become useless. This duty of the mud is investigated by its thermal conductivity (William *et al.*, 2014). Generally, thermal conductivity of solids are greater than thermal conductivity of liquids; hence, it is acceptable that the thermal conductivity of the drilling mud could be improved by introducing the nanoparticles in it (Xie *et al.*, 2011).

It must be noted that for adequate dispersion and uniform distribution of nanoparticles throughout the drilling fluid, polymers have also been used as a component of the base drilling mud fluid (William *et al.*, 2014).

2 Rheological models

2.1 Power law model

The Power law model is a type of generalized Newtonian fluid model in which the shear stress (τ) is given by:

$$\tau = \mu \cdot \gamma, \quad (1)$$

$$\tau = K\gamma^n, \quad (2)$$

$$\mu = K\gamma^{n-1}, \quad (3)$$

where, τ is the shear stress (Pa), μ is the viscosity (Pa s), K (Pa s^{*n*}) is known as consistency coefficient which is the amount of viscosity when the shear rate (γ) is 1 s⁻¹, and n (dimensionless) is the flow behavior index; when n is less than unity, it implies that the fluid has shear thinning characteristics and when n is more than unity, it means that the fluid acts more like a shear thickening fluid. If equation (3) is plotted in a log-log diagram, the slope of the line will be the value of ($n - 1$). With more drop of the parameter n to below unity, small differential in shear rate shale causes larger differential in the amount of viscosity.

2.2 Herschel-Bulkley model

This rheological model is similar to Power law model except for parameter τ_0 (yield stress) which is added to the formula. In this equation, the concept of yield stress is ambiguous since the fluid may deviate at values less than τ_0 (Barnes *et al.*, 1989; Herschel and Bulkley, 1926):

$$\tau - \tau_0 = K\gamma^n. \quad (4)$$

Nonlinear regressions are utilized for determination of τ_0 , n and K ; however, when experimental data are available, the estimated values of models should not be used owing to the fact that the nonlinear regressions just try to minimize the error and do not lead to a precise answer (Rao and Cooley, 1983).

2.3 Herschel-Bulkley-Papanastasiou model

This model is the modified version of Herschel-Bulkley model in which another parameter is added, as follows (Papanastasiou, 1987):

$$\tau - \tau_0(1 - \exp(-m\gamma)) = K\gamma^n. \quad (5)$$

The parameter m (known as stress growth exponent) is another parameter added to the formula which results in more precise answer in comparison with Herschel-Bulkley model.

In this study, the effect of different parameters such as concentration of nanoparticles, concentration of salt, temperature, after cooling effect and shear rate on the viscosity of mud was investigated experimentally. In the experiments, concentration of the nanopowder and the salt are "0, 0.5, 0.75 wt%" and "0, 0.5, 1.5, 3 wt%", respectively. The applied temperatures are 30, 50, 70 and 90 °C. The tests were implemented in such a way that a specific concentration of a nanopowder is mixed with different concentrations of salt in different temperatures and the influence of different shear rates (γ) on the viscosity (μ) of fluid was recorded.

For the purpose of avoiding noise in logging operation (which is a consequence of low electrical conductivity) and investigating the stability of mud and cooling the bit, electrical and thermal conductivity tests were conducted.

Moreover, three models (Power law, Herschel-Bulkley, Herschel-Bulkley-Papanastasiou) applicable for rheology of non-Newtonian fluids are introduced and the best model fitted with the experimental data is represented.

3 Materials and experimental procedure

3.1 Materials

The implemented nanopowder throughout this investigation is titanium oxide (TiO_2) supplied by *Tecnan*[®]. Based on TEM image, the shape of particles is approximately sphere. Physical properties of TiO_2 are illustrated in [Table 1](#). Potassium hydroxide (KOH), potassium chloride (KCl) and formaldehyde (HCHO) were provided from *Merck*[®] *Chemicals* and Xanthan Gum (XG) was supplied by *Sigma-Aldrich*[®]. Moreover, bentonite, Partially Hydrolyzed Polyacrylamide (PHPA) and Carboxy Mechyl Cellulose-Low Viscosity (CMC-LV) are granted by *National Iranian South Oil Company (NISOC)*.

3.2 Experimental procedure

Initially, in order to provide a basic pH range (9.5–10) in the fluid, 0.025 wt% of KOH was added to deionized water in the 60 °C. Then, to prevent degradation of xanthan gum (which is a natural polymer), 0.1 wt% of paraformaldehyde (which is an antibacterial material) was poured to the fluid. After that, a considered amount of nanopowder was added to the solution and for dispersion and stabilization of the particles, the fluid was placed for 45 min in an ultrasonic device (UIP500hd) supplied by *Heilscher-Ultrasonic Technology*. Next, a considered amount of salt (KCl), 0.4 wt% of XG polymer (for enhancing viscosity and shear thinning characteristics of water base mud), 0.4 wt% CMC-LV (as mud loss control agent), 0.1 wt% of PHPA (to prevent aggregation of particles) and 1.5 wt% of prehydrated Bentonite (for establishing mud cake in drilling mud), were added respectively and mixed well by means of a stirrer. Then, the polymeric fluid containing nanoparticles was exposed to different temperatures in viscometer device (supplied by Brookfield Programmable DV-II+ viscometer) and by changing the shear rate, different amounts of viscosity were recorded.

Firstly, the mud was prepared with specific concentrations of salt and nanoparticle; then, the temperature of the mud was elevated to 90 °C by means of Brookfield viscometer. Different shear rates were applied and the viscosity of each one was measured; thereafter, the temper-

ature of the fluid was lowered to 70 °C and the experiment was re-conducted for this temperature and then to the next temperature until the lowest one (30 °C).

Since one of the practical applications of utilizing nanoparticles in mud is in drilling engineering which deals with continuous changes of temperature that alter the rheological behavior of mud from large depth of wells to the surface, after lowering the temperature and recording the viscosity of different shear rates for each one, for the purpose of investigating the stability and non-degradability of the mud and the nanoparticles inside it, the temperature was again elevated to 90 °C and the experiment was repeated. After carrying the cuttings out, the mud is cooled to ambient temperature on the surface and after removing the cuttings, the mud is re-pumped to the well. Therefore, in order to find out whether the mud containing nanoparticles can maintain its stability by changing temperature, it is important to examine the mud conditions in continuous temperature changes. The results demonstrated that by changing temperature, there is no significant change in nanoparticles stability.

In order to measure the thermal and electrical conductivity of drilling mud, first, the fluid was prepared according to the aforementioned steps and then thermal and electrical conductivity of fluid were determined by means of KD2 Pro and Sartorius Professional meter pp-20, respectively.

Augmenting the concentration of nanoparticle must be tangible and economical compared to enhancement of rheological conditions. In this experiment, as indicated in thermal and electrical conductivity diagrams in figures, increasing the concentration of nanopowder more than 0.75 wt% is not economically justified. This will be discussed in details later.

4 Results and discussion

In this section, the effectiveness of each parameter is separately and copiously investigated and simultaneous addition of nanopowder and salt in different temperatures is discussed from an overall perspective. Moreover, three models applicable for rheology of non-Newtonian fluids are introduced and the best model fitted with the experimental data is represented.

4.1 Effect of temperature

Temperature is the most effective parameter among the investigated rheological parameters and its effect is more evident than the other parameters. Temperature ultimately influences the viscosity of the base fluid. In this test, the viscosity change of various concentrations of salt and nanoparticles in four different temperatures (90, 70, 50 and 30 °C) was examined in various applied shear rates, [Figures 1a–1l](#). Augmentation of temperature lowers the viscosity of fluid; however, this reduction is not uniform. The difference of viscosity usually decreases at high shear rates and the four diagrams become closer to each other.

According to [Figure 1](#), for $\gamma = 1$ in the absence of salt and nanoparticle, increasing the temperature of mud from

Table 1. Characterization of TiO_2 nanopowder.

Property	Value
Color	White
Average particle size	10–15 nm
Specific Surface Area (SSA)	100–150 m^2/g
Polymorph	78.8% anatase 21.2% rutile
True density	3.84 g/cm^3

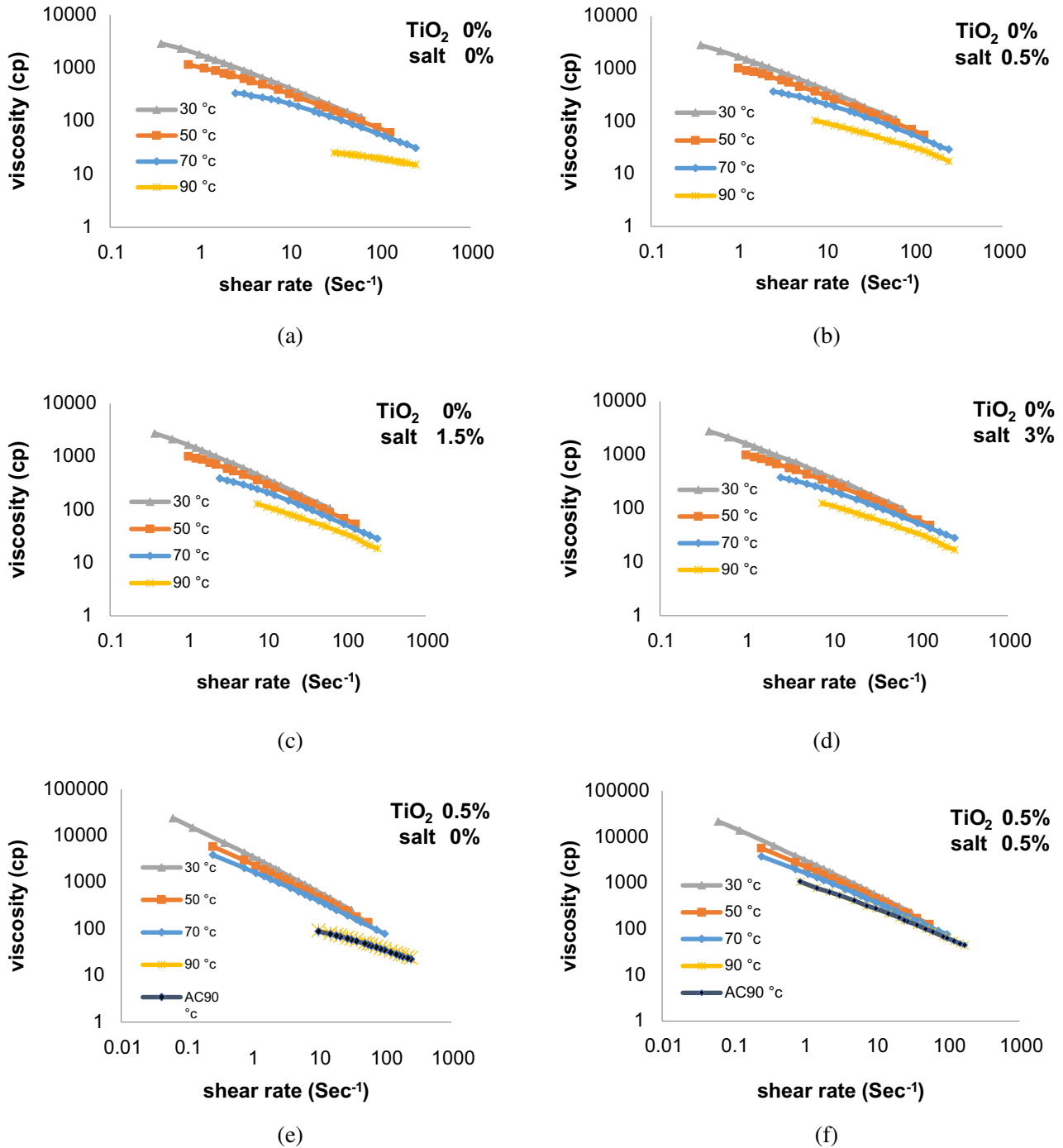
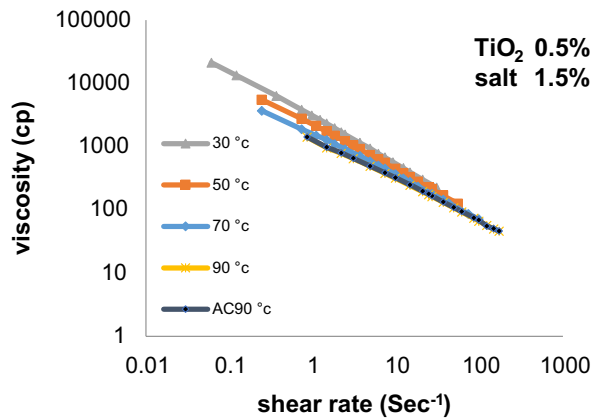


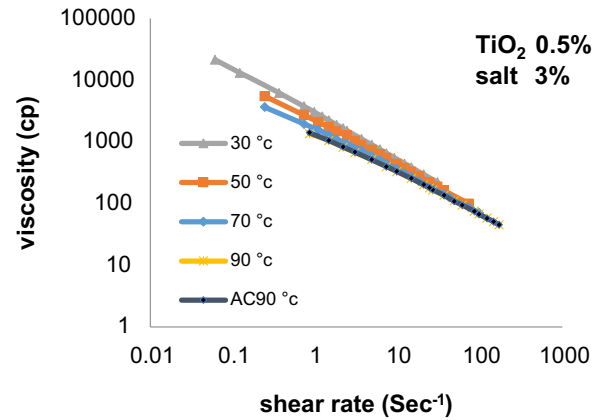
Fig. 1. Effect of temperature and after cooling (AC) on the viscosity of fluid with different concentrations of TiO₂ nanopowder and KCl salt.

30 °C to 90 °C lowers the viscosity of fluid 96.4% while increasing the temperature from 30 °C to 90 °C in the same fluid for $\gamma = 1000$ decreases the viscosity 48.1% (which is approximately half of the reduction of viscosity in $\gamma = 1$). Therefore, the effect of temperature in high shear rates is much less than low shear rates. It can also be seen that for a specific nanoparticle concentration and a constant shear

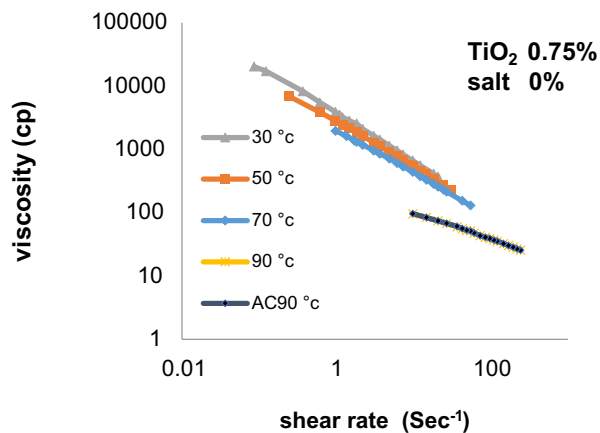
rate, by changing the concentration of the salt in a specific temperature, the viscosity varies in a certain range but raising or lowering the temperature in different concentrations of salt can significantly change the range of viscosity compare to previous temperature range. This phenomenon assesses that temperature changes have a much more effect on viscosity than changes in concentration of the salt.



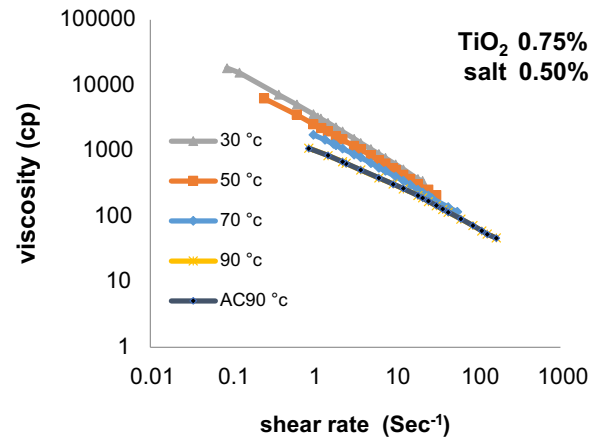
(g)



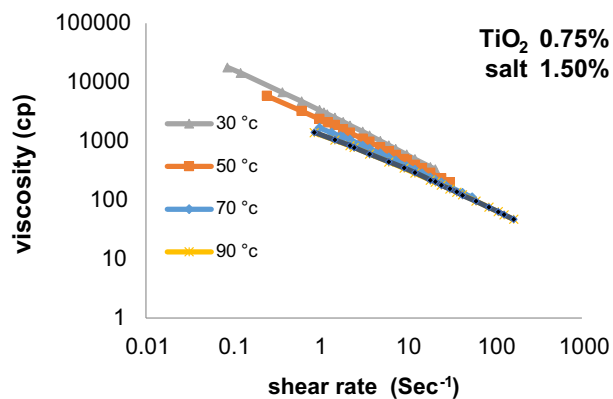
(h)



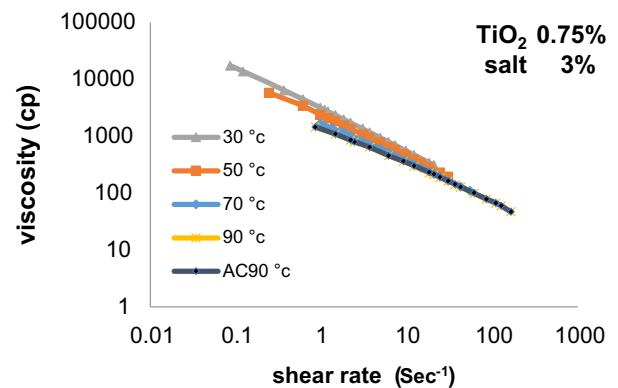
(i)



(j)



(k)



(l)

Fig. 1. Continued.

4.2 Thermal conductivity

Thermal conductivity is one of the crucial rheological features of fluids. The importance of this property lies in the instability and degradation of fluid that high temperatures are bound to bring about. In other words, if a fluid could

not transfer the heat into ambient under high temperatures, it would decompose and lose its main characteristics. Furthermore, cooling the bit is one of the tasks of drilling mud; hence, addition of nanopowder to the mud can increase its thermal conductivity and enhance the heat removal from the bit. Therefore, the mud must remove

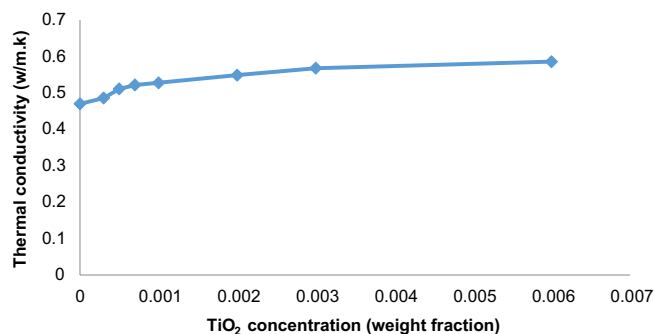


Fig. 2. Thermal conductivity of fluid with 3 wt% KCl salt and 30 °C.

the heat of the bit primarily and then loose the heat to ambient in order to release itself from instability.

In thermal conductivity tests, the effect of presence of nanopowder and salt in enhancing this property of mud is examined. As shown in Figure 2, addition of 3 wt% of KCl salt can increase the thermal conductivity of base mud up to 25%. It is worth to note that this augmentation was obtained in presence of a low percentage of TiO₂ nanoparticles. Since nanoparticles have large SSA and high surface charge, addition of TiO₂ nanoparticles can enhance the thermal conductivity of the base fluid.

4.3 Electrical conductivity

In the case of addition of nanoparticles to drilling mud, electrical conductivity of mud must be investigated; owing to the fact that in logging operation, low conductivity of mud is associated with noise. Therefore, identifying any consequences of utilizing nanoparticles for well services is essential. Figure 3 indicates that addition of nanoparticles in the absence of salt reduces the electrical conductivity of the fluid while adding 3 wt% of KCl salt to the same base mud can change the trends toward enhancement of conductivity. As shown in Figure 4, addition of TiO₂ nanopowder to the mud containing salt can increase the electrical conductivity up to 43% and it has a trend similar to thermal conductivity diagram in Figure 2. Therefore, presence of salt improves the behavior of the mud containing nanopowder. The isoelectric point of TiO₂ nanoparticles is close to 6

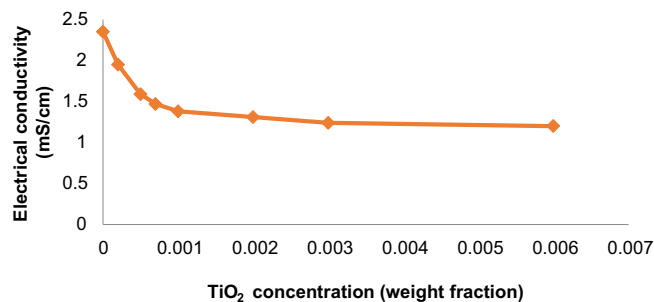


Fig. 3. Electrical conductivity of fluid with 0 wt% KCl salt concentration and 30 °C temperature.

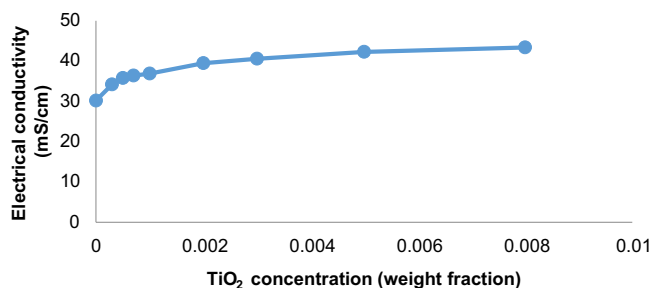


Fig. 4. Electrical conductivity of fluid with 3 wt% KCl salt concentration and 30 °C temperature.

and it slightly increases with temperature. Based on this fact and also the pH of the medium which was maintained at (9.5–10), one can conclude that increasing temperature decreases the electrical conductivity of the fluid.

4.4 Flow behavior models

Viscosity data associated with different shear rates in different conditions are implemented by three famous and accurate models (Power law, Herschel-Bulkley, Herschel-Bulkley-Papanastasiou). These rheological models are briefly described in this section.

In Table 2, viscosities and shear rates of experimental data for different concentrations of nanoparticle and salt in different temperatures are compared with the aforementioned models. As indicated in Table 2, although all of the models are very precise and have negligible errors, it can be said that Herschel-Bulkley-Papanastasiou and Herschel-Bulkley result in the most accurate and inaccurate answers respectively. Among these three models, even though Power law model has only two parameters (*n* and *K*), it leads to very accurate answers (in comparison with the other models which has three and four parameters) and accordingly, it is very simple and easy for interpretation of the data. For this reason, in the following sections, only the two parameters of Power law model (*n* and *K*) are used to justify the behavior of fluid in different conditions.

According to Power law equation and the obtained *n* and *k* in Table 2, increasing the temperature always decreases the value of *k* and increases the value of *n*. This means that reduction of *k* leads to reduction of viscosity and augmentation of parameter *n* can lower the shear thinning characteristics of fluid. The parameters *k* and *n* act in regard of lowering and raising the viscosity of fluid respectively, however, *k* has the dominant effect due to the fact that the viscosity is decreased by increasing the temperature.

4.5 Effect of salt

One of the main constituents of polymeric mud is salt which the reason of its presence is to prevent shale swelling. In the drilling, if the mud reached a layer that there was shale in its structural formation, the water in the mud would react with the shale inside the formation and the shale would swell and cause drilling string sticks due to friction with

Table 2. Comparison of rheological models.

Nano (wt%)	Salt (wt%)	T (°C)	Herschel-Bulkley-Papanastasiou					Power law			Herschel-Bulkley			
			τ_o	m	k	n	R^2	k	n	R^2	τ_o	k	n	R^2
0	0	30	1.5701	0.544	2.982	0.37	1	3.712	0.358	0.9972	1.488	2.718	0.32	0.9992
0	0	50	2.2753	0.189	1.838	0.42	1	2.406	0.416	0.9945	0.9653	2.842	0.39	0.9954
0	0	70	2.9798	0.064	0.95	0.48	0.999	1.388	0.467	0.9886	1.589	1.264	0.38	0.9968
0	0	90	1.7224	0.011	0.072	0.81	1	0.132	0.746	0.9924	0.3349	0.603	0.65	0.995
0	0.5	30	1.6151	0.427	2.887	0.35	0.999	3.543	0.353	0.9972	1.289	2.909	0.36	0.9952
0	0.5	50	1.8817	0.144	2.021	0.38	0.999	2.408	0.394	0.9963	1.237	2.164	0.38	0.9928
0	0.5	70	3.1458	0.064	1.041	0.44	0.999	1.526	0.435	0.99	1.188	1.524	0.4	0.9882
0	0.5	90	6.6548	0.011	0.726	0.23	0.999	0.627	0.503	0.9936	0.4437	0.702	0.46	0.9719
0	1.5	30	1.3569	0.566	2.779	0.36	1	3.432	0.35	0.9977	0.9909	2.631	0.39	0.9913
0	1.5	50	1.966	0.187	1.869	0.39	1	2.392	0.39	0.9963	1.826	1.746	0.41	0.9931
0	1.5	70	2.1655	0.091	1.11	0.44	1	1.579	0.42	0.9946	1.8	1.088	0.45	0.9944
0	1.5	90	3.2987	0.018	0.712	0.39	0.998	0.857	0.454	0.9947	1.337	0.57	0.49	0.9718
0	3	30	1.3756	0.349	2.896	0.33	0.999	3.385	0.341	0.9978	1.2	2.453	0.37	0.9918
0	3	50	2.2764	0.134	1.896	0.36	1	2.349	0.377	0.9958	1.789	1.804	0.38	0.9876
0	3	70	2.3005	0.082	1.076	0.44	1	1.535	0.423	0.9941	1.278	1.311	0.42	0.9957
0	3	90	3.6433	0.017	0.784	0.34	0.998	0.885	0.432	0.9941	0.7114	0.858	0.41	0.9679
0.5	0	30	1.4659	1.472	6.147	0.26	1	7.054	0.267	0.9989	9.052	0.802	0.24	0.9981
0.5	0	50	1.2325	0.567	4.438	0.29	1	5.052	0.294	0.9991	2.142	2.331	0.29	0.9949
0.5	0	70	1.5695	0.299	3.095	0.34	1	3.616	0.343	0.9982	2.021	1.935	0.31	0.998
0.5	0	90	1.4029	0.033	0.38	0.61	1	0.56	0.569	0.9954	0.6961	1.008	0.52	0.9987
0.5	0.5	30	1.2011	1.078	5.685	0.25	1	6.359	0.262	0.9992	2.347	2.693	0.25	0.9928
0.5	0.5	50	1.1228	0.448	4.298	0.28	1	4.796	0.29	0.9993	1.935	2.749	0.25	0.997
0.5	0.5	70	1.155	0.32	3.136	0.33	0.999	3.526	0.338	0.9985	2.527	1.551	0.3	0.9977
0.5	0.5	90	1.4963	0.118	1.872	0.39	1	2.194	0.395	0.9982	1.228	2.334	0.33	0.9955
0.5	1.5	30	1.1481	1.901	5.447	0.26	1	6.22	0.262	0.9991	2.157	2.946	0.24	0.9985
0.5	1.5	50	1.1193	0.794	4.049	0.29	1	4.706	0.289	0.9991	1.907	2.47	0.28	0.9979
0.5	1.5	70	1.407	0.286	2.95	0.33	1	3.399	0.334	0.9982	2.426	1.519	0.3	0.9975
0.5	1.5	90	1.5046	0.124	2.444	0.35	1	2.801	0.351	0.9987	1.459	2.043	0.33	0.9958
0.5	3	30	0.97808	2.659	5.37	0.26	1	6.099	0.259	0.9994	2.114	2.864	0.25	0.9981
0.5	3	50	1.3764	0.89	3.845	0.29	0.999	4.694	0.284	0.9987	2.209	2.005	0.29	0.9907
0.5	3	70	1.3507	0.478	2.837	0.33	1	3.433	0.328	0.9981	1.288	2.619	0.32	0.994
0.5	3	90	1.7657	0.136	2.506	0.34	1	2.93	0.346	0.998	1.801	1.762	0.32	0.9948
0.75	0	30	1.4354	1.82	6.878	0.25	0.997	7.851	0.256	0.9985	3.029	2.665	0.23	0.9976
0.75	0	50	1.57	0.654	5.03	0.28	1	5.839	0.287	0.9989	2.121	2.8	0.27	0.9948
0.75	0	70	1.3512	0.317	3.689	0.32	1	4.263	0.324	0.9993	2.688	1.739	0.29	0.9983
0.75	0	90	1.0814	0.03	0.434	0.61	1	0.559	0.581	0.9967	0.7881	1.105	0.49	0.9904
0.75	0.5	30	1.6363	1.558	6.13	0.26	0.998	7.18	0.263	0.9984	2.761	2.771	0.22	0.9926
0.75	0.5	50	1.8962	0.452	4.572	0.27	0.999	5.352	0.29	0.9985	2.411	2.397	0.25	0.9918
0.75	0.5	70	1.6194	0.384	3.143	0.33	0.999	3.914	0.318	0.9987	1.691	2.565	0.28	0.9962
0.75	0.5	90	2.2943	0.13	1.853	0.39	0.999	2.372	0.391	0.9963	1.368	2.372	0.31	0.9927
0.75	1.5	30	1.2572	1.532	5.922	0.26	1	6.742	0.267	0.9991	2.567	2.783	0.23	0.9973
0.75	1.5	50	1.4979	0.658	4.184	0.29	0.999	4.954	0.291	0.9986	2.223	2.354	0.26	0.9967
0.75	1.5	70	1.4624	0.499	2.904	0.34	0.999	3.719	0.318	0.999	2.314	1.665	0.3	0.9982
0.75	1.5	90	1.6019	0.112	2.612	0.34	1	2.923	0.35	0.9984	1.535	1.995	0.33	0.9916

(Continued on next page)

Table 2. (Continued)

Nano (wt%)	Salt (wt%)	T (°C)	Herschel-Bulkley-Papanastasiou					Power law			Herschel-Bulkley			
			τ_o	m	k	n	R^2	k	n	R^2	τ_o	k	n	R^2
0.75	3	30	1.008	1.723	5.733	0.26	1	6.427	0.262	0.9994	2.185	3.011	0.24	0.9992
0.75	3	50	0.94664	0.677	4.43	0.28	0.999	4.929	0.283	0.999	1.801	2.845	0.26	0.9987
0.75	3	70	1.0928	0.286	3.258	0.31	1	3.688	0.317	0.9993	2.724	1.446	0.29	0.9987
0.75	3	90	1.9389	0.095	2.747	0.33	0.998	3.063	0.349	0.9981	1.647	2.427	0.28	0.9852

the wellbore. Therefore, the reason of presence of salt in mud lies not only in amelioration of electrical conductivity of nanoparticles (as discussed before) but also in preventing shale swelling. The presence of salt in fluid considerably affects the SSA, size, and charge of nanoparticles. Therefore, the presence of salt changes the effectiveness and properties of nanoparticles. Usually, presence of salt would decrease the surface charge of nanoparticles and hence, causes the agglomeration and increment in size of nanoparticles (Bizmark and Ioannidis, 2015). As a result, the effects of salt presence must be investigated. Effects of various salt concentrations on rheological behavior of mud for different temperatures and nanoparticle concentrations are shown in Figures 5–10.

Results show that presence of salt in mud changes its rheological behavior. At low temperatures (30 °C and

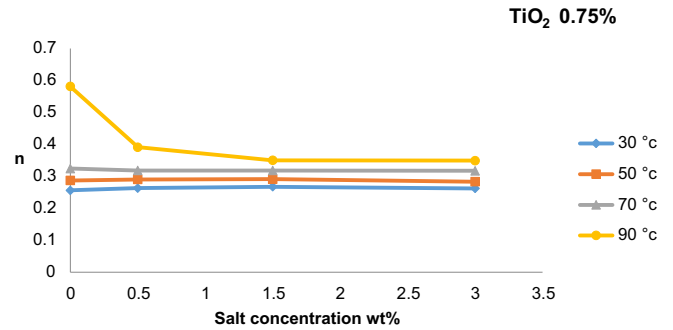


Fig. 7. Effect of salt concentration and temperature on the flow behavior index (n) in 0.75 wt% nanopowder concentration.

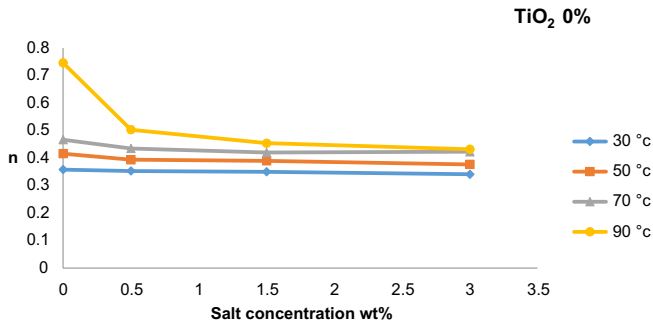


Fig. 5. Effect of salt concentration and temperature on the flow behavior index (n) in 0 wt% nanopowder concentration.

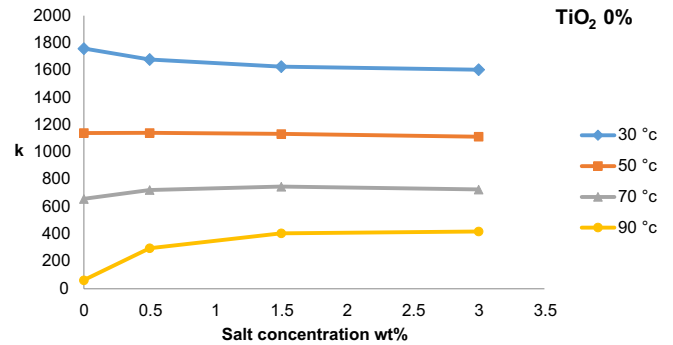


Fig. 8. Effect of salt concentration and temperature on the consistency coefficient (k) in 0 wt% nanopowder concentration.

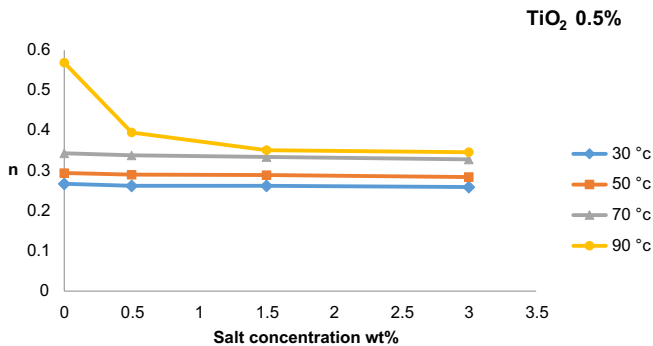


Fig. 6. Effect of salt concentration and temperature on the flow behavior index (n) in 0.5 wt% nanopowder concentration.

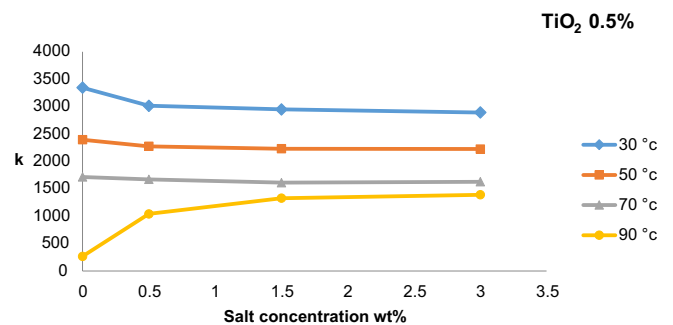


Fig. 9. Effect of salt concentration and temperature on the consistency coefficient (k) in 0.5 wt% nanopowder concentration.

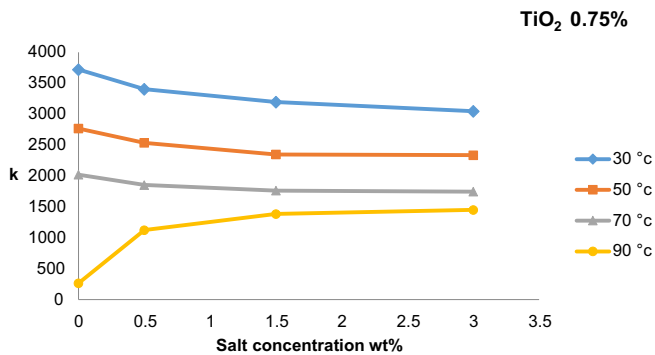


Fig. 10. Effect of salt concentration and temperature on the consistency coefficient (k) in 0 wt% nanopowder concentration.

50 °C), for a specific concentration of nanoparticle, addition of salt decreases the viscosity of mud but this can be reversed by increasing the temperature. For instance, in 90 °C, increasing salt concentration leads to viscosity elevation, however, this amount of augmentation is not the same for various salt concentrations. In temperature of 90 °C, addition of 0.5 wt% salt to the mud elevates the viscosity of fluid considerably. However, addition of one more weight percent of salt to the mud (a total concentration of 1.5 wt% of salt) in the same temperature (90 °C) increases the viscosity of the mud less than previous condition. Therefore, increasing the salt concentration lowers the rate of viscosity elevation.

The amount of salt affects the rheological parameters of Power law model (n , k). As illustrated in Figures 8–10, augmentation of salt concentration descends the value of k in low temperatures and ascends in high temperatures. This also goes for different concentrations of nanopowder.

According to Figures 5 and 6, the value of n decreases by adding salt to 0 and 0.5 wt% of nanoparticle at any temperature. For 0.75 wt% concentration of nanopowder in low temperatures (30 °C and 50 °C), elevating the concentration of salt from 0 to 1.5 wt% leads to augmentation of parameter n and from 1.5 to 3 wt% leads to reduction in the value of n while increasing the amount of salt in high temperatures (70 °C and 90 °C) decreases the value of this parameter. Based on Figures 5–7, what all the diagrams have in common is that the augmentation of salt concentration in 90 °C sharply decreases the value of n and then it lowers with gentle slope. Therefore, another important feature of salt is that in high temperatures, it severely lowers the value of n and hence, it significantly enhances the shear thinning characteristics of the fluid (slope of diagram is increased $\mu = k\gamma^{n-1}$); this means that a slight increase in shear rate leads to considerable reduction in viscosity. This feature is extremely useful in drilling and cementation of wells.

4.6 Effect of salt on viscosity

According to Power law equation, increase of n or k represents the elevation in viscosity of fluid. Therefore, investigation of viscosity effect can be categorized as follows:

- (a) 0 and 0.5 wt% of nanopowder (Figs. 5, 6, 8 and 9).
- (b) In low temperatures of these nanoparticle concentrations, increasing the amount of salt results in reduction of both n and k , but ultimately leads to reduction of viscosity.
- (c) In high temperatures, augmentation of salt raises the value of k and lowers the value of n . As discussed before, elevating the concentration of salt augments the viscosity of mud. Therefore, the value of k has the controlling effect in this range of temperature.
- (d) 0.75 wt% of nanopowder (Figs. 7 and 10).
- (e) In low temperatures, increasing the concentration of salt in this amount of nanoparticle reduces the value of k but the value of n has not a unique trend.
 - (I) In concentration of 0–1.5 wt% of salt, addition of salt leads to elevation of parameter n , but because the viscosity is lowered by increasing the salt concentration, it can be concluded that k has the dominant influence in viscosity.
 - (II) In 1.5–3 wt% of salt, increasing the percentage of salt leads to reduction of n and hence both values of k and n help the reduction of viscosity.
 - (III) In high temperatures, augmentation of salt concentration increases the value of k and decreases the value of n ; inasmuch as the viscosity is increased, it can be said that k is again the controlling parameter.

One can draw a conclusion that when k and n parameters act in opposite directions, the dominant and controlling parameter is k .

4.7 Effect of TiO₂ nanoparticles

Addition of small amount of nanopowder improves the rheological behavior of fluid. However, as mentioned before, increasing the concentration of TiO₂ nanoparticles more than 0.75% is not economical. In a specific concentration of salt and a specific temperature, addition of nanopowder increases the value of k and decreases the value of n ; however, augmentation of k by changing the concentration from 0 to 0.5 wt% is less than augmentation of k by increasing the concentration from 0.5 to 0.75 wt%. It can also be seen that reduction of n in low concentrations of nanoparticle is more than that in high ones. Therefore, increasing the nanoparticle leads the mud toward a non-Newtonian fluid with good shear thinning characteristics which are favorable in drilling industry. The intensity of the shear thinning behavior of the fluid is highly impacted by the agglomeration and deagglomeration of the TiO₂ nanoparticles which can be affected by temperature, salt addition, and also the shear rate. This is the reason of different behaviors shown by the base mud containing nanoparticles and salt at various conditions.

k and n act in opposite direction but augmentation of nanopowder ultimately increases the viscosity of fluid. Accordingly, it can be concluded that k is the main controlling parameter in rheological behavior of mud. It is also worth to note that by increasing the concentration of titanium dioxide nanoparticles from 0.5 to 0.75 wt% at high

temperatures, the changes in viscosity and the values of both parameters (k and n) are negligible.

5 Conclusion

Based on the results obtained in this study, the following conclusions can be drawn:

1. Addition of TiO_2 nanoparticles ameliorates the characteristics of fluids such as thermal and electrical conductivity. This has an important application in costly industries such as oil well drilling. Addition of 0.75 wt% TiO_2 to the base fluid containing 3 wt% of salt enhances the thermal and electrical conductivity of fluid up to 25% and 43% respectively.
2. Augmentation of TiO_2 concentration in the absence of salt decreases the electrical conductivity to the extent that in 0.75 wt% concentration of TiO_2 , the electrical conductivity of fluid decreases by 49%. In contrast, presence of salt in base mud increases the electrical conductivity of fluid in the absence of nanopowder and by augmentation of TiO_2 concentration; it improves this characteristic of base fluid to the extent that in 0.75 wt% concentration of TiO_2 , the electrical conductivity is enhanced up to 43%.
3. The experimental data are well fitted and consistent with the models representing the rheological behavior of a fluid containing salt and nanoparticle.
4. Augmentation of temperature decreases the viscosity of mud and among various investigated parameters such as temperature, nanopowder concentration and salt concentration; temperature has the most significant role in increasing or decreasing the viscosity of fluids. Moreover, according to after cooling data, it can be concluded that continuous cooling and heating has no effect on stability of the mud containing salt and nanopowder. The fluid can maintain its characteristics and there is no degradation.
5. Addition of salt leads to reduction of viscosity in low temperatures and augmentation of viscosity in high temperatures. In middle range temperatures (60 °C and 70 °C), increasing the concentration of salt has no tangible influence on viscosity. Furthermore, the highest impact of salt on enhancing the rheological characteristics of the drilling mud is achieved by 0.5 wt% of KCl in a high temperature (90 °C). In this case, the value of n is reduced sharply and provides good shear thinning characteristics to the fluid which means that by increasing the shear rate, the viscosity of fluid decreases. This phenomenon is favorable in drilling industries since increasing the viscosity helps removing the cuttings from the drilling mud.
6. Increasing the concentration of TiO_2 nanoparticle results in reduction of n and augmentation of k which leads to elevating the viscosity and enhancing the shear thinning characteristics of drilling mud.
7. The two parameters of Power law model, n and k , can explain the rheological behavior of drilling mud. When these two parameters act in opposite direction

of each other, k is the controlling agent which has the dominant rheological effect and the viscosity changes in the same direction of k variations.

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