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Statistical Analysis of Drilling Fluid Heat Transfer in HTHP Well in the Gulf of Mexico

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Abstract

During the well construction process of an HTHP well, the drilling fluid constantly exchanges heat with the formation in the drilling process. In HTHP wells such heat exchange can increase the drilling fluid temperature to values that present challenges for both the drilling fluid and the bottom hole assemblies (BHA). When the temperature exceeds the thermal limits of the drilling fluid or the BHA, non-productive time becomes a high risk as well as the potential for increased drilling cost due to delays and lost time to mitigate these failures. Therefore, it is important to know and quantify the main factors involved in heat transfer to determine operating parameters that will cause the minimal impact in drilling fluid temperature variations.

In this paper, heat transfer in a HTHP well in shallow waters in the Gulf of Mexico was analyzed. The total vertical depth was 7,000 meters (22,965 feet), the maximum bottom hole temperature was 172°C (342°F), and maximum pore pressure was 17,000 psi. The statistical method used in this study was a factor analysis considering operational parameters and the properties of the drilling fluid. The dominant factors and parameters with which the lowest drilling fluid temperature was obtained at the bottom of the hole were identified and quantified. The optimized results were implemented in the field and the drilling operation was performed successfully without negative events associated with the thermal effects in the well.

Introduction

As drilling technology has advanced, it has been possible to drill at greater depths and in environments with increasingly higher bottomhole temperatures(BHT), in these situations it is important to know the dynamic temperature profile, which is a complicated task due to the complexity of heat transfer phenomena within the well under dynamic conditions (Corre et al. 1984, Olea et al. 2007, Wei-Tao et al. 2017), since in addition to the heat flow between the fluid and the formation, heat is generated by the friction of the fluid with the surfaces of the flow lines (Wooley 1980, Santoyo 1997, Liqun 2016, Dan 2018), so it is important that the determination of the dynamic temperature profile includes all the heat transfer mechanisms to correctly determine the operating parameters that minimize the temperature inside the well.

In some cases it is common to use mud coolers, which helps to dissipate heat from the fluid and reducing or controlling the temperature of the fluid returning to the well, this practice has proven to be useful in mitigating the thermal effects (El-Dorry et al. 2015), although this solution is not feasible when spaces in the drilling rig are limited, and in these cases are available operational practices such as frequently changing the hot fluid by fluid of lower temperature, which demands more resources to have extra fluid volume in the well. At this point it becomes relevant to be able to optimize the drilling design to minimize the temperature inside the well.

Methodology

The present work deals with the optimization of the choice of operating parameters to obtain the lowest fluid temperature inside the well, for this purpose a multifactorial statistical analysis (Montgomery 2001) was performed considering 4 drilling parameters and 3 properties of the drilling fluid, the parameters are

- Flow rate, Q.
- BHA rotation, RPM.
- Rate of penetration, ROP.
- Total flow area of bit, TFA.
- Oil water ratio, OWR.
- Solids content, Sol.
- Rheologies, Rheol.

The variables (factors) were chosen based on their relevance during the design planning, as well as their ease of modification during the execution of the operations. The factorial analysis considered the minimum and maximum values of the operating range of each factor. The maximum temperature in the annular space was considered as the analysis response, which was determined for each case by means of a commercial simulator, 128 simulations were performed for the design of 7 factors, the magnitude of the effect of each factors on the maximum temperature is shown, also the magnitude of the interactions between factors is shown, being the binary interactions the ones with the highest magnitude.

After the analysis of the 7 factors, a second analysis was carried out considering a reduction to the factors with the greatest magnitude of effect, considering a variation in the range of the dominant factor to analyze the effect on the less dominant factors, and the optimized option of factors chosen for the operational execution is also presented.

Case Study

The exploratory well S1 Exp is located in the shallow waters of the Gulf of Mexico, the total depth was settled at 7240 m in drilling program with bottom hole temperature of 177°C.

The use of a mud cooler was considered to reduce the impact of temperature on the BHA, however, the limitations of the rig prevented its use, so a statistical analysis was performed to determine the operating parameters that would contribute to have the minimum temperature during drilling. Table 1 shows the well information for planning, Table 2 shows the variables (factors) selected and their values for the statistical analysis, Table 3 shows additional parameters of the drilling fluid.

Table 1. S1 Exp well data for planning

Description	Value
Shoe OD	7 3/4 in
Shoe depth	6720 m
End section	7240 m
Open hole	6 1/2 in
Drilling Fluid	Diesel based mud
Mud weight	1.75 g/cm^3
Seafloor	52 m
Max inclination	12 degree
Reservoir	Upper Jurassic Kimmeridgian
BHT	177 °C
Pore pressure	17000 psi

Results

The factorial analysis shows that, within the range established for the factors analyzed, the maximum temperature is influenced to a greater extent by the flow rate, such that when the flow rate is increased from 200 to 250 gpm, the maximum temperature inside the well increases by 6.9 °C, while when the rheologies are increased, the temperature decreases by 4.7 °C. Figure 1 shows the individual effect of each factor, with the factors that increase the maximum temperature being, from highest to lowest impact, flow rate, ROP, rpm, the factors that decrease the temperature with their increase are, from highest to lowest impact, rheological properties, total flow area, solids content, and oil water ratio. In all cases, the changes in the maximum temperature correspond when the factors go from their minimum to maximum value; in the case of negative values, these indicate that the temperature is reduced when the factors increase their value.

Table 2. Factors and its values for factorial analysis.

Factor	Unit	Low Value	High Value
Flow rate	gpm	200	250
BHA rotation	rpm	100	130
ROP	m/h	2	10
Total Flow Area	in^2	0.752	1.046
OWR	oil, %	75	85
Solids	% vol	28	32
Rheologies (PV, YP, L3)	cp, lbf / 100ft^2	29/ 17/8	39/24/12

Table 3. Mud properties

Mud properties	Unit	Value
Mud weight	g/cm^3	1.75
Water Phase Salinity	% wt $CaCl_2$	23.5
Thermal Conductivity	W/m°K	0.23
Specific Heat Calculator	kJ/kg°K	1.163

In addition to the change attributed to each of the factors, there are the changes attributed to the interactions between the different factors, which occur when one or more factors are increased, and may include two or more factors, for example, the change generated by the interaction between flow rate and rheologies is 3.8 °C, and the triple interaction between ROP, solids content and rheologies, generates a change of -0.11 °C. Figure 2 and figure 3 show respectively the highest magnitude double and triple interactions. Table 4 shows all interactions between the seven factors analyzed. Although only the double interaction between flow rate and rheologies is greater than 1 °C and in the first instance are the ones that could be the subject of more attention from an operational point of view, statistically all interactions with effects greater than 0.005 °C are significant at 95% confidence according to Lenth's method (Montgomery 2001).

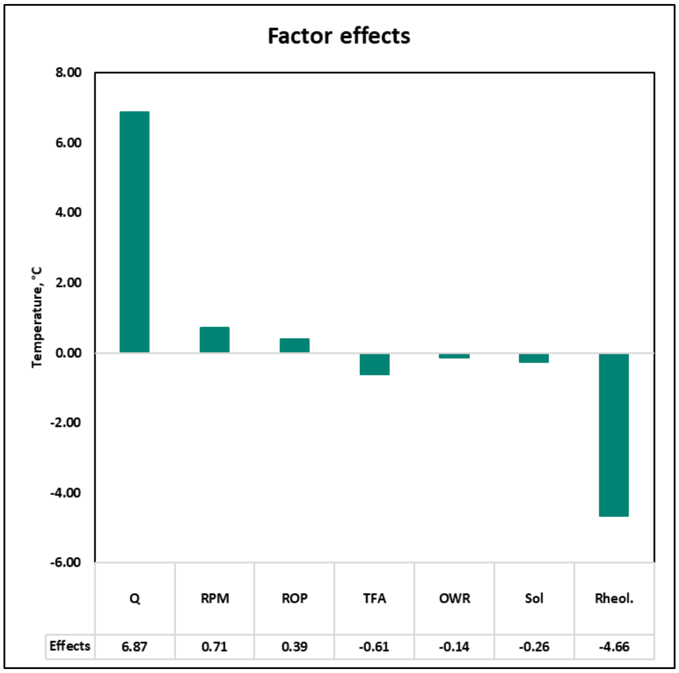

Figure 1. Effects of used factor in analysis.

Table 4. Factor interaction effects.

2 Factors		3 Factors		4 Factors		5 & 6 Factors	
A*B	-0.01	A*B*C	0.001	A*B*C*D	-0.002	A*B*C*D*E	-0.002
A*C	-0.84	A*B*D	-0.002	A*B*C*E	0.001	A*B*C*D*F	-0.001
A*D	-0.18	A*B*E	0.001	A*B*C*F	0.000	A*B*C*D*G	0.002
A*E	-0.02	A*B*F	0.000	A*B*C*G	-0.004	A*B*C*E*F	0.001
A*F	-0.03	A*B*G	-0.004	A*B*D*E	-0.001	A*B*C*E*G	-0.001
A*G	3.28	A*C*D	0.020	A*B*D*F	-0.001	A*B*C*F*G	0.000
B*C	-0.09	A*C*E	0.000	A*B*D*G	0.001	A*B*D*E*F	-0.001
B*D	0.00	A*C*F	-0.026	A*B*E*F	0.002	A*B*D*E*G	0.002
B*E	0.00	A*C*G	-0.005	A*B*E*G	-0.002	A*B*D*F*G	0.001
B*F	0.01	A*D*E	0.002	A*B*F*G	0.000	A*B*E*F*G	-0.001
B*G	0.02	A*D*F	0.004	A*C*D*E	0.001	A*C*D*E*F	0.001
C*D	0.06	A*D*G	-0.002	A*C*D*F	0.003	A*C*D*E*G	-0.002
C*E	0.01	A*E*F	-0.001	A*C*D*G	-0.002	A*C*D*F*G	-0.003
C*F	0.05	A*E*G	0.001	A*C*E*F	-0.001	A*C*E*F*G	0.001
C*G	0.12	A*F*G	0.057	A*C*E*G	0.002	A*D*E*F*G	-0.001
D*E	0.00	B*C*D	0.002	A*C*F*G	0.015	B*C*D*E*F	0.001
D*F	0.01	B*C*E	-0.001	A*D*E*F	0.001	B*C*D*E*G	-0.001
D*G	0.00	B*C*F	0.011	A*D*E*G	-0.001	B*C*D*F*G	-0.002
E*F	0.00	B*C*G	0.013	A*D*F*G	-0.003	B*C*E*F*G	0.002
E*G	0.00	B*D*E	0.001	A*E*F*G	0.002	B*D*E*F*G	-0.001
F*G	-0.12	B*D*F	0.002	B*C*D*E	0.001	C*D*E*F*G	0.002
		B*D*G	-0.002	B*C*D*F	0.002	A*B*C*D*E*F	-0.001
		B*E*F	-0.002	B*C*D*G	-0.001	A*B*C*D*E*G	0.002
		B*E*G	0.001	B*C*E*F	-0.001	A*B*C*D*F*G	0.001
		B*F*G	-0.012	B*C*E*G	0.002	A*B*C*E*F*G	-0.001
		C*D*E	-0.002	B*C*F*G	-0.012	A*B*D*E*F*G	0.001
		C*D*F	0.012	B*D*E*F	0.001	A*C*D*E*F*G	-0.001
		C*D*G	-0.012	B*D*E*G	-0.001	B*C*D*E*F*G	-0.001
		C*E*F	0.001	B*D*F*G	-0.002	A*B*C*D*E*F*	0.001
		C*E*G	-0.003	B*E*F*G	0.001		
		C*F*G	-0.116	C*D*E*F	-0.002		
		D*E*F	-0.002	C*D*E*G	0.001		
		D*E*G	0.002	C*D*F*G	-0.012		
		D*F*G	-0.012	C*E*F*G	-0.001		
		E*F*G	-0.002	D*E*F*G	0.002		

Letter code: A(Q), B(RPM), C(ROP), D(TFA), E(OWR), F(Sol), G(Rheol.)

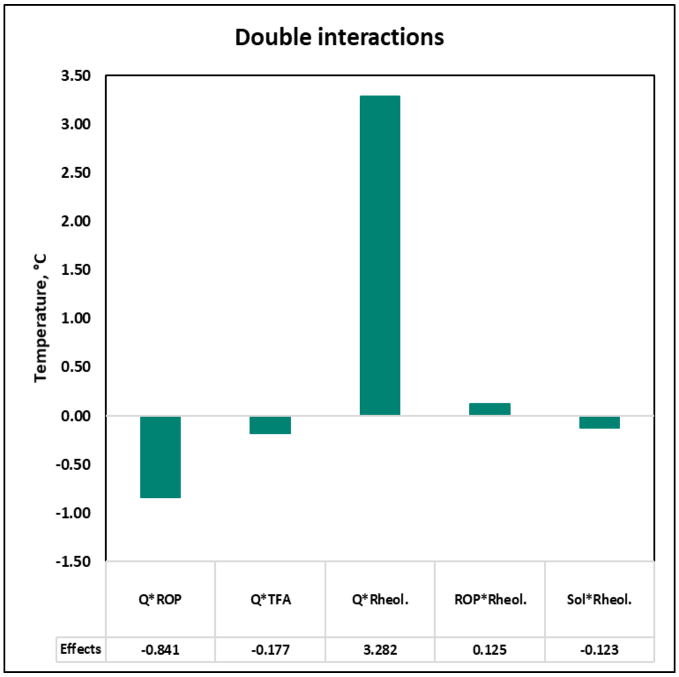

Figure 2. Effects of dual factor interactions.

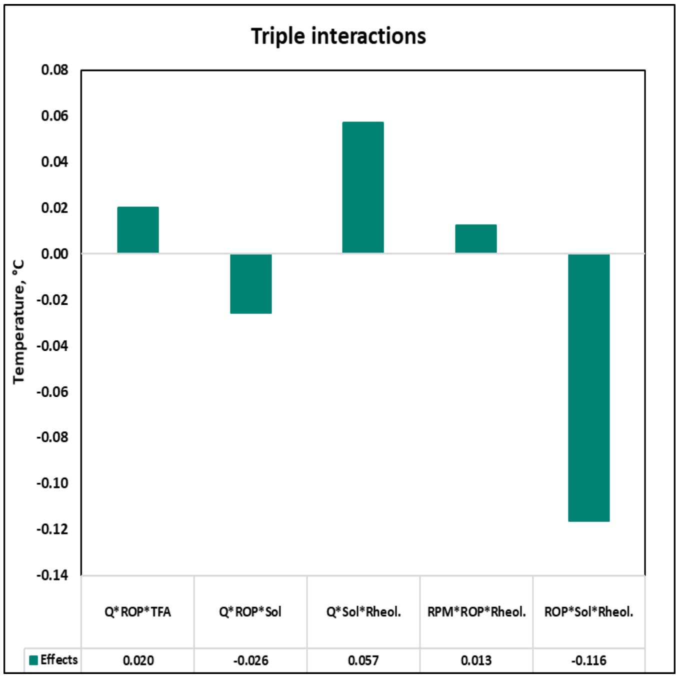

Figure 3. Effects of three-factor interactions.

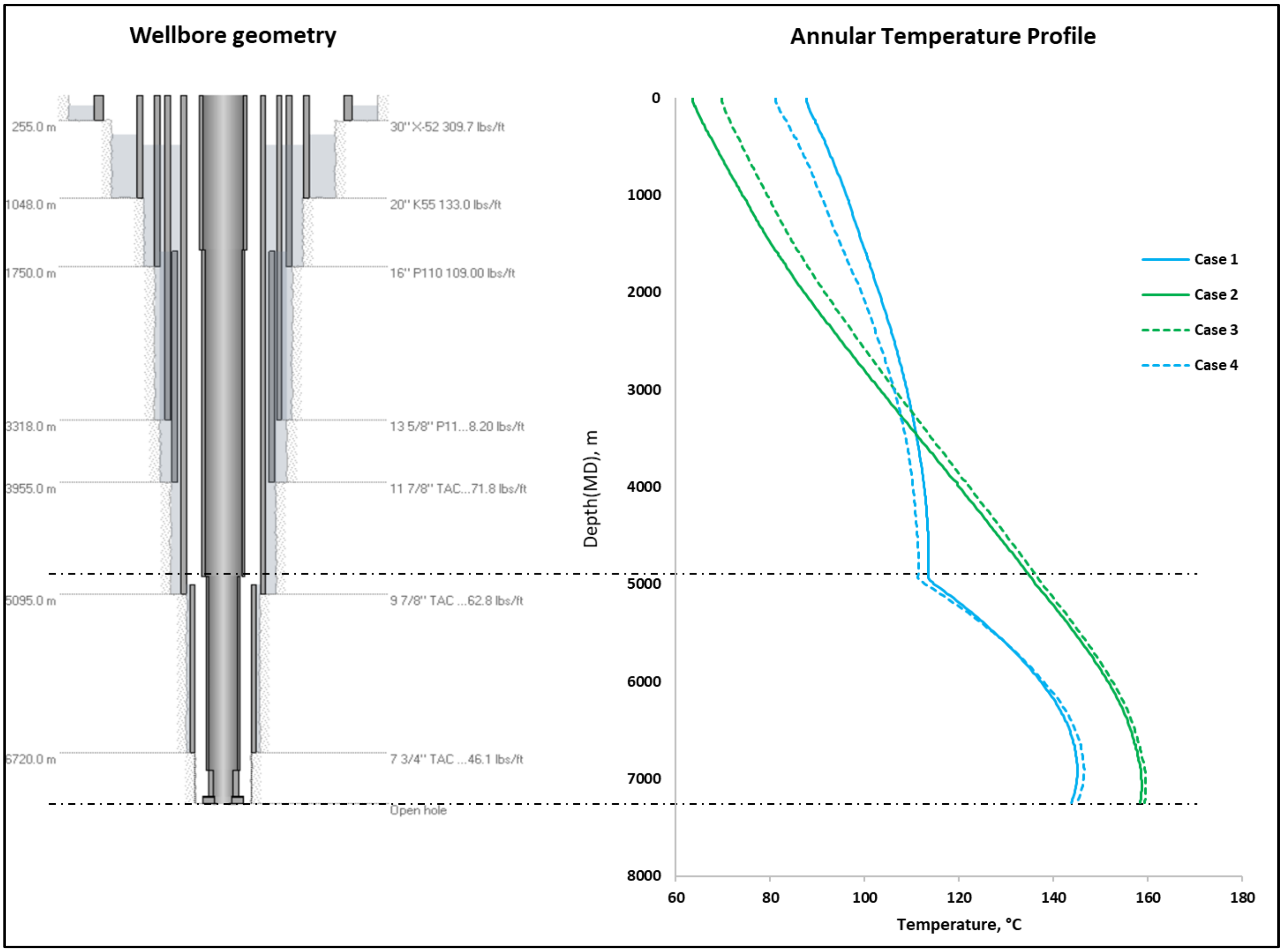

Figure 4. Annular temperature calculated for several cases.

Of the 128 simulations performed, figure 4 shows the temperature profiles of 4 simulations, two of them are related to lowest maximum temperatures (case 1 and 4), and in the other two the highest maximum temperatures are obtained (case 2 and 3), the lowest maximum temperature is obtained when the factors that increase the temperature (flow rate, ROP, rpm) are at their minimum value and the factors that decrease it (TFA, solids content, OWR, rheologies) are at their maximum value (figure 4, case 1), with this, it would be expected that the highest value would be reached with the flow rate, rop and rpm, at their maximum value and the minimum value for TFA, solids content, OWR, rheologies (figure 4, case 2), but the contribution of the effects of the interactions takes participation in this case, then the maximum temperature is obtained when only the flow rate and rpm are at their maximum value (figure 4, case 3), and the rest of the factors at their minimum value. At this point it would seem that the case 1 which the lowest temperature is obtained is the best option, however this option considers keeping the rop at its minimum value which is not the best option for the profitability of the business, although the rop increases the temperature, keeping the rop at its maximum value increases 1.4 °C over the minimum possible temperature (case 1), so the optimized option is to keep the flow rate and rpm at its minimum value and the rest of the factors at their maximum value, (figure 4, case 4). Figure 5 shows the maximum temperatures for each profile in Figure 4.

The results of optimization using statistical optimization are comparable to the benefits that can be obtained with the use of a mud cooler (El-Dorry et al. 2015).

It is important to note that the results of the statistical analysis apply within the range used for the factors, outside these limits, the factors and their interactions may have different behaviors, a second statistical analysis was performed with a reduction of factors from 7 to 4, in which the 4 factors of greater magnitude were considered: Flow rate, rheologies, ROP, and TFA, with the reduction of the analysis of the factors, the purpose was to

a) Case 4F-A: To know the change in the effects excluding the 3 factors of lesser impact, maintaining the range of the 4 factors of greater impact.
b) Case 4F-B. To know the effect of the dominant factor, flow rate, on the effects of the other factors, when the range of the dominant factor is increased from 200-250 gpm to 300-350 gpm.

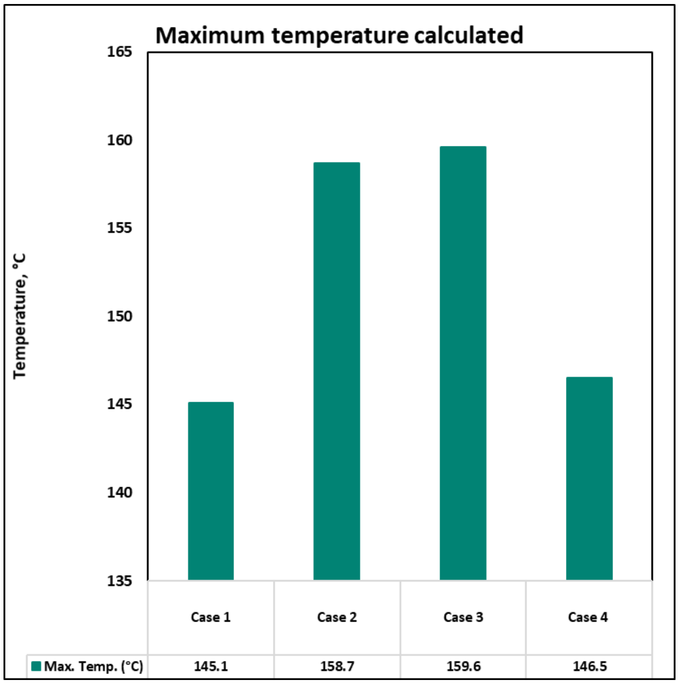

Figure 5. maximum temperatures for each profile in Figure 4.

Table 5 shows the factor ranges for the reduced analysis and Figure 6 shows the calculated effects for both cases as well as for the case with 7 factors (Case 7F) analyzed previously, in case 4F-A the calculated effects of the factors present the same tendency of case 7F but slightly different in magnitude. Case 4F-B shows that the increase in magnitude of the dominant factor in the range of values used generates changes in the effects of the other factors. Flow rate, when increased from 200 to 250 gpm generates an increase of 6.5 °C, while when increased from 300 to 350 °C generates a 5.9 °C change.

Table 5. Minimum and maximum values of the factors for the analysis reduced to 4 factors.

Factors	**Unit**	**Case 4F-A**	**Case AF-B**
Flow rate	gpm	200-250	300 – 350
BHA rotation	rpm	100 – 130	
Total Flow Area	in^2	0.752 - 1.046	
Rheologies (PV, YP, L3)	cp, lbf / 100ft^2	29/ 17/8 - 39/24/12	

Rheologies, in the scenario where the flow rate is maintained in the range of 200-250 gpm, when rheologies increase, the temperature decreases 4.6 °C, but when the flow rate is maintained between 300 and 350 gpm, the temperature increases 0.5 °C, in this case the impact of rheology is dulled to a degree that its contribution is reversed generating an increase in temperature.

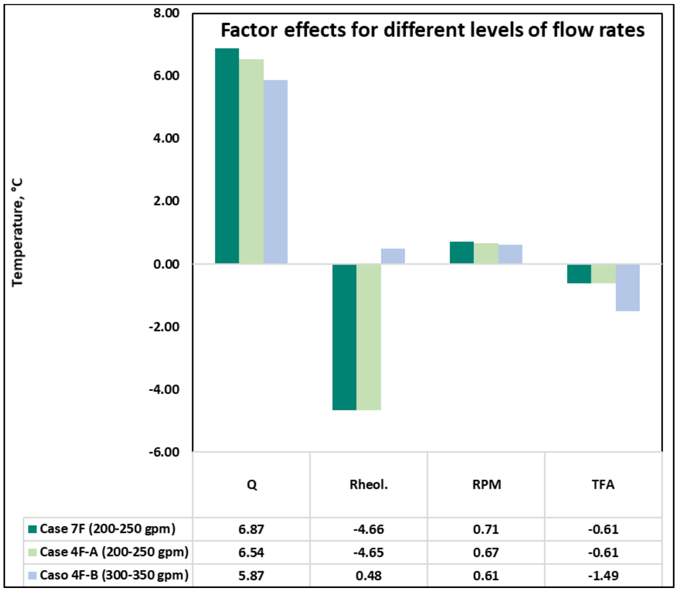

Figure 6. Comparison of calculated effects for different levels of flow rate.

The effect of rotation remains operationally unchanged with a change in flow rates. TFA, the temperature decrease caused by the increase in TFA goes from 0.6 °C to 1.5 °C, when the flow rate goes from 200-250 gpm to 300-350 gpm, although the magnitude of the effect triples, from an operational point of view the change is relatively small. Table 6 shows the interaction effects for all factors in the reduced analysis.

Table 6. Interactions for reduced factors analysis.

Interaction	Case 4F-A	Caso 4F-B
Q*Rheol.	3.259	0.320
Q*TFA	-0.180	-0.290
RPM*Rheol.	0.018	0.011
Q*RPM	-0.014	-0.005
TFA*Rheol.	0.008	0.011
RPM*TFA	0.006	-0.001
Q*RPM*TFA	0.006	-0.001
RPM*TFA*Rheol.	0.006	0.000
Q*TFA*Rheol.	-0.005	0.007
Q*RPM*Rheol.	-0.003	0.001
Q*RPM*TFA*Rheol.	0.006	0.000

As has been shown, the solution is valid within the range of factors used for the analysis, likewise, the magnitude of the effect of the factors may vary depending on the range chosen, on the other hand, in any analysis it is advisable to use as many factors as possible in the initial analysis, although this requires more effort, in case of doing an initial analysis with a reduced number of factors, there is the risk of not considering factors with significant effects and the calculated effects will not contribute to the best optimization, after identifying and quantifying the largest number of factors that influence the maximum temperature inside the well, the optimization can be done using only the most significant factors.

These results were used for operations, drilling was flawless. At the end of drilling, the logs indicated a BHT of 172 °C.

Conclusions

The analysis carried out allowed identifying and quantifying the operating parameters that influence the temperature of the fluid inside the well, which were optimized and applied in the drilling of the exploratory well S1 exp.

In the results for the design of the S1 Exp well, the flow rate was the factor with the greatest impact on temperature, causing an increase of up to 6.87 °C, as a mitigation variable of the thermal effect, the rheological properties showed a decrease of up to 4.66 °C.

In this design, the combined variation of the parameters generated a difference in maximum temperature of up to 14.5 °C in the annulus for all parameter combinations performed in the statistical analysis, which allowed defining the best combination of parameters to optimize drilling as well as minimize the thermal impact. With the optimized design, a maximum downhole temperature of 146.5 °C was obtained, which was only 1.5 °C above the minimum possible value (145.1 °C).

Even when the reduction in temperature could be relatively small, however, it is extremely important when close to the thermal limit of the BHA components, and can be the differentiator of completing operations on time or having NPT as well as damage to the BHA.

The results of the statistical analysis were applied in the execution of the operations and the HTHP section was successfully drilled. The adverse temperature effects that were anticipated during planning were mitigated with the optimization of drilling parameters.

Acknowledgments

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Nomenclature

Q: Flow rate, Q.
RPM: BHA rotation.
ROP: Rate of penetration.
TFA: Total flow area of bit.
OWR: Oil water ratio
Sol: Solids content.
Rheol: Rheologies.
BHA: bottom hole assemblies
HTHP: High temperature high pressure.

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