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Mathematical Modeling of the Differential Sticking Coefficient of Clay Drilling Fluids

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ABSTRACT

The main objective of this work is to propose a mathematical model for the differential sticking coefficient of clayey drilling fluids with a lubricant as an additive and evaluate the influence of differential pressure and lubricant content on filter cake thickness and permeability. Tests were carried out on fluids composed of water and 4.86% of active bentonite clay prepared in Hamilton Beach agitators at a high rotation speed (17000 rpm) for 20 minutes. After a 24-hour time-out in a closed container, lubricants were added to the fluids at different levels. To obtain the differential sticking coefficient (DSC), and the filter cake, a differential sticking tester by Fann with a spherical torque plate was used, and the filter cake thickness was determined in an extensometer. The setting time, differential pressure, and lubricant content were defined as the input variables (independent variables) to the DSC mathematical model. The differential pressure and lubricant rate were the independent variables to the mathematical model of filter cake thickness (FCT) and permeability (K), which varied according to a factorial planning, was known as a second order model. The experimental data regression was performed utilizing Statistic software, version 7.0. The results clearly showed that it was possible to obtain a statistically meaningful and predictive mathematical model for DSC. It was also observed that the increase in the lubricant content was responsible for a DSC value reduction due to the fact that the lubricant was a dispersing agent reducing the filtrate volume and the filter cake thickness, and thereby decreasing the sticking risk due to differential pressure. Finally, from the analysis of point values and response surfaces for FCT and K, it was possible to observe tendencies that made clear that the differential pressure and lubricant content influenced filter cake properties.

Keywords: Fluids, Differential Sticking, Modeling

INTRODUCTION

Within the petroleum exploration context, a well drilling process presents itself as one of the most complex and primordial stages to the success of the whole operation chain, which constitutes the petroleum industry, as the well is characterized as a link between the surface and the reservoir, where the hydrocarbon is found. The well drilling success depends, among other factors, upon

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the physicochemical characteristics of the drilling fluids used in the operation [1].

The drilling fluids, also called mud, play an essential role in the drilling process. They are compounds made of a base (water, oil, or air) and additives (viscosifiers, lubricants, filtrate control agents, densifiers, etc.) that are circulated into the wellbore during the drilling process with a number of objectives such as cooling the drilling bit, removing gravel from the bottom of the well, creating a solid permeable layer on the formation wall, and controlling pressures between formation and wellbore. Nowadays, several types of drilling fluids are available, from which clayey fluids can be highlighted [2].

The effect of mud composition on wear and friction between tool joints and casing has been stated by Darley and Gray. Tests with this instruments showed that wear was very high with bentonite suspensions, but decreased with the addition of barite. The addition of 0.5-2% of commercial lubricants all reduced wear by about the same amount. The coefficients of friction were calculated and the results showed that polymeric additives, diesel, oil, and glass beads had no effect on reducing the wear [2].

In order for the drilling fluid to have its performance maximized in all the functions aforementioned, it is necessary that its properties be properly adequate to situations that will be faced during the drilling process, otherwise several problems such as wellbore collapse, poor gravel circulation, pipe sticking, and total wellbore loss may occur [3].

According to Miura et al. [4], most of the non-productive time of drilling operations is due to problems classified by maneuver difficulty, advancing difficulty, and pipe sticking.

According to Bushnell-Watson and Panesar [5], the problems of tubing sticking are generally divided into two categories: mechanical sticking and differential sticking. The mechanical sticking is caused by a physical obstructi/on that partially or totally prevents the fluid circulation in the wellbore during the drilling process. This way, a cutting accumulation occurs on the bottom of the wellbore and, consequently, the drill string sticking takes place in the borehole. The differential sticking, in turn, is caused by a differential pressure, that is, when the drilling fluid column exerts excessive pressure on the drill string over the filter cake placed on the permeable formation [6]. In this kind of sticking, the drilling fluid circulation is kept; however, it is neither possible to perform vertical movements nor spins with the drill string.

The differential sticking is most of the times associated with inadequate drilling fluids, excessive solid contents, high densities, and high rates of filtrate and filter cake [7] as well as formation characteristics and contact area between drill string and permeable formation [8].

It is not possible to dispose of all conditions linked to pipe sticking. Few drilling parameters may be altered to reduce the probability of occurring differential sticking, being the drilling fluid the most easily adjustable parameter. Variables like density, solid content, fluid type and formulation, filtrate volume, and filter cake quality (thickness, resistance, and filter cake lubricity) meaningfully affect the differential sticking and their control may guarantee the drilling success. Beyond those aforementioned, the lubricant presence is another factor that reduces the differential sticking risk, as there will be a decrease of the friction between the drill string and the filter cake surface and, consequently, less torque is necessary to start the movement [9].

Bushnell-Watson and Panesar [5] observed that the necessary strength to release the stuck pipe was greater with a higher-density fluid and ascribed this increase to the kind of fluid utilized. Tests were carried out with saline fluids and the authors observed that this kind of fluid showed small setting tendency; however, the addition of drilling active solids led to higher forces to release the stuck string.

Isamburg et al. [10] observed, during his studies, the same behavior described by Bushnell-Watson and Panesar [5]; they associated this increase to filter cake permeability instead of fluid type though. Thus they concluded that the higher-density fluid created a filter cake less permeable, and thereby with a less porous pressure, a much greater pressure was required to release the pipe.

For a differential pressure, two situations must take place: fluid hydrostatic pressure must exceed the formation pressure, and permeable formations must be present. The combination of both factors leads to the invasion of the fluid base in the formation, as well as the filter cake placement on its walls [11], and thereby generating conditions for the drill string to set on the formation wall.

Once the differential sticking is established, the necessary strength to release the drill pipe will depend upon the present differential pressure and filter cake resistance during the pipe releasing attempt. Filter cake pore pressure decrease rate depends on the filter cake permeability, once compacted. Thus, according to Isambourg et al. [10], the parameters that cause sticking by differential pressure are:

- The use of fluids that exert excessive pressure on the formation;
- Compacted filter cake permeability;
- Compacted filter cake strength, and
- Exposition time, i.e., time the pipes remain attached to the filter cake.

Few drilling variables can be adjusted to reduce the probability of differential sticking occurrence [11]. According to Courteille and Zurdo [12], controlling and reducing the filtrate volume have a direct consequence on the filter cake thickness; smaller filtrate volumes lead to less thick filter cakes. This way, there must be a minimum drill pipe penetration in the filter cake before a meaningful pressure change in the interface pipe/filter cake may occur. Therefore, if the filter cake is thin enough, sticking may be avoided.

Another factor that must be taken into account is the filter cake permeability; once the filter cake shows a substantial permeability, it allows the filtration process (drilling fluid continuous phase penetrates into the crossed formations) to continue. Once the sticking is already established, there will be the deposition of solid particles on the filter cake surrounding the drill string, increasing the contact area between them, and consequently, the strength needed to move and/or loosen the string. Byck [13] showed that filtration rate only depended on the filter cake permeability. Beyond that, filter cake permeability provides useful information about the electrochemical conditions which prevail in the fluid.

Krumbien and Monk [14] investigated the effect of drilling fluid grain size and shape on the filter cake permeability, and observed that filter cake permeability decreases with the particle average diameter, while rises with the width size of filter cake particles.

The flocculation and aggregation phenomena also affect the filter cake permeability, once the mud flocculation allows the particles to associate themselves in an open net shape. This structure persists only to a limited extension of the filtrate, which causes considerable increases in the filter cake permeability. The greater the filtration pressure, the flatter the structure becomes, creating a permeability decrease when the pressure increases. In a reciprocal way, the fluid deflocculating occurs; when an agent is added, which causes the filter cake permeability to decrease [2].

According to the data presented by Reid et al. [8], on North Sea, 29% of the costs related to stuck pipes were caused by differential pressure. On Gulf of Mexico, the differential sticking was responsible for 61% of the total drilling costs [15].

Being a serious problem that results in costs over 250 million dollars per year for the petroleum industry, a number of methods to analyze the fluid differential sticking risk have been proposed throughout the years. The first mechanisms of differential sticking were proposed by Helmick and Longley in 1950 [8]. In 1985, Courteille and Zurdo [12] measured, by simulation, the drilling fluid pressure under the fluid cake right below the drill collar, as well as the strength needed to release the stuck pipes. Isambourg et al. [10] developed a work that was seen as an extension on the differential sticking phenomenon. To do so, equipment was used to help comprehend pressure variation phenomena of the pores inside the filter cake and the strengths associated with the differential pressure and, eventually, evaluate the performance of lubricants and fluids called spot fluid, i.e. an oil-based fluid used to release stuck pipes.

In 2000, Santos [16] introduced new concepts on the mechanism of sticking by differential pressure, and described premature symptoms during drilling, which are essential to detect the rising risk of column sticking. Beyond that, he proposed new tests in order to define, more realistically, drilling fluid penetration characteristics in a permeable formation. In the end, he presented new equipment, considered a simple one, to evaluate the differential sticking risks using three drilling fluid formulations, with the objective of evaluating the non-invasive characteristic of drilling fluids [17].

Although this equipment does not provide a straight measure of the differential pressure coefficient, it positively contributes to elucidate and prevent pipe sticking, once it becomes possible to know the invasive behavior of different fluids using the same permeable media.

Nowadays, the differential sticking tester by Fann has been commercialized having as its main goal to gauge the differential sticking coefficient of drilling fluids. This test also enables the obtaining of fluid filter cake volume data before and after sticking, allowing a quantitative and qualitative analysis of the formed filter cake characteristics [17].

With the aid of factorial planning and measurement equipment for differential sticking coefficient, more trustworthy results can be obtained, once it becomes possible to know the invasive behavior of different fluids using the same permeable media, and to define mathematical models that are predictive and reduce the number of experiments, with better information quality on the results.

In light of the foregoing, the main objective of this work is to propose a mathematical model for the differential sticking coefficient of clayey drilling fluids with a lubricant as an additive and evaluate the influence of differential pressure and lubricant content on filter cake thickness and permeability.

EXPERIMENTAL PROCEDURES

Material and Methods

The drilling fluids were prepared utilizing activated sodium bentonite clay, which is provided by Bentonit União Nordeste--BUN, commercially known as Brasgel PA, and widely used in drilling fluids as a viscosifying, thixotropic and filter cake maker agent in the petroleum industry. For those fluids containing lubricants, a lubricant sample was used, which was provided by System Mud Fluidos de Perfuração, and is commercially known as SM Lube.

Drilling fluids were prepared at a concentration of 4.86% of clay in 350 ml of deionized water (clay was slowly added to the water so that no flocculation was happened), at a stirring velocity of 17,000 rpm for 20 minutes in a mechanical agitator by Hamilton Beach (model 936). Then, the fluid remained at rest for 24 hours in a closed container. For the fluids, in which lubricants were added, the lubricants were added after the 24-hour resting period (the mixture of the lubricant and the fluid was prepared by manual agitation).

To evaluate the influence of differential pressure, setting time, and lubricant content on the differential sticking coefficient of clayey fluids, a 2^3-type factorial design with three experiments on the central point was utilized, adding up to 11 experiments. The experimental data regression was carried out using the software Statistica, version 7.0. The coded and real levels of input variables employed in the design are found in Table 1.

Table 1: Coded and real values for the input variables.

Input Variables	Coded and Real Levels		
	-1	0	+1
Setting Time, *t* (min)	30	90	150
Differential Pressure, *P* (psi)	300	400	500
Lubricant Content, *L* (%)	0	0.75	1.5

To evaluate the influence of differential pressure and lubricant content on filter cake properties (thickness and permeability) of clayey fluids, a 2^2-type factorial design with three experiments on the central point was utilized, adding up to 7 experiments. The experimental data regression was carried out using Statistica software, version 7.0. The coded and real levels of input variables employed in the design are found in Table 2.

Experiments

After the 24-hour rest period, the fluids were stirred for 5 minutes at the maximum rotation speed (17,000 rpm) so that there would be gelling breakage. When that was done, the fluids were transferred to the cell of the differential sticking tester equipment by Fann. In this experiment, the spherical torque plate, i.e., a radius plate was used. In Figure 1, the differential sticking tester equipment and the radius plate are illustrated.

Table 2: Coded and real values of input variables.

Input Variables	Coded and Real Levels		
	-1	0	+1
Lubricant Content, *L* (%)	0	0.75	1.5
Pressure Differential, *P* (psi)	300	400	500

Figure 1: Differential sticking tester by Fann and the radius plate.

Once inside the cell, the prepared fluids were put under different differential pressures and setting times; after 10 minutes, as a sufficient time for filter cake formation on the filter paper, the first filtrate (V1) was collected, and a load was applied to the radius plate, in such a way that it would press it against the filter cake for approximately 2 minutes in order to guarantee that the radius plate would remain attached to the filter cake.

After the pre-determined time passed on each test, according to the planning matrix, the second filtrate (V2) was collected and, with the aid of a torque wrench, was attached to the upper part of the radius plate; six torque measures were done (with 30-second intervals between every reading) and the average torque for each fluid (which could contain or lack lubricant depending on the test condition defined by the planning matrix) was calculated in each time interval and expected pressure. Finally, the fluid differential sticking coefficient (DSC) was calculated by Equation 1.

$$DSC = \frac{(Torque)\cdot(Pressure)\cdot(0.001)}{477.5} \qquad (1)$$

To obtain the filter cake, the differential sticking tester equipment was utilized. The prepared fluids were put through different differential pressures and different lubricant contents were added according to the planning matrix presented in Table 4. After 10 minutes, as a sufficient time for filter cake formation on the filter paper, the filtrate volume was collected.

To determine filter cake thickness (FCT), the methodology developed by Farias et al. (2006) [18] in the Research Laboratory on Drilling Fluids—PeFLab, based on the norm API 13B-1 (2003) was used. This methodology consists of the stages presented below:

- Collect filter paper with filter cake on after carrying out the test to determine filtrate volume;
- Wash the filter paper three times with a flow rate of approximately 110 l/hr with the aid of a container with a constant level of adjustable flow rate at a distance of approximately 7.0 cm from the flow rate controller that has a diameter of 15.0 mm and a water flow rate attack angle of approximately 45°;
- Place the filter paper with filter cake between the two glass slides and apply a pressure of approximately 277.6 N/m² for a period of 2 min;
- Measure the filter cake thickness with the aid of an extensometer.

Five measurements at distinct points were made for the thickness of the glass slides and the paper with filter cake. After obtaining the results, an arithmetic mean for the five determinations was computed.

Filter cake permeability was determined by Equation 2.

$$K = 8.95\cdot 10^{-5} Q_F \cdot FCT \cdot \mu \qquad (2)$$

where,

K = Filter cake permeability (mD)

Q_f = Filtrate volume (cm^3)

μ = Fluid liquid phase viscosity (cP)

FCT = Filter cake thickness (mm)

RESULTS AND DISCUSSION

The point values for differential sticking coefficient (DSC) and final filtrate volume (V2) of the studied fluids can be found in Table 3.

Table 3: Studied fluids DSC values.

Experiments	Dimensionless	V2 (ml)
1	0.008	9.6
2	0.017	17.6
3	0.017	11
4	0.046	18.6
5	0.005	7.2
6	0.010	14.2
7	0.010	7.2
8	0.032	16.6
9	0.017	12
10	0.018	11.8
11	0.019	12.6

According to Table 3, a substantial increase in the studied fluid DSC is seen as the differential pressure grows. There is an increase in the fluid DSC from experiment 1 to experiment 3 of 0.009 and from experiment 2 to experiment 4 of 0.029. This increase in the differential sticking coefficient in accordance with the increase in the differential pressure is explained by the fact that an increase in the pressure, while keeping a constant contact area, requires an even greater strength to release the stuck tool; consequently, a greater DSC is obtained. The measured DSC values are presented in Figures 2 and 3 respectively.

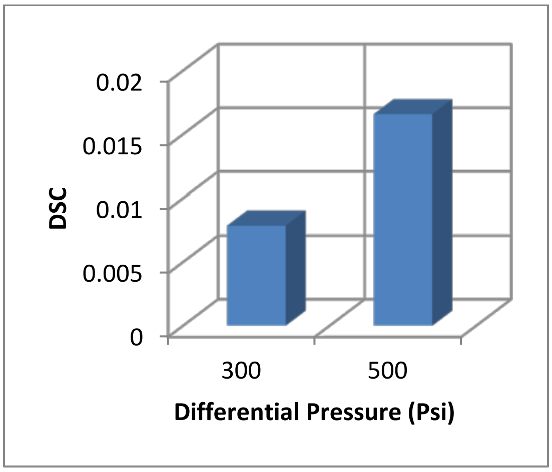

Figure 2: DSC in accordance with the differential pressure for experiments 1 and 3.

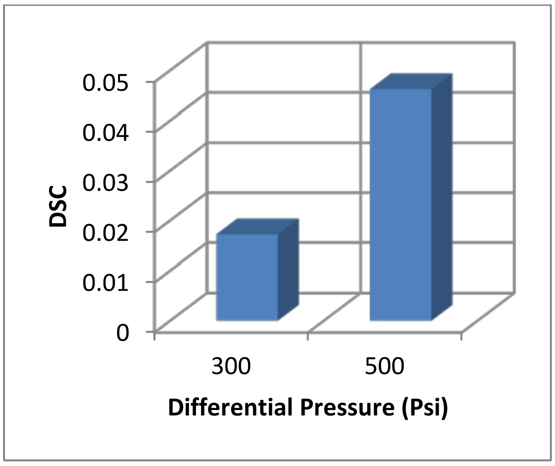

Figure 3: DSC in accordance with the differential pressure for experiments 2 and 4.

For tests with the same setting time and differential pressures of (1 and 5; 2 and 6; 3 and 7, and 4 and 8) a DSC and filtrate volume (V2) decrease was observed, when the lubricant SM Lube is present. This is due to the lubricant action mechanism that dilutes the fluid, acts as a dispersive additive, reduces the friction between the drill string and the filter cake surface, and, consequently, diminishes the torque required to initiate the string movement [9]. As a consequence of a low filter cake volume, there is a filter cake thickness reduction, which in practical cases, cuts down the risk of sticking by differential pressure [19].

Still in Table 3, an increase in DSC is observed as the setting time increases. It occurs due to the tool spherical profile (radius plate), which allows a contact area variation between the tool and the filter paper. Considering the differential pressure applied to the system and the increase in setting time, there is a progressive filter cake deposition on the contact section tool-filter paper, and thereby resulting in greater values for DSC as the setting time increases.

After obtaining the fluids DSC values for all of the experiments, the experimental data regression was performed utilizing the Statistic software, version 7.0. Hence Equation 3 was obtained that represents the empirical, coded mathematical model, with all the respective statistic parameters and standard deviation; *t* is the setting time, *P* is the pressure differential, and *L* is the lubricant content. Table 4 shows the results of ANOVA (variance analysis) for DSC.

$$\begin{aligned}DSC =& (0.018156 \pm 0.000250) + \\ &(0.008266.\mathrm{t} \pm 0.000293) + \\ &(0.008213.\mathrm{P} \pm 0.000293) - \\ &(0.003789.\mathrm{L} \pm 0.000293) + \\ &(0.004595.\mathrm{t.P} \pm 0.000293) - \\ &(0.001478.\mathrm{t.L} \pm 0.000293) - \\ &(0.001216.\mathrm{P.L} \pm 0.000293)\end{aligned} \quad (3)$$

Analysis of the main effects (*t*, *P*, and *L*) and the interaction between them (*t.P*, *t.L*, *P.L*) presents a statistically meaningful influence in all the variables studied, to a 5% level of confidence. By an increase from level -1 to +1 in the setting time (*T*), the pressure differential (*P*), and the interaction between setting time and pressure differential (*t.P*) contribute for greater DSC values, while the lubricant content (*L*) and the other interactions (*t.L* and *P.L*) contribute to smaller DSC values. Also, the variables of setting time and differential pressure showed a bigger influence on the differential sticking coefficient of the studied fluids.

Table 4: Variance analysis (ANOVA) for the differential sticking coefficient

Response	Explained Variation (%)	Correlation Coefficient	$F_{calculated}/F_{tabulated}$
DSC	99.8	0.9990	55.22

By means of the variance analysis presented in Table 4 and knowing that the explained percentage variation quantifies the adjusting quality, varying from 0 to 100%, and that an F value (ratio between $F_{calculated}$ and $F_{tabulated}$) higher than 1 represents a statistically meaningful regression (and when it is higher than 5, it means a predictive and statistically meaningful regression), it is verified that the model is satisfactory, being statistically meaningful with a correlation coefficient of 0.999 and an explained variance percentage of 99.8%. Test F also showed that the ratio between $F_{calculated}$ and $F_{tabulated}$ for the DSC was higher than 5 with a 95% confidence, indicating that the model was well adjusted, statistically meaningful, and predictive.

Considering the model statistically meaningful, from Equation 2 it was possible to generate response surfaces for DSC. Figures 4 and 5 present response surfaces for the differential sticking coefficient of fluids, while the lubricant content is considered as a constant parameter.

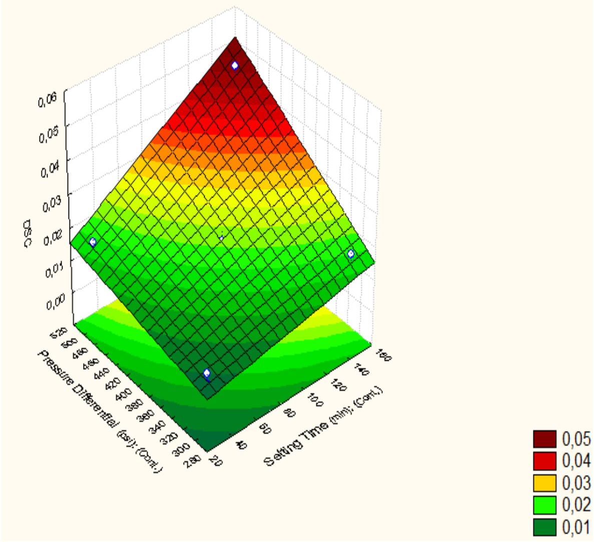

Figure 4: Response surface for the differential sticking coefficient (DSC) fixing the lubricant content in 0%.

According to Figure 4, in which the lubricant content is fixed at 0%, it is possible to observe that an increase in setting time conducts to an increase in DSC. The setting time is rather significant; the greater the setting time is, the thicker the filter cake becomes. Both factors result in an increasingly greater contact area of the radius plate tool with the filter cake. The DSC value is also in line with the differential pressure: the greater the differential pressure is, the greater the DSC becomes. Therefore, both input variables directly influence the output variables.

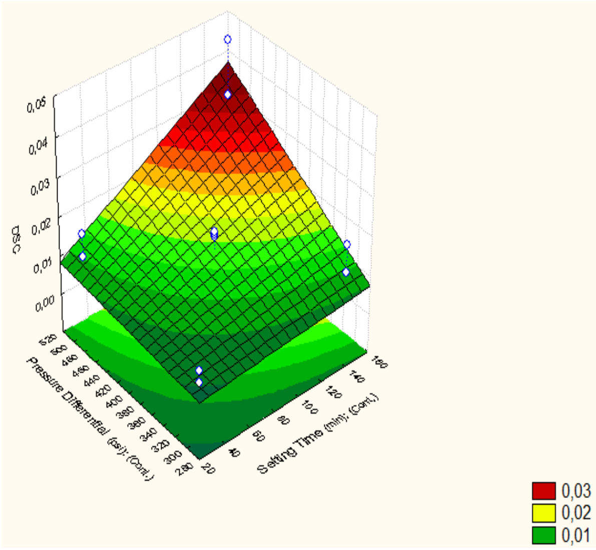

Figure 5: Response surface for differential sticking coefficient (CPD) fixing the lubricant content at 1.5%.

Observing Figure 5, a similar behavior to Figure 4 can be noticed; however, the addition of 1.5% of lubricant promoted a substantial reduction in the DSC values. This way, the greatest DSC values registered are observed for higher setting times and differential pressures, and lower lubricant content values. Figures 6 and 7 present the response surfaces for the DSC, while keeping the differential pressure constant.

Figures 6 and 7 present similar behavior and have fixed values for differential pressure of 300 psi and 500 psi respectively. From Figures 6 and 7, it can be perceived that an increase in the values of the setting time variable provokes an increase in the DSC values. On the other hand, an increase in the lubricant content value causes a decrease in the

DSC values. A bigger influence of the setting time on the DSC values is also observed.

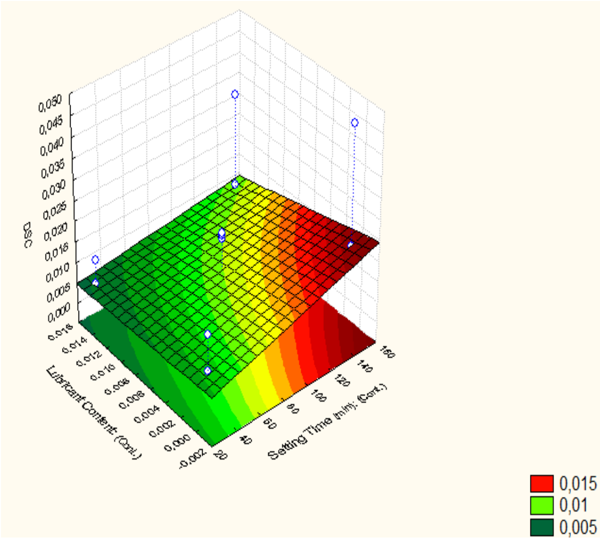

Figure 6: Response surfaces for differential sticking coefficient fixing the differential pressure at 300 psi.

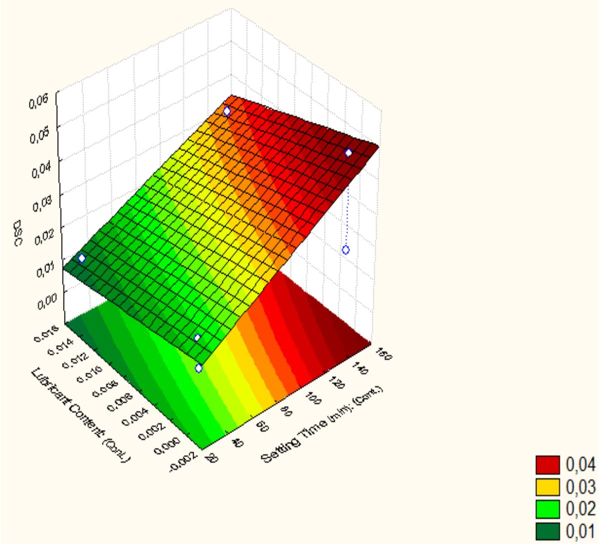

Figure 7: Response surfaces for differential sticking coefficient fixing the differential pressure at 500 psi.

This way, greater DSC values are observed for higher setting time values and lower lubricant content values. Moreover, the analysis of the response surface inclinations points to a greater influence of the setting time, when compared to the lubricant content variable.

The point values for the filter cake properties (thickness and permeability) and filtrate volume (FV) of the studied fluids are listed in Table 5.

It is observed from Table 5 that a substantial reduction in the FCT, *K*, and FV values from experiment 1 to experiment 2, and from experiment 3 to experiment 4 of the studied fluids is seen with the addition of lubricant. This substantial reduction in the studied variable values, with the lubricant addition, is explained by the fact that the lubricant acts as a dispersive, acting on the filter cake in a corrective way; in other words, it reduces the filter cake thickness of very thick filter cakes by clay particle dispersion on the exposed side of the filter cake layer in a similar way of the acid stripping action over a metal plate. However, it must maintain the filter cake impermeable characteristic, not completely removing it or turning it more permeable [7]. Smaller FCT and *K* values were still observed, when the fluid was put through a smaller differential pressure and without the lubricant (experiment 1).

Table 5: Values for filter cake properties (thickness and permeability) and filtrate volume of the studied fluids.

Experiments	FCT	K (mD)	FV
1	1.7532	0.0008158462	5.2
2	1.6991	0.00063869	4.2
3	1.5801	0.000810229	5.8
4	1.4243	0.000586384	4.6
5	1.3609	0.000609002	5.0
6	1.3571	0.00059518	4.9
7	1.3758	0.000664234	5.5

Equations 4 and 5 show empirical mathematical models for the filter cake properties (thickness and permeability), which are 2nd order coded with their respective parameters and standard deviation; *P* the differential pressure and *L* is the lubricant content; Table 6 presents the ANOVA (variance analysis) for the FCT and *K* responses. The equation values in bold are the statistically meaningful parameters. The models were obtained by the linear regression of the experimental data using the Statistica software, version 7.0.

$$\begin{aligned}\mathrm{FCT} = {} & (1.507223 \pm 0.0713) \\ & - (0.0524 \cdot \mathrm{L} \pm 0.0944) \\ & - (0.111975 \cdot \mathrm{P} \ \pm 0.0944) \\ & -(0.02542 \cdot \mathrm{P} \cdot \mathrm{L} \ \pm 0.0944)\end{aligned} \tag{4}$$

$$\begin{aligned}K = {} & (0.000676 \pm 0.000029) \\ & - (0.000103 \cdot L \pm 0.000038) \\ & - (0.000012 \cdot P \ \pm 0.000038) \\ & - (0.000014 \cdot P \cdot L \ \pm 0.000038)\end{aligned} \tag{5}$$

The main effects (*P* and *L*) analysis and the interaction between them (P.L) do not present statistically meaningful influence on all of the variables studied. The increase from level -1 to +1 in the lubricant content (*L*), the differential pressure (*P*), and the interaction between them (P.L) contribute to smaller FCT and *K* values.

Table 6: Variance analysis (ANOVA) for all filter cake properties.

Response	Explained Variation (%)	Correlation Coefficient	$F_{calculated}/F_{tabulated}$
FCT	37.35	0.62	0.15
K	71.55	0.8459	0.30

It was verified that the model fitting for permeability (*K*) was satisfying with a correlation coefficient of 0.8459 and the explained variance percentage of 71.55%. But, the ratio between $F_{calculated}$ and $F_{tabulated}$ was lower than 1 for both models, not representing a statistically meaningful model.

Considering that the model was not statistically meaningful, the response surfaces for FCT and *K*, from Equations 4 and 5, represent the tendencies of the independent variables over the dependent variables. Figures 8 and 9 present the response surfaces for the filter cake thickness (FCT) and permeability (*K*).

Figure 8 analysis makes evident that the increase in the differential pressure variable (*P*) results in a reduction of the filter cake thickness (FCT) variable. The lubricant content (*L*) variable acts in a similar way to *P* variable, as the FCT value decreases when the *L* value increases. This way, the filter cake thickness assumes minimum values for maximum *P* and *L* values.

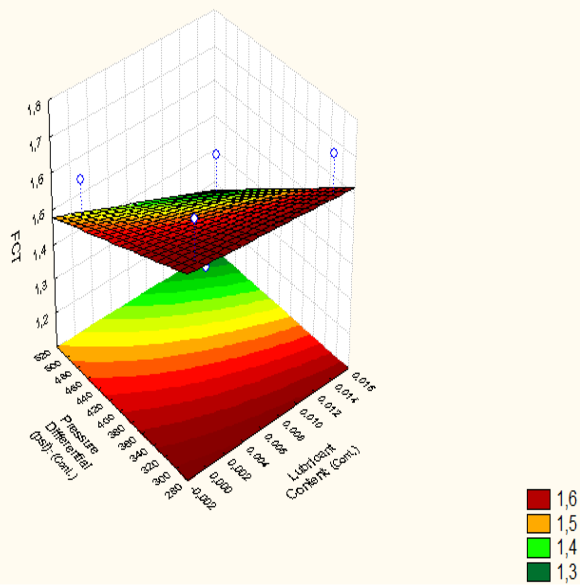

Figure 8: Response surface for filter cake thickness (FCT) of the studied fluids.

According to Bushnell-Watson and Panesar [5], in both water-based fluids and oil-based fluids, the lubricant usage significantly affects the way the pipes are released. In the absence of lubricant, the tubing is released in the interface of filter cake/formation, whereas with the presence of lubricant, the tubing is released in the interface of pipe/filter cake, which then reduces drilling risks. The necessary strength to release stuck pipes by differential sticking must be more than the pipe adherence to the filter cake and the pressure exerted by the fluid. It was verified that the lubricant addition in clayey fluids promotes the reduction in the filter cake thickness and the differential sticking coefficient. As a consequence, smaller strength will be necessary to release the pipe stuck to the filter cake.

According to Figure 9, it can be observed that *P* has no meaningful influence on the values of *K*. The values of *L*, in its turn, directly influence the *K* values: they decrease as the lubricant content is increased. Therefore, one way to avoid the differential sticking phenomenom is increasing the lubricant content in order to decrease permeability and filter cake thickness.

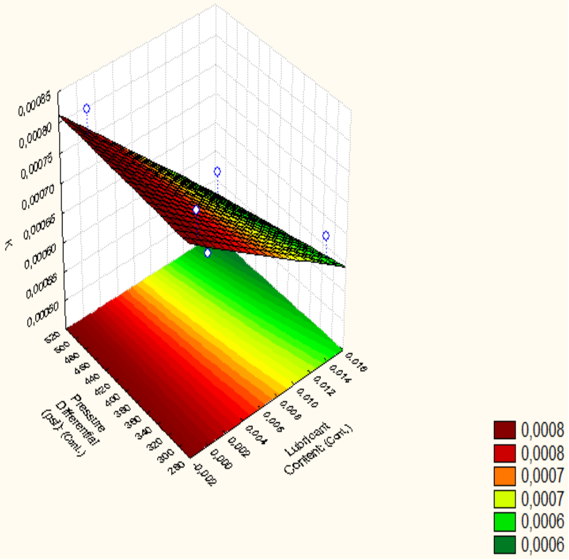

Figure 9: Response surface for permeability (*K*) of the studied fluids.

According to Courteille and Zurdo [12], controlling and reducing filtrate volume has a direct consequence on the filter cake thickness; smaller filtrate volumes lead to less thick filter cakes. This way, there must be a minimum penetration of the drilling pipe in the filter cake before a meaningful change of pressure in the interface of pipe/filter cake may happen. Therefore, if the filter cake is thin enough, sticking may be avoided.

In general, there was a variation in the differential sticking coefficient of the studied fluids with an increase in the input variables (setting time, differential pressure, and lubricant content). Hence, in typical cases, if a drilling string is differentially stuck and the filter cake properties are not altered, the more time the column remains stuck, the harder it is to release it from the filter cake, because the latter increases its contact surface with the drill string. Similarly, it is observed for the differential pressure that a high differential pressure may favor the displacement and, consequently, the contact between the drill string and the formation. Added to what has been shown, the high pressure exerted by the fluid will result in a greater strength to release the drill string. As for the lubricant, smaller differential sticking risks will take place, when a fluid with lubricant characteristics is utilized, as it reduces the friction created between the drill string and the formation and acts as a dispersing agent in the drilling fluid, being incorporated to the filter cake and providing a better fluid loss control (resulting in thin filter cakes) [19]. Thus a reduction in permeability and filtrate volume is obtained and DSC values are substantially decreased.

CONCLUSIONS

It may be concluded that it was possible to obtain representative and meaningful results utilizing factorial design for the differencial sticking coefficient; also, the analysis of variance and response surfaces showed that all the three studied input variables (setting time, differential pressure, and lubricant content) influenced the differential sticking coefficient values in a statistically meaningful way. The variables with a greater influence on the string differential sticking are the differential pressure and setting time. Furthermore, it was possible to conclude that the filter cake properties (thickness and permeability) had a direct influence on the differential sticking process; even if a staticsally meaningful model was not obtained for filter cake thickness and permeability depending on the differential pressure and lubricant content, it was possible to observe tendencies from the response surfaces. Finally, when analyzing the point values, it was clear that lubricant, due to its dispersing agent characteristics, contributed to reduce filter cake thickness and permeability, which in practical cases, might contribute substantially to a reduction in differential sticking coefficient.

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