SIMCARR: A COMPUTATIONAL TOOL FOR OVERCOMING OIL WELL DRILLING CHALLENGES IN CRITICAL SCENARIOS

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Abstract. *Oil wells construction in Brazilian scenarios presents several challenges to overcome. In ultra deep water scenarios, rock formations present low competency and, consequently, hydraulics should contemplate the narrow operational window between pore and fracture pressures. Beside that, heavy oil reservoirs require long horizontal wells sections, challenging the current technology. The construction of long horizontal sections in narrow operational window scenario, requires the development of new technologies to expand hydraulic limits. Among the operational aspects related to borehole hydraulic, the following are critical: cuttings transporting, managing pressure, resuming circulation (breaking gel) and fluid displacement.*
PETROBRAS has an oil well hole cleaning and hydraulic simulator (SIMCARR) that helps designing and monitoring drilling operations in several different scenarios. The simulator has some modules responsible for optimizing and to ensure drilling job is carried out within operational limits. Some of these modules are listed below and are detailed in this paper.

- *Drilling and enlarging holes with reamer.*
- *Bottom hole pressure variations due to drillstring movement (Surge and Swab).*
- *Temperature gradient effects on drilling fluid properties and friction losses.*
- *Prediction of pressure peaks when resuming circulation*
- *Fluid displacement*

***Keywords**: Oil well drilling, Cuttings transport, Hydraulic simulator, Hole cleaning analysis*

1. INTRODUCTION

Wellbore hydraulic simulators should be able to capture all phenomena governing the cuttings transport to surface. These phenomena include the response of solid-liquid annular flow, the wellbore pressure profile while drilling and other important aspects, such as: bit jets optimization, pump pressure estimative, solids concentration, among others. Thus, models used should properly predict the effects of the relevant operational parameters, such as: the drilling fluids rheological properties, flow rate, drillstring rotation and eccentricity, the rate of penetration, drillstring geometry, cuttings properties (density and diameter), different casings and friction loss calculus.

The SIMCARR is the wellbore hydraulic and cuttings transport simulator of PETROBRAS, for vertical and horizontal wells, developed in partnership with GTEP – PUC-RJ.

The study of stratified solid-liquid annular flow is of great interest for petroleum engineering specially for drilling issues. The kind of flow describes the phenomena governing cuttings transport in horizontal and highly inclined sections. Due to gravitational segregation, both solids and drillstring will have the tendency to be in the lower portion of the annulus formed by the well walls and the drillstring. This process is characterized by stratified solid-non Newtonian fluids flow in eccentric annuli. Is hydraulic condition permit, the solids may be kept in suspension avoiding operational problem such as abnormal torque and drag during the drillstring movement.

This paper aims to show the PETROBRAS' simulator is able to consider many of the relevant phenomena in drilling and provide some features.

2. ADOPTED MODEL

The hole cleaning module is based on a mechanistic model to characterize the solid-fluid flow non-Newtonian in eccentric annular. An useful approach for modeling stratified two phase flow consists in writing the one dimensional momentum equation for two different layers. The bottom layer represents the stationary cuttings bed, deposited on an annular horizontal section by the action of the gravitational forces. The upper layer represents the drilling fluid, which flows through the unobstructed portion of the annular. For a general situation, where both layers move and there is mass transport from the suspended layer and vice-versa, the problem may be formulated by writing two mass and two momentum equations (Martins and Santana, 1992). This approach considers the several flow patterns in which the solids-liquid system may flow in horizontal annulus.

This model allows calculating hole cleaning parameters, such as, solids concentration, bed height, and flow pattern.

The SIMCARR model was proposed by Martins (1990) and finds a mean of two stratified layers, bed and suspension to represent the sliding mechanism of the bed. This model allows further, characterizing the system within the following flow patterns proposed by Iyoho (1980):

1. Stationary bed flow: deposition of solid particles at the bottom of the annular, forming a static bed;
2. Non-stationary bed flow: deposition of solid particles at the bottom of the annular, forming a mobile bed;
3. Heterogeneous flow: it is characterized by a system fully in suspension and solid phase presents a concentrations profile along the cross section.
4. Pseudo-homogeneous flow: it is characterized by a system fully in suspension, but in this case, there is no profile concentration and the solid phase is equally dispersed along the section.

For the implementation of this model, the following simplifying assumptions were considered:

- Bed height constant over time;
- The rheological parameters constant along the cross section;
- The solids are characterized by an average diameter and a sphericity;
- Surface tension effects and mass transfer between the solid and liquid phases are negligible;
- The slip effects between the liquid and solid phases in each of the layers are negligible.

3. DATA INPUT

The data input for a hole cleaning well simulation are: well geometry, drilling fluid properties and cuttings parameters and other operational parameters. The well geometry includes well path, casing data and drillstring composition. Figure 1 shows the presentation screen.

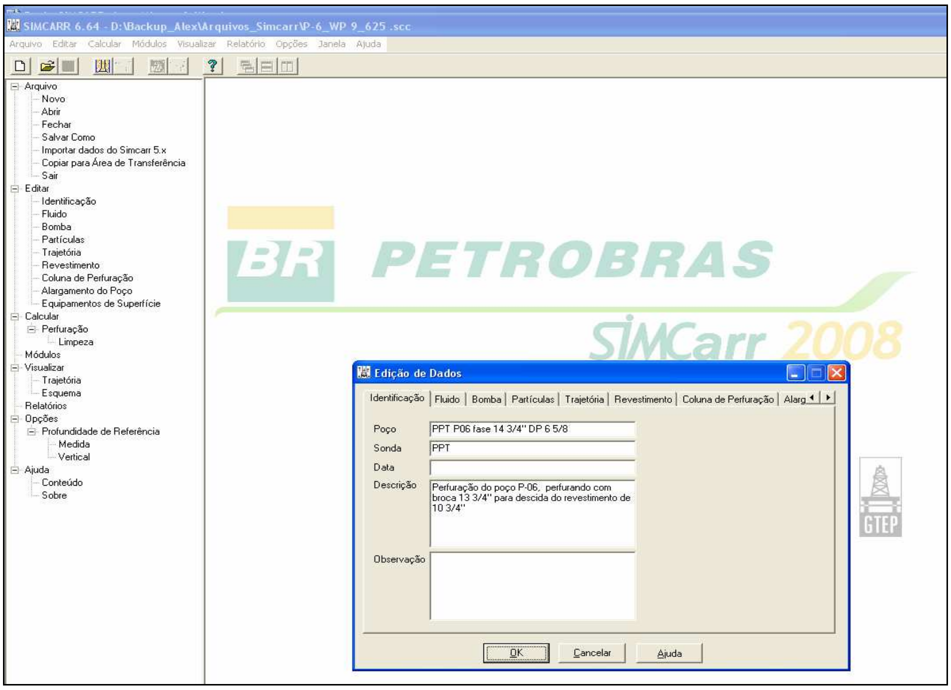

Figure 1. Presentation screen

3.1 Drilling fluids

The choice of the drilling fluid type is very important in order to obtain an accurate response. The fluid must be designed to minimize friction losses and provide an effective cutting transport. Thus, a good drilling fluid should have pseudoplastic behavior, presenting high viscosity at low shear rates (providing good solids transportation) and low viscosity at high shear rates (minimizing friction losses). The software allows the user to choose differents rheological models, such as, Power Law, Bingham, Herschel-Bulkley and Robertson–Stiff. It is possible to consider different rheological properties for the riser due to temperature effects. Figure 2 shows data input for rheological parameters determination.

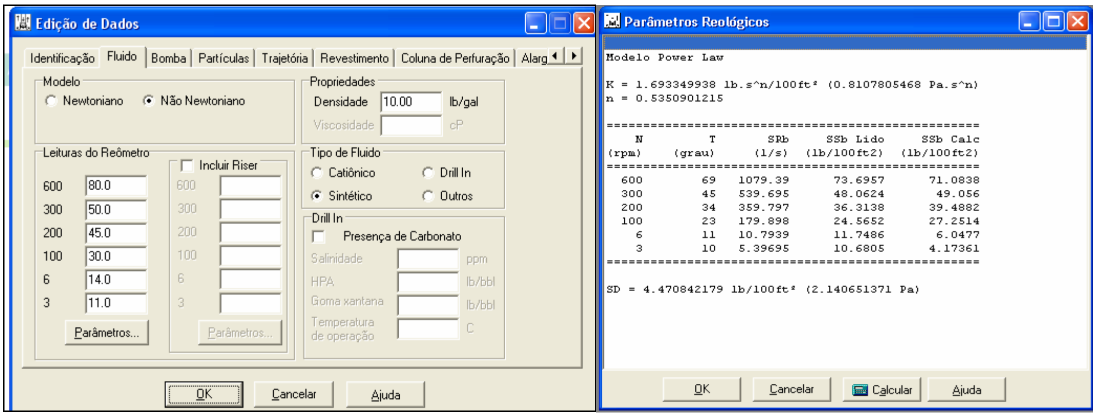

Figure 2. Data input for rheologic parameter determination

3.2 Pumps

In this item, flow rate, pressure limit, power and pump efficiency are inserted. The pressure limit and power data are used on bit jets optimization. Also, pressure limit is used as a parameter to alert the user when the pump pressure exceeds the limit value.

3.3 Particle

The particles properties are very important for the hydraulic and hole cleaning parameters determination. Basically, the informations included are: average diameter and density. An average diameter does not represent the real situation, once there is a particle size distribution in the well. A particle size distribution would be more appropriate and studies are being made toward implementing this change. The default of particle diameter of 0.25 inches is used in simulations for clay formation. For sand, it is recommended the value of 0.15 inches.

The response of cuttings transport modulus has a great influence in hydraulics, once solids concentration increases a hydrostatic pressure and friction losses.

3.4 Well path

The well path data is very important for friction losses and cuttings transport calculations. To draw up a trajectory in the project mode must specify KOP data (measured depth), build-up or drop-off (measured depth, inclination and azimuth and inclination rates) and slant (final depth). In the monitoring is necessary to insert the data for each point of directional (measured depth, inclination and azimuth). The figure below shows the entry of data for the trajectory of the well.

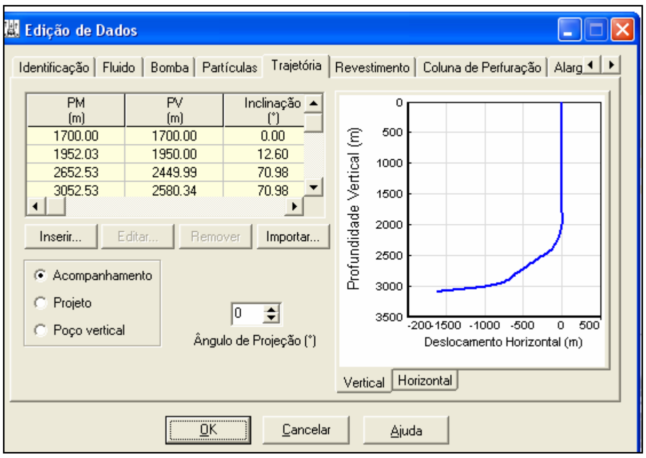

Figure 3. Well path data input

3.5 Casing

In this section, casing data are inserted. The data edition depends on the casing type added: riser (external and internal diameters and final depth), final casing (external diameter associated with weight and depth of the last casing shoe), liner (same parameters for selection of the final casing) and open hole (diameter and depth of the end the well). Figure 4 represents the casing data window.

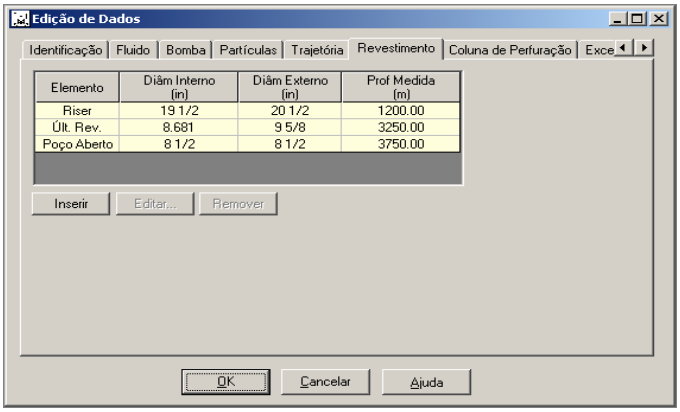

Figure 4. Casing data input

3.6 Drillstring

In this module, drillstring composition (drillpipes, heavy weights, drill collars, reamers, subs, bits, MWD/LWD, etc) is inserted. The drillstring composition is important to an accurate calculus of friction losses and correct estimative of pump pressure and bottom hole pressure.

3.7 Hole enlargement

In some oil wells, unconsolidated formations can cause enlargement of the open hole sections. SIMCARR allows the user to insert a well section with a diameter greater than the bit diameter.

4. DATA OUTPUT

4.1 Hole Cleaning Analysis

The main parameter used to analyze hole cleaning conditions are bed height (for horizontal and inclined sections), solids concentration (for vertical sections) and generalized transport ratio.

The bed height indicates the fraction of the annular space filled by a cuttings bed. The parameter value can vary from 0 to 100%. Bed height above 15% is critical.

The solids concentration is the main parameter to be considered in hole cleaning analysis for vertical sections. It is the volumetric fraction of the annular occupied by solids in suspension. High values of solids concentration can cause operational problems. Some authors have defined a solids concentration of 5% as maximum acceptable limit for a safe operation.

The generalized transport ratio is a parameter to evaluate the efficiency of solids removal. For vertical sections GTR is given by the equation bellow:

$$GTR = \frac{100(V_a - V_s)}{V_a} \tag{1}$$

Where Va is the fluid velocity in the annular space, Vs is the particle sedimentation velocity.

For inclined and horizontal sections the solids have a tendency to sediment, forming a cuttings bed. The GTR for inclined and horizontal sections is given by equation bellow:

$$GTR = \frac{100C_i}{\frac{A_T - A_L}{A_T} C_T} \tag{2}$$

Where A_T is the annular space total área, A_L the fraction of annular space area occupied by the cuttings bed, C_i is the solids concentration in suspension and C_T is the total solids concentration (suspension + bed).

Figure 5(a) shows the graphic results of a hole cleaning simulation. Figure 5(b) shows a table with, solids concentration (%), bed height (%) and GTR (%) for each section of the well.

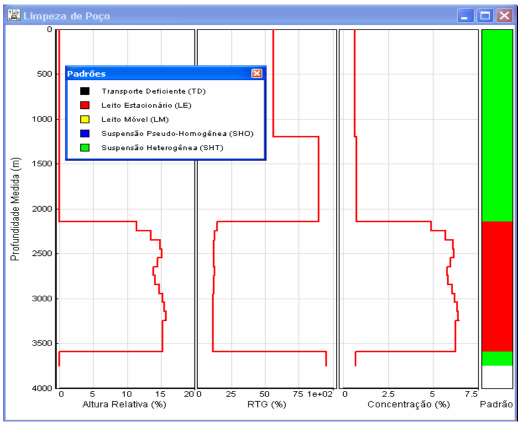

Figure 5(a). Hole cleaning results - graphs

Limpeza de Poço

	Trecho (m)	Inclinação (°)	Padrão	Perda por Fricção (Pa/m)	Perda por Fricção (psi)	Concentração Total (%)	Altura Relativa (%)	RTG (%)
1	0.0 - 1200.0	0.00	SHT	19.80	3.45	1.78	0.00	25.72
2	1200.0 - 1300.0	0.00	SHT	849.68	12.32	1.24	0.00	85.87
3	1300.0 - 1550.0	1.00	SHT	259.80	9.42	1.40	0.00	75.78
4	1550.0 - 1649.8	7.50	SHT	259.80	3.76	1.40	0.00	75.78
5	1649.8 - 1750.0	12.50	SHT	259.80	3.78	1.40	0.00	75.78
6	1750.0 - 1850.0	17.50	LE	180.43	2.62	9.61	24.55	13.30
7	1850.0 - 1949.6	22.49	LE	183.40	2.65	11.04	28.82	11.97
8	1949.6 - 2049.5	27.48	LE	180.67	2.62	13.08	34.58	10.64
9	2049.5 - 2149.5	32.48	LE	184.55	2.68	13.51	35.75	10.41
10	2149.5 - 2249.5	37.47	LE	188.32	2.73	13.67	36.19	10.33
11	2249.5 - 2349.1	42.46	LE	191.71	2.77	13.67	36.17	10.34
12	2349.1 - 2448.2	47.43	LE	194.71	2.80	13.53	35.80	10.41
13	2448.2 - 2548.1	52.41	LE	197.37	2.86	13.29	35.16	10.53
14	2548.1 - 2648.4	57.41	LE	211.79	3.08	12.98	34.31	10.69
15	2648.4 - 2747.5	62.40	LE	200.29	2.88	12.46	32.87	10.99
16	2747.5 - 2847.7	67.38	LE	200.62	2.92	12.21	32.18	11.14
17	2847.7 - 2946.2	72.35	LE	200.54	2.87	12.27	32.34	11.11
18	2946.2 - 3045.2	77.28	LE	200.47	2.88	12.33	32.50	11.07
19	3045.2 - 3144.2	82.24	LE	212.26	3.05	12.40	32.71	11.03
20	3144.2 - 3242.9	87.18	LE	212.49	3.04	12.48	32.94	10.98
21	3242.9 - 3250.0	89.82	LE	212.53	0.22	12.52	33.04	10.96
22	3250.0 - 5100.0	90.00	LE	237.72	63.79	12.42	32.86	11.02
23	5100.0 - 5130.0	90.00	LE	237.72	1.03	12.42	32.86	11.02
24	5130.0 - 5250.0	90.00	SHT	1203.01	20.94	1.20	0.00	88.34

Figure 5(b). Hole cleaning results - Table

4.2 Hydraulic Analysis

The main output parameters are ECD and friction losses along the well. Figure 6 (a) shows a table with the summary of simulated pressure and friction loss. The main results shown in this table are the friction loss inside the drillstring and in the annular space, ECD in the casing shoe region and bottom hole. Figure 6 (b) shows the hydraulic results.

Hidráulica por Trechos

Trechos | Resumo

Perda de Carga no Interior da Coluna (psi)	1241.17
Perda de Carga no Espaço Anular (psi)	179.78
Perda de Carga nos Equipamentos de Superfície (psi)	150.00
Perda de Carga nos Equipamentos de Direcional (psi)	273.33
Perda de Carga Parasita (psi)	1570.95
Perda de Carga na Broca (psi)	252.28
Coeficiente Hidráulico (%)	13.84
HSI	0.64
Tempo de Ciclo (min)	231.33
Tempo de Bottom Up (min)	195.22
Pressão de Bombeio (psi)	2096.56
Pressão na Sapata (psi)	4592.71
ECD na Sapata (lb/gal)	10.38
Pressão no Fundo do Poço (psi)	4660.68
ECD no Fundo do Poço (lb/gal)	10.53

Hidráulica por Trechos

Hidráulica | Outras Informações

	Trecho (m)	Coluna	Revestimento	Perda de Carga no Tubo (psi)	Perda de Carga no Anular (psi)	Velocidade no Tubo (ft/min)	Velocidade no Anular (ft/min)	Velocidade Crítica no Tubo (ft/min)	Velocidade Crítica no Anular (ft/min)	Regime - Tubo	Regime - Anular
1	0.0 - 840.0	Tubo	Últ. Rev.	70.81	44.34	402.15	134.71	399.89	451.39	Turbulento	Laminar
2	840.0 - 879.9	Tubo	Últ. Rev.	3.37	2.11	402.15	134.71	399.89	451.39	Turbulento	Laminar
3	879.9 - 919.9	Tubo	Últ. Rev.	3.37	2.11	402.15	134.71	399.89	451.39	Turbulento	Laminar
4	919.9 - 959.7	Tubo	Últ. Rev.	3.36	2.10	402.15	134.71	399.89	451.39	Turbulento	Laminar
5	959.7 - 999.8	Tubo	Últ. Rev.	3.38	2.12	402.15	134.71	399.89	451.39	Turbulento	Laminar
6	999.8 - 1374.8	Tubo	Últ. Rev.	31.62	19.80	402.15	134.71	399.89	451.39	Turbulento	Laminar
7	1374.8 - 1700.4	Tubo	Últ. Rev.	27.45	17.19	402.15	134.71	399.89	451.39	Turbulento	Laminar
8	1700.4 - 1800.4	Tubo	Últ. Rev.	8.42	5.28	402.15	134.71	399.89	451.39	Turbulento	Laminar
9	1800.4 - 2350.3	Tubo	Últ. Rev.	46.36	29.03	402.15	134.71	399.89	451.39	Turbulento	Laminar
10	2350.3 - 2439.7	Tubo	Últ. Rev.	7.54	4.72	402.15	134.71	399.89	451.39	Turbulento	Laminar
11	2439.7 - 2479.3	Tubo	Últ. Rev.	3.34	2.09	402.15	134.71	399.89	451.39	Turbulento	Laminar
12	2479.3 - 2519.4	Tubo	Últ. Rev.	3.38	2.12	402.15	134.71	399.89	451.39	Turbulento	Laminar
13	2519.4 - 3232.9	Tubo	Últ. Rev.	60.16	37.67	402.15	134.71	399.89	451.39	Turbulento	Laminar
14	3232.9 - 3265.9	Tubo	Últ. Rev.	2.78	1.74	402.15	134.71	399.89	451.39	Turbulento	Laminar
15	3265.9 - 3298.9	Tubo	Últ. Rev.	2.78	1.74	402.15	134.71	399.89	451.39	Turbulento	Laminar
16	3298.9 - 3331.7	Tubo	Últ. Rev.	2.77	1.74	402.15	134.71	399.89	451.39	Turbulento	Laminar
17	3331.7 - 3365.0	Tubo	Últ. Rev.	2.81	1.76	402.15	134.71	399.89	451.39	Turbulento	Laminar
18	3365.0 - 3398.5	Tubo	Últ. Rev.	2.82	1.77	402.15	134.71	399.89	451.39	Turbulento	Laminar
19	3398.5 - 4000.0	Tubo	Últ. Rev.	50.71	31.75	402.15	134.71	399.89	451.39	Turbulento	Laminar

Figure 6(a). Hydraulic analysis results

Figure 6(b). Hydraulic analysis results

4.3 Sensibility Analysis

The software allow the user to evaluate the impact of some operational parameter on hydraulics and hole cleaning. The user can choose the maximum and minimum value of the parameter it wants to evaluate (so as the increment) and the software simulates the variation of solids concentration, bed height, ECD, annular and pump pressure, etc. Figures 7 (a) and 7 (b) illustrate the data input for hole cleaning and hydraulic analysis.

Matriz de Limpeza

	Mínimo	Máximo	Incremento	
Vazão	100.00	300.00	50.00	gpm
Densidade do Fluido	7.00	12.00	1.00	lb/gal
Taxa de Penetração	5.00	10.00	1.00	m/h
Teta 600	60.00	90.00	5.00	
Teta 300	40.00	60.00	5.00	
Teta 3	5.00	15.00	3.00	

OK | Cancel

Figure 7(a). Hole cleaning matrix

Matriz de Hidráulica

	Mínimo	Máximo	Incremento	
Vazão	100.00	300.00	50.00	gpm
Densidade do Fluido	8.00	12.00	1.00	lb/gal
Taxa de Penetração	5.00	10.00	1.00	m/h

OK | Cancel

Figure 7(b). Hydraulic matrix

5. NEW MODULUS

Beside the modules shown above, other routines and features are being developed and incorporated to the software. The new modules are described bellow:

5.1 Reamer's modulus

Reamers can have a strong impact on hydraulics and hole cleaning if it is positioned far from the bit. Part of the fluid passes through the reamers jets, decreasing the flow rate between the bit and the reamer. This affects directly the cuttings removal in the region (annular space between bit and reamer) and the pressure profile along the well (once a smaller flow rate leads to smaller friction loss). Beside that, reamer generates more solids and it is very important to simulate how this extra quantity of solids will be removed.

Because of the increasing importance of drilling with reamers technique, a modulus was developed as shown in the figure bellow.

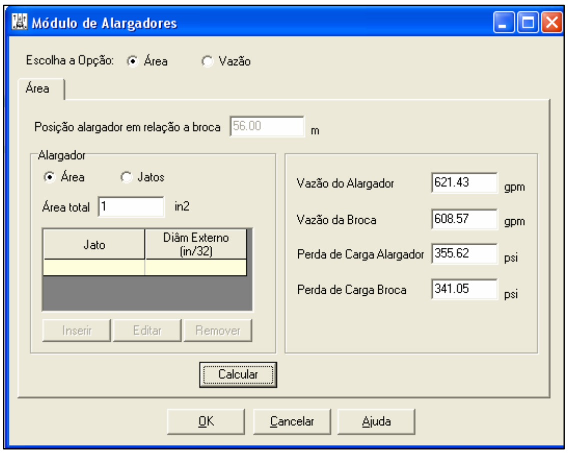

Figure 8. Reamer's modulus

5.2 Surge and Swab modulus

Drillstring movements can cause variations on bottom hole pressures. When the drillstring goes up quickly, the annular pressure tends to decrease (swab pressures). On the other hand, when the drillstring goes down, annular pressure tends to increase (surge pressures).

In a narrow operational window scenario, surge pressures can easily fracture the formations. Swab pressures, during drilstring trips, can also induce undesirable fluids formations invasion (kicks).

The surge & swab modulus predicts the maximum drillstring velocity (up and down) acceptable to avoid formation fractures and kicks.

The correct prediction of surge and swab pressure is a very important issue to determine the maximum velocity allowed on drillstring trips. The modulus allow the user to simulate the annular surge and swab pressure for a given drillstring trip and the maximum velocity permitted for a given operational window.   Figure 9 shows the surge & swab modulus screen.

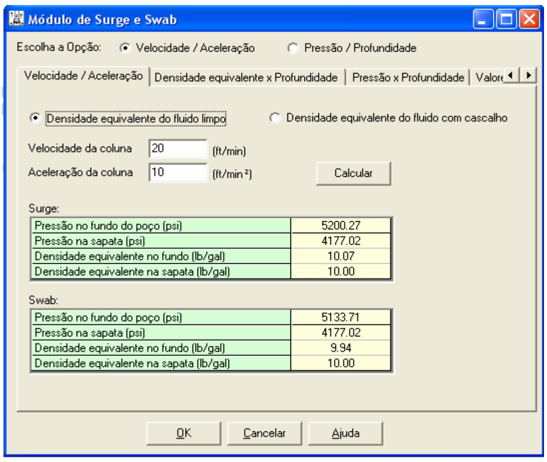

Figure 9. Surge and Swab module

5.3 Temperature's module

The correct prediction of friction losses along the circulation system and the solids transportation depend on the fluid rheology. However, the rheological parameters vary strongly when temperature changes. Thus, the fluid rheology corrections for different temperatures is a must on the correct prediction of friction losses and, consequently, pump pressure and ECD predictions.

Mathematical correlations were developed, for drilling fluids used in PETROBRAS, to describe rheological parameters behavior as a function of temperature. The Temperature Modulus generates a temperature profile in the wellbore and corrects the fluid rheology. This way, the prediction of friction losses (pump pressure and ECD) and the solids concentration are more accurate. Figure 10 shows the rheological parameters of a given fluid as a function of the mud weight and the temperature.

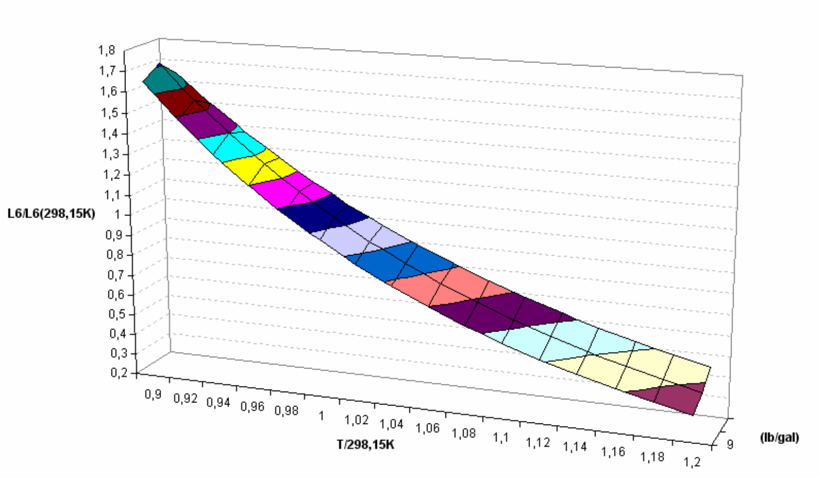

Figure 10. Rheological parameters variation as function of temperature and mud weight.

5.4 Gel module

The gelation phenomenon is a very important characteristic of drilling fluids, once it helps to keep drilled solids in suspension during pumps-off. However, when the circulation is resumed, an extra energy must be dispended to break the gel structure formed and pressure peaks are observed. In a narrow operational window scenario, pressure peaks can cause detrimental effects when fracture pressure is reached. Important parameters governing gelation are temperature, pumps off time, drillpipe rotation and start up flow rate (Gandelman, 2007).

Given the frac pressure, the Gel Modulus simulates the maximum flow rate permitted to avoid bottom hole pressure to be greater then this value (for a given temperature profile and pump off time).

6. FUTURE STEPS

The next version of the software has the new modulus described above implemented and will be used by PETROBRAS staff. A new modulus of temperature profile prediction will be developed and implanted in a future version.

Studies are being carried out with drilling fluids used in PETROBRAS to develop new and more accurate correlations to their friction coefficients.

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