PERFORMANCE OF WATER-BASED DRILLING FLUIDS WITH BENTONITE IN HIGH TEMPERATURES

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Abstract. *During the well drilling, the fluids get exposed to high temperatures for long periods, forming gels and with excessive pressure loss during flow. In the past, these problems were overcome with the use of oil-based fluids. However, because of the environmental laws, these fluids are being replaced and the water-based fluids are the most indicated for they are environmentally friendly and of lower cost. Because of this, the study of the properties of water-based fluids upon different thermal conditions is extremely important, because it exposes the fluids to thermal conditions similar to the field conditions. It is acknowledged that, over approximately 393.15K, and in high salinity conditions, the colloidal systems composed of bentonite increase their viscosity considerably. So, having the challenge of developing water-based fluids with bentonite which present stable rheological and filtration properties at high temperatures, it was used a* 2^3 *+ star configuration factorial design and three experiments in the central point to evaluate the influence of temperature and the clay concentration (entrance variables) over the rheological and filtration properties. The fluids were prepared with the bentonite concentration ranging between 0,0250x103 kg/m3 a 0,0640x103 kg/*m^3*and submitted to thermal treatment between 311 and 449K for 16 hours in static conditions. It was concluded that the concentration of bentonite clay and the aging temperature influence statically in the rheological and filtration properties of the drilling fluids, in a 95% confidence level. Bigger values of AV and VP are obtained with the increase in the clay content from* $0.250x10^3 kg/m^3$ *to* $0.0640x10^3$ *kg/*m^3*, as for the increase in the temperature from 311K to 449K. Fluids with less and, therefore, better values of VF ate obtained with higher contents of clay and lower aging temperatures. In the end, it became evident that the clay and thermally stable clay and water fluids can be obtained with contents of clay ranging from 0.0580kg/L, if they are exposed to temperatures between 331 and 429K.*

Keywords: *drilling fluid, temperature, rheological parameters*

1.0 INTRODUCTION

The drilling fluids are complex mixtures of solids, liquids, chemical products and, sometimes, even gases. From the chemical point of view, they can assume suspension, colloidal dispersion or emulsion aspects, depending on the physical state of the components (Thomas, 2001).

The composition of the fluid depends on the particular demands of each drilling. For simple and not so deep drillings a fluid consisting of water and clay in low concentrations is appropriate. However, in difficult drilling situations and/or deep depths a more elaborate fluid is necessary, with the addition of one or several additives (Amorim, 2003). These additives are chemical substances that, when added, give the fluids special properties, required during the drilling activities (Serra, 2003).

The drilling fluids are traditionally classified by their main component: gas based fluids, oil based fluids and water based fluids. The gas based fluids consist of an air or natural gas flux injected in the well with high speed. The oil based fluids are those in which the continuous liquid phase is constituted by oil, while for the water based fluids, the continuous phase is constituted by water (Darley and Gray, 1988).

Among the aqueous fluids, the clay and water based fluids stand out, constituted of water and sodium bentonite clays of high swelling degree. The clays give the fluids an increase in viscosity and thixotropic properties, besides reducing filtration by forming a low permeability cake (Nascimento et al., 2010).

The clay and water based fluids are generally put in the first phases of the well drilling, generally composed by unconsolidated sediments (Thomas, 2001). In later phases, where the wells reach deep depths, it is common the presence of geological formations that are hard to drill, for example expansive shales, as well as high temperature conditions.

When the drilling reaches, therefore, these phases, the drilling fluids become exposed to the present conditions for long time periods, more even when there is the necessity of routine operations for instance maneuvers, in which the drilling column is removed for the substitution of the bit.

The clay and water fluids are sensitive to high temperatures and when exposed for long periods form hard gels, which can compromise the drilling operations. In the past, to overcome these problems, diesel oil based fluids were used, because they remained stable in high temperatures. However, due to environmental considerations, logistics and the high costs, the use of this type of fluid (even the most recent formulated with a synthetic base) became impracticable (Clark, 1994).

According to Kelly (1961), the rheological properties of the drilling fluids can present great differences in an environmental temperature and in the interior of the well. The temperature inside the well depends on the geothermal gradient and can be higher than 533.15K. Even the moderate temperatures can have significant influence in the rheological properties of the fluids. The fluid inside the well can be thicker or thinner than in the surface, and an additive that reduces the viscosity in the surface can increase the viscosity of the fluid inside the well.

Due to the large number of variables involved, the behavior of the drilling fluids in high temperatures, particularly the water based drilling fluids, are unpredictable and, in fact, still not completely understood. Even small differences in the composition of this fluid can make considerable differences in its rheological behavior, in a way that it is necessary to test each fluid individually, in order to obtain reliable data (Knechtel et al., 1956).

Annis (1967) studied the water based fluid's rheology in high temperature. The results showed that the effect of the temperature is the following: if the suspension is totally deflocculated, the plastic viscosity and the yield strength decrease with the increase of the temperature as far as 450.15K, while if the suspension is flocculated, just the plastic viscosity decreases and the yield strength increases drastically in temperatures higher than 373.15K.

According to Clark (1994), the water based fluids containing bentonite can be used in these difficult environments and several additives are used to allow stability in these high temperatures.

As mentioned before, bentonite is an essential component in drilling fluids. This clay has as main component the montmorillonite and when mixed with water forms non-Newtonian dispersions (property in which the viscosity varies according to the deformation degree applied). Besides that, it has the unique ability to form a gel when in rest and return to the solution state under agitating. This property is called thixotropy and turns the bentonite valuable to the oil industry, since it guarantees the suspension of the debris formed by the drill and its transportation from the bottom of the well to the surface. The bentonite also forms a low permeability membrane on the walls of the well, called cake, ensuring the stability of the well's walls, avoiding collapses and undesirable infiltrations in the geological well-formation (Rossi eta al, 1999;. Kelessidis et al, 2007a, b, c).

Several studies indicate that the effect of the temperature over the rheological properties of the drilling fluids' additives with bentonite is unpredictable, so the action mechanisms are not included (Hiller, 1963, Kelly, 1965, Annis, 1967, Singh e Sharma, 1991, Briscoe et al., 1994, Clark, 1994, Luckham e Rossi, 1999, Santoyo et al., 2001).

The aim of this study is to develop aqueous fluids with bentonite that have stable rheological and filtration properties in high temperatures. Therefore, it was used a type 2^2 factorial plan type with three experiments on the central point and a star configuration to evaluate the influence of the temperature and the clay content (input variables) over the rheological and filtration properties of the developed fluids.

2.0 MATERIALS AND METHODS

2.1. Materials

A sample of industrialized sodium bentonite clay was studied in Campina Grande (PB), from the deposits located in the city of Boa Vista (PB), courtesy of the company Bentonit União Nordeste - BUN and commercially known by Brasgel PA. This clay is widely used in the oil industry as a thickening, thixotropic and cake agent.

2.2 Methods

2.2.1 Factorial Plan

To evaluate the influence of the input variables (clay content and temperature) over the rheological properties (apparent and plastic viscosity) and filtration (filtered volume) of the water and clay based drilling fluids, was used a factorial design type 2^2 with three experiments on the central point. However, the linear model obtained didn't present satisfying results. So, it was used, based on Barros Neto et al. (1996), a quadratic model by amplifying the design, in other words, by making use of the star planning. So, it was added to the original design another identical one, but rotated by 45o in relation to the departure orientation.

The regression of the experimental data was developed using the Statistic software, version 5.0 (Statsoft, 2000). The encoded and real values of the input variables used in the design are found in Tab. 1.

Table 1 – Encoded and real values of the input variables used in the factorial design

Entrance variables	Codified level				
	Level -1.4142	Level -1	Central point 0	Level +1	Level +1.4142
Clay concentration (kg/L)	0.0250	0.0307	0.0445	0.0582	0.0640
Aging temperature (K)	311	331	380	429	449

2.2.2 Preparation of the drilling fluids

For the preparation of the clay and water based drilling fluids, the clay was added in concentrations of 0.025 kg/L, 0.0307 kg/L, 0.0582 kg/L and 0.0640 kg/L under constant agitation with a speed of 13.000 rpm in a Hamilton Beach agitator, model 936. After the clay was added, the velocity of the agitator was increased to 17.000 rpm, remaining 1200 seconds under agitation.

2.2.3 Aging of the drilling fluids

After the preparation of the drilling fluids, they were submitted to aging in a Roller Over model 704 ES from the brand Fann in the following temperatures: 311K, 331K, 380K, 429K and 449K. The aging was performed under static conditions during a period of 16h.

2.2.4 Rheological study

For the rheological study after aging, the fluid was agitated during 300 seconds in a mechanical agitator Hamilton Beach model 936 in a velocity of 17.000 rpm. Then, the fluid was transferred to the viscometer's recipient Fann model 35A. The equipment was set at a speed of 600 rpm during 120 seconds and made the reading. Then, the velocity was changed to 300 rpm and made the reading after 15 seconds.

The apparent and plastic viscosities were obtained following the rule N-2605 (PETROBRAS, 1998a). The apparent viscosity (AV) is the value obtained by dividing the value of the measure at 600 rpm by 2, given in cP. The plastic viscosity (PV) is the difference between the readings performed at 600 rpm and at 300 rpm, also given in cP. Then, the viscosities were converted to Pa.s (cPx10^{-3}).

2.2.5 Filtered volume

After determining the rheological parameters was determined the filtered volume (VF). For this, the fluids were agitated during 60 seconds, in mechanical agitator Hamilton Beach model 936, in the velocity 17.000 rpm. Then, they were transferred to the recipients of the filter press API and submitted to a pressure of the order of 0.1 MPa. After 1800 seconds, the filtered volume was read and the measure of the filtered volume was obtained, expressed in m^3.

The rheological properties (AV and PV) and the filtered volume (VF) were also determined with the fluids in ambient temperature.

1.0 Results and discussion

In Table 2 are found results of the apparent viscosity (AV), the plastic viscosity (PV) and the filtered volume (VF) of the clay and water fluids prepared with the clay concentration of 0. 0250 kg/L, 0.0307kg/L,0.0445kg/L, 0.0582kg/L and 0.0640kg/L obtained in an ambient temperature.

The results (Table 2) show that the increase in the concentration of clay leads to an increase in the values of AV and PV and reduce the values of VF.

According to the standards of PETROBRAS (1998b), the bentonite clay with additives can be classified as clays type I or type II. The clays from type I are those which in dispersions, with concentrations of 0. 0243 kg/L, present limits of AV$\geq$ 0.015Pa.s, PV $\geq$ 0.004Pa.s and VF $\leq$ 18 x $10^{-6}m^3$, and the type II clays present the limits of AV $\geq$ 0.015Pa.s, PV $\geq$ 0.006Pa.s and VF $\leq$ 16 x $10^{-6}m^3$.

Comparing the results presented in Tab. 2 with the limits above for qualification of bentonite clays with additives for water based drilling fluids, could be observed that the fluids prepared with clay concentration of 0.0640 kg/L (experiment 5) are found to be according to the standards. The fluids prepared according to the experiment 4 also present proper properties, following the limits of PETROBRAS (1998b) for clays from type I, although they have been prepared with clay concentration of 0.0582 kg/L.

Table 2: Clay and water based fluids' Rheological (apparent viscosity (AV) and plastic viscosity (PV)) and filtration (VF) properties in ambient temperature.

Experiments	Clay Concentration (kg/L)	AV (Pa.s)	PV (Pa.s)	VF (10^{-6} m^3)
1	0.0250	0.0047	0.0033	28.1
2	0.0307	0.0067	0.0043	25.2
3	0.0445	0.0125	0.0065	25.6
4	0.0582	0.0195	0.0097	16.8
5	0.0640	0.0256	0.0087	15.4

In Table 3 are found the matrix of the factorial design and the results of the apparent viscosity (AV), plastic viscosity (PV) and the filtered volume (VF) obtained with the clay and water drilling fluids.

Through the results presented in Table 3, was observed that the rheological and of filtration properties studied are influenced by the concentration of the clay, by the temperature and by the combination of them.

Generally, there is an increase in the values of AV and PV with the increase in the concentration of clay and temperature. This increase in the viscosities arises from the greater intensity of the electrical and mass interactions between particles, which become dominant with the increase in the concentration of the clay and also of the temperature. The high value of AV obtained especially for the fluids submitted to the aging in the more elevated temperatures and with higher clay concentrations (experiments 4 and 6) characterizes the gelation state of the fluid.

According to Stefan (1966), the PV is a variable that depends on the interaction of the present solids and/or a measurement of friction resultant of a collision of two particles, being influenced by their degree of hydration and by the electrical field resultant of the repulsive forces in the particles of clay that are negatively charged. The interactions between particles promote the formation of more or less rigid lattices. The lattices, on the other hand, retain the water molecules from the system, lowering the quantity of free water, and, therefore, the filtered volume (VF)

Regardless of the behavior obtained for the VF, it was observed that it decreases with the concentration of the clay and increases quite expressively with the increase of the aging temperature. That way, it became evident that the increase in the temperature, for the fluids with low or high concentrations of clay, lead the systems to greater losses by filtration, in other words, even if the fluids are in gelation state, these present higher filtered volume, suggesting that the water present or a portion of the water present are found to be free and not stuck on the lattices according to Stefan (1966). Therefore, it is believed that the lattices formed by the interactions between particles retain the water molecules depending on the degree of flocculation of the dispersion, may having gels with large quantities of free water and, therefore, elevated filtered volume, as well as gels with low quantities of free water that generate low filtered volume.

Table 3 – Matrix of the factorial design and the rheological (apparent viscosity (AP) and plastic viscosity (PV)) and of filtration (VF) properties of the clay and water fluids.

Experiments	Clay Concentration (C)	Aging Temperature (T)	AV (Pa.s)	PV (Pa.s)	VF (10^{-6} m^3)
1	-1	-1	0.0060	0.0040	28.2
2	1	-1	0.0210	0.0090	16.0
3	-1	1	0.0090	0.0065	38.6
4	1	1	0.0380	0.0140	23.0
5	-1.4142	0	0.0065	0.0050	33.4
6	1.4142	0	0.0367	0.0145	17.6
7	0	-1.4142	0.0122	0.0070	19.8
8	0	1.4142	0.0168	0.0115	28.4
9	0	0	0.0187	0.0095	24.0
10	0	0	0.0195	0.0100	23.8
11	0	0	0.0187	0.0095	23.4

In Tab. 4, are presented the analysis of the variance and the codified mathematical models for the rheological properties (AV, PV) and for the filtered volume (VF) of the drilling fluids.

In the studied cases, the analysis of statistical significance showed that the correlation coefficients (R) and the coefficients of explained variation (R^2) of the experimental results for AV, PV and VF of the fluids prepared according to the design were satisfactory, over 0.98 and 97.0%, respectively. Therefore, it can be said that the mathematical models presented in Tab. 3 have more than 97. 0% of the variations obtained explained by the design.

For the AV, PV and VF properties, statistically significant and predictive mathematical models were obtained, since the ratio between the $F_{Calculated}$ and the $F_{tabulated}$ presented a value superior than 5.

According to Rodrigues (2010), the F test shows if there is a relation between the dependent (AV, PV and VF) and independent (clay concentration and temperature) variables; if the value obtained is superior to 1, the regression is statistically significant, and if superior to 5, as in the AV, PV and VF cases, besides being statistically significant, the mathematical model is considered predictive.

Table 4 – Variance analysis (ANOVA) and codified mathematical models of the apparent (AV) and plastic (PV) viscosities and the filtered volume (VF) of the clay and water fluids for the factorial design used.

Source of variation	AV (Pa.s)	PV (Pa.s)	VF (10^{-6} m^3)
Correlation coefficient (R)	0.989	0.987	0.986
% of explained variation*	97.934	97.397	97.154
$F_{calculated}/F_{tabulated}$	9.385	10.228	9.330
Codified mathematical models for the water based drilling fluids			
AV (cP) = $18.97 \times 10^{-3}** \pm 12.6 \times 10^{-4} + (10.84 \times 10^{-3}C** \pm 7.71 \times 10^{-4}) + (1.43 \times 10^{-3}C^2 \pm 9.18 \times 10^{-4}) + (3.31 \times 10^{-3}T** \pm 7.71 \times 10^{-4}) - (2.12 \times 10^{-3}T^2 \pm 9.18 \times 10^{-4}) + (3.50 \times 10^{-3}CT** \pm 10.91 \times 10^{-4})$			
PV (cP) = $9.67 \times 10^{-3}** \pm 4.45 \times 10^{-4}) + (3.24 \times 10^{-3}C** \pm 2.72 \times 10^{-4}) - (0.24 \times 10^{-3}C^2 \pm 3.24 \times 10^{-4}) + (1.73 \times 10^{-3}T** \pm 2.72 \times 10^{-4}) - (0.49 \times 10^{-3}T^2 \pm 3.24 \times 10^{-4}) + (0.63 \times 10^{-3}CT \pm 3.85 \times 10^{-4})$			
VF (mL) = $23.73 \times 10^{-6}** \pm 0.92 \times 10^{-6} - (6.27 \times 10^{-6}C** \pm 0.57 \times 10^{-6}) + (1.30 \times 10^{-6}C^2 \pm 0.67 \times 10^{-6}) + (3.70 \times 10^{-6}T** \pm 0.57 \times 10^{-6}) + (0.60 \times 10^{-6}T^2 \pm 0.67 \times 10^{-6}) - (0.85 \times 10^{-6}CT \pm 0.80 \times 10^{-6})$			

Where: SQ_R is the quadratic sum of the regression, SQ_T is the total quadratic sum, C is the clay concentration and T is the aging temperature.

$*R^2 = \left(\frac{SQ_R}{SQ_T}\right) x\ 100$

**Statistically significant at the level of 95% of reliability.

The Fig.1 presents the response surfaces obtained from the codified mathematical designs presented in Table 4, for the AV, PV and VF properties.

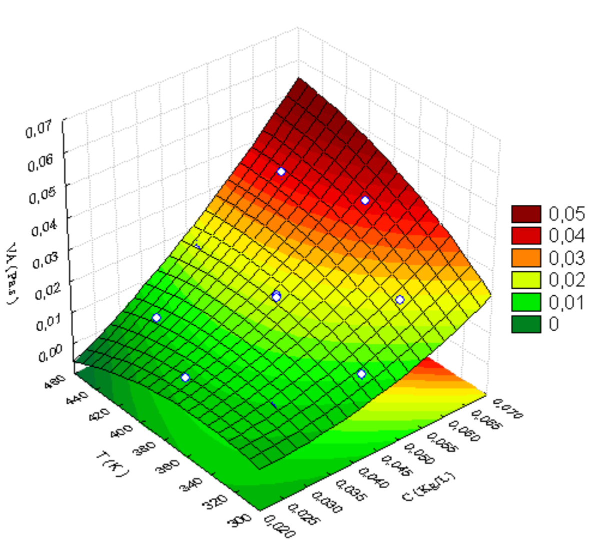
According to the Figs. 1(a) and 1(b) and to the mathematical designs presented in Tab. 4, it was observed that the AV and the PV are statistically influenced by the input variables (clay concentration and temperature) at the level of 95,0% of reliability, in other words, higher values of AV and PV are obtained with the increase of the clay concentration of 0.0250 kg/L to 0.0640 kg/L, as well as the increase in the temperature of 311K to 449K.

According to the Fig. 1(c) and the mathematical design presented in Tab. 4, it was observed that higher values of VF are obtained with the increase of the temperature and decrease of the clay concentration. On the other hand, smaller, and therefore, better values of VF are reached for the fluids prepared with higher levels of clay and submitted to aging in the lower temperatures.

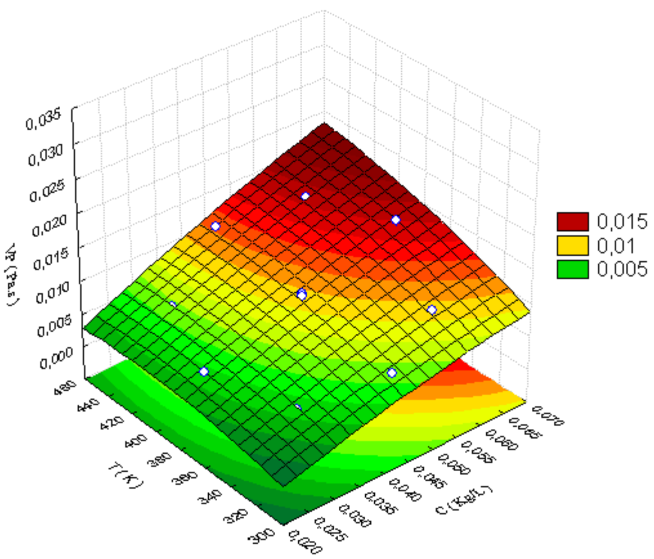
Comparing the obtained results of AV, PV and VF (Tab. 3) with the limits specified by PETROBRAS (1998b) for the qualification of bentonite clay for water based drilling fluids (VA ≥ 0.015Pa.s; VP ≥ 0.004Pa.s e VF ≤ 18 x 10^{-6}m^3), it was observed that among the 11 fluids studied, 07 (experiments 2, 4, 6, 8, 9, 10 and 11) presented AV values according to the standard above. Concerning the PV values, all of the fluids presented values superior to 0,004Pa.s. Finally, only the fluids prepared according to the experiments 2 (VF = 16 x 10^{-6}m^3) and 6 (VF = 17.6 x 10^{-6}m^3) obtained VF under the maximum allowed. It is important to highlight that the limits specified by PETROBRAS are used for fluids with 0.0486kg/L of clay.

Summarizing, the fluids prepared according to the experiments 2 (clay concentration of 0.0580 kg/L and temperature of 331K) and 6 (clay concentration of 0.0640kg and temperature of 380K) present AV, PV and VF values according to the above standards and so, even with the clay concentrations superior to the concentrations used in the PETROBRAS standard, it can be affirmed that these fluids present appropriate behavior when submitted to temperatures of 331K (experiment 2) and 380K (experiment 6).

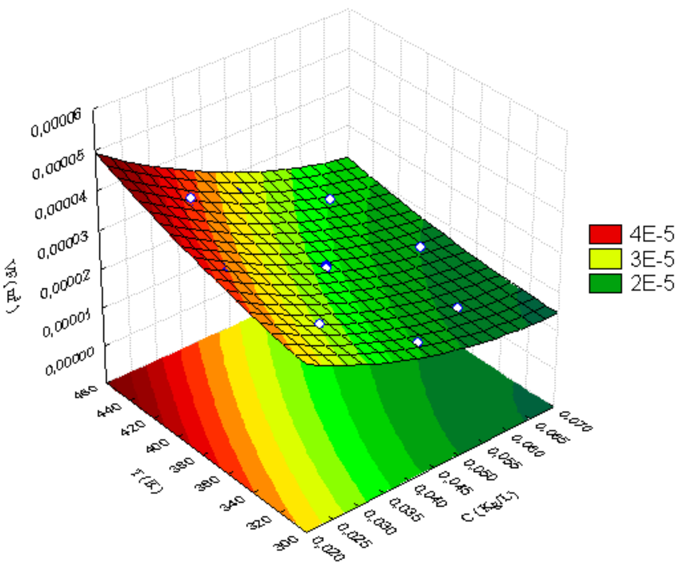
Comparing the values of the rheological properties and the filtration of the aging fluids (Tab. 3) with the fluids in ambient temperature (Tab. 2), it was observed that the prepared fluids with clay concentration of 0.0582kg/L are thermally stable within the temperature interval of 311 to 429K., it was also observed that the prepared fluids with clay concentration of 0.0640kg/L and submitted to a temperature of 380K presented low variations in the AV and PV values and low increases in the VF values, however it still remained under 18 x 10^{-6}m^3, reference value.



(a)



(b)



(c)

Figure 1 – Response surfaces for (a) apparent viscosity (AV), (b) plastic viscosity (PV) and filtered volume (VF) of the drilling fluids prepared with the Brasgel PA clay.

4. CONCLUSIONS

With the aim to develop aqueous fluids with bentonite that have stable rheological and filtration properties at high temperatures, was used a factorial design type 2^2 with three experiments in the central point and a star configuration to evaluate the influence of the temperature and the clay content (input variables) over the rheological and filtration properties of the fluids developed, and was concluded that:

- The fluids AV, PV and VF properties are statistically influenced by the input variables, clay concentration and aging temperature, at a 95.0% reliability level;
- Higher values of AV and PV are obtained with the increase in the clay concentration of 0.0250kg/L to 0.0640kg/L, as well as the increase in the temperature of 311K to 449K;
- The increase in the aging temperature gives the fluids bigger losses by filtration;
- Fluids with lower, and therefore, higher values of VF are obtained with higher concentrations of clay and lower aging temperatures and

- Fluids prepared with clay concentrations of 0.0582kg/L are thermally stable within the temperature interval of 311 to 429K.

In sum, it can be concluded that the properties of the clay and water fluids are influenced substantially by the temperature and clay concentration and when these are prepared with high content of clay and exposed to high temperatures develop gelled systems, with high viscosity. Besides that, it became evidenced that the thermally stable clay and water fluids can be obtained with concentration of clay ranging from 0.0580kg/L, as long as they are exposed to temperatures between 331 and 429k.

5. ACKNOWLEDGEMENTS

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