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Abstract

Challenging wells require an accurate hydraulic model to achieve maximum performance for drilling applications. This work was conducted with a simulator capable of recreating the actual drilling process, including on-the-fly adjustments of the drilling parameters. The paper focuses on the predictions of the drilling simulator's pressure losses inside the drill string and across the open-hole and casing annuli applying the most common rheological models. Comparison is then made with pressure losses from field data.

Drilling data of vertical and deviated wells were acquired to recreate the actual drilling environment and wellbore design. Several sections with a variety of wellbore sizes were simulated in order to observe the response of the various rheological models. The simulator allows the input of wellbore and bottom-hole assembly (BHA) sizes, formation properties, drilling parameters, and drilling fluid properties. To assess the hydraulic model's performance during drilling, the user is required to input the drilling parameters based on field data and match the penetration rate. The resulting simulator hydraulic outputs are the equivalent circulation density (ECD) and standpipe pressure (SPP).

The simulator's performance was assessed using separate simulations with different rheological models and compared with actual field data. Similarities, differences, and potential improvements were then reported. During the simulation, the most critical drilling parameters are displayed, emulating real-time measured values, combined with the pore pressure, wellbore pressure, and fracture pressure graphs. The simulation results show promise for application of real-time hydraulic operations.

The simulated output parameters, ECD and SPP, have similar trends and values with the values from actual field data. The simulator's performance shows excellent matching for a simple BHA, with decreasing system's accuracy as the BHA design becomes more complex, an area of future improvement.

The overall approach is valid for non-Newtonian drilling fluid pressure losses. The user can observe the output parameters, and by adding a benchmark safety value, the simulator gives a warning of a potential fracture of the formation or maximum pressure at the mud pumps. Thus, by simulating the drilling process, the user can be trained for the upcoming drilling campaign and reach the target depth safely and cost-effectively during actual drilling.

The simulator allows emulation of real-time hydraulic operations when drilling vertical and directional wells, albeit with a simple BHA for the latter. The user can instantly observe the output results, which allows proper action to be taken if necessary. This is a step towards real-time hydraulic operations. The results also indicate that the simulator can be used as an excellent training tool for professionals and students by creating wellbore exercises that can cover different operating scenarios.

Introduction

Drilling fluid rheological models are represented by mathematical correlations between shear rate and shear stress, and a well-known ratio of shear rate to shear stress is viscosity. Therefore, through the rheological behavior classification, fluids whose viscosity is constant with changing shear rate are known as Newtonian fluids. On the other hand, the viscosity of non-Newtonian fluids varies with the changing shear rate, i.e. shear stress is not directly proportional to shear rate (Table 1). In general, but also as per standard API methods for drilling hydraulics, most drilling fluids are non-Newtonian and for better understanding of the fluid flow behavior, it is of great importance to understand the relationship between shear rate and shear stress and thus viscosity (American Petroleum, 2017).

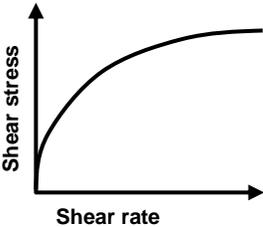
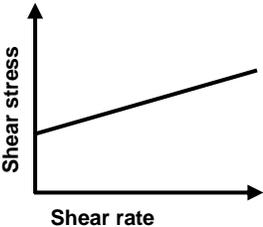
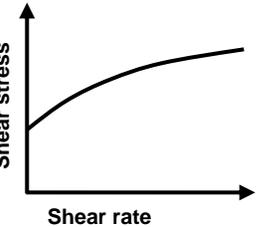
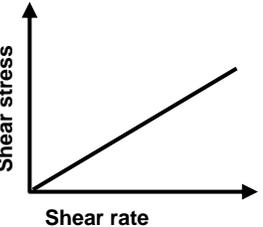
Bingham plastic and power-law (Ostwald-de Waele) rheological models are standard models used to describe simple drilling fluids for conventional drilling. They use a simple two-parameter approach, primarily because of their simplicity and satisfying predictions with the rheograms (Kelessidis et al., 2006; Founargiotakis et al., 2008; Muherei, 2016). However, the Bingham plastic model was found to overestimate the fluid yield point while the power-law model leads to substantial errors if the fluid exhibits yields stress (Hemphill et al., 1993).

The greater demand for energy resources and geothermal energy has led to the increased drilling of more complex wells (Baba Hamed & Belhadri, 2009; Cunha et al., 2009; Ma et al., 2016). Therefore, in recent decades, because of the need for the drilling of increasingly more challenging wells, more precise and appropriate rheological models are needed to predict and achieve maximum performance for drilling applications and fluid behavior modeling (Kelessidis et al., 2011). One of these is the Herschel-Bulkley rheological model, which combines both Bingham and power-law models. This model offers many advantages in describing rheological data of most of the drilling fluids but with a disadvantage of having a rather complex derivation of a three-parameter model and therefore is less frequently used (Hemphill et al., 1993; Merlo et al., 1995; Kelessidis et al., 2006; Founargiotakis et al., 2008). The Herschel-Bulkley rheological model is also used in a variety of industries such as pharmaceutical, cosmetics, food, concrete, mining and civil engineering (Kočevar-Nared et al., 1997; de Larrard et al., 1998; Ahmed & Ramaswamy, 2006; Mangesana et al., 2008; Morávková & Stern, 2011).

Since it is of great importance to minimize drilling operation problems such as poor hole cleaning, excessive ECD and stuck pipe, it is essential to have complete understanding of drilling fluid rheology as well as a correct approach in accurate predicting and modeling of pressure losses. The most important factors affecting pressure losses are fluid rheology, wellbore geometry and flow parameters (Simon, 2004). The appropriate choice of these parameters will help in wellbore hydraulic optimization, which will contribute in more precise pressure losses calculation. Suitable selection of rheological parameters will have a significant influence on computing hydraulic parameters, e.g. velocity profiles and pressure drop, resulting in avoiding many drilling problems (Kelessidis et al., 2006). The simulator used in the present research has an improved integrated component for determining the appropriate rheological model from viscometer data (Kelessidis et al., 2015).

Literature review shows that the non-linear Herschel-Bulkley rheological model describes the most accurate fluids rheology, compared with the Bingham rheological model which overestimates pressure losses or the power-law model which underestimates the losses (Langlinais et al., 1983; Hacıislamoglu, 1994). Therefore, choosing the right model plays a vital role in hydraulic calculations for applications in drilling processes (Bern et al., 2007).

Table 1 Flow behavior for Newtonian and non-Newtonian fluids; equations and flow curves

Power-law (pseudoplastic)	Bingham (plastic)	Herschel-Bulkley (yield power-law)	Newtonian fluid
$\tau = K * \dot{\gamma}^n$	$\tau = \tau_0 + \mu_p * \dot{\gamma}$	$\tau = \tau_0 + K * \dot{\gamma}^n$	$\tau = \mu * \dot{\gamma}$
			

Using the Herschel-Bulkley rheological model in the past, researchers calculated pressure drops and showed very good matching with collected field data (Merlo et al., 1995; Ayeni & Osisanya, 2004).

It should be highlighted that the software is mainly used as a drilling mechanics simulator providing ROP; thus the aim of this paper is to compare the simulated pressure losses for given well with field drilling data, using a simulator capable of recreating the actual drilling process. We do this by calculating pressure losses inside the drill string and across the open-hole and casing annuli, including on-the-fly adjustment of the drilling parameters.

Methodology

Flow parameters, such as fluid viscosity, fluid velocity and flow passage geometry, govern drilling fluid behavior. The flow regime can be characterized as laminar or turbulent, and appropriate flow models are available to determine pressure drop for laminar or turbulent flows.

The most common approach to establish the turbulence criteria, i.e. the nature of flow regime is identified by Reynolds number. Reynolds number is the ratio of inertial forces to viscous forces (Mitchell et al., 2011; American Petroleum, 2017).

Knowing the flow regime is of great importance in estimating pressure losses. Flow in annulus space during drilling is usually considered as laminar, with an exception of turbulent displacement flows in narrow annular gap during primary cementing job (Kelessidis et al., 1996). During the drilling process, it is hard to manage and support laminar flow due to the complex control of pumped drilling fluids at prevailing high flow rates (Bourgoyne et al., 1991). Laminar flow during drilling operations is favorable due to the less friction pressures and wellbore erosion (Madlener et al., 2009).

The flow type is determined from the values of the Reynolds number, which is expressed in field units, by:

$$Re = \frac{928 * \rho * v * d}{\mu} \quad (1)$$

Reynolds number of Eq. (1) is only valid for fluids with a constant viscosity. Most of the drilling fluids are non-Newtonian (Bourgoyne et al., 1991). Therefore, a straightforward expression of Reynolds number now become complex (Eq. 2).

Actual drilling software works with an algorithm that calculates the drillstring pressure losses, drill bit nozzle pressure drops and the additional equipment losses. These losses change depending on flow rate, mud properties, and the wellbore and drilling assembly (pipes, collars) geometry. Tool joints are neglected.

The first part of calculation refers to Reynolds number calculation for each individual part of drilling assembly, as far as in the drillpipes, collars, casing annulus and open hole annulus. Depending on whether flow is turbulent or laminar, pressure losses are calculated as the part of the second stage.

For Reynolds number we make standard use of reported equations, for e.g., for power-law fluids, one uses equations (2) & (3) below (Bourgoyne et al., 1991). Similar equations and transition criteria are used for Bingham plastic and Herschel-Bulkley fluids.

$$Re = \left(\frac{89100 * \rho * v^{2-n}}{K} \right) * \left(\frac{0.0416 * ID}{3 + \frac{1}{n}} \right)^n \quad (2)$$

$$Re = \left(\frac{109000 * \rho * v^{2-n}}{K} \right) * \left(\frac{0.0208 * annulus}{2 + \frac{1}{n}} \right)^n \quad (3)$$

Where,

$$annulus = OD - ID. \quad (4)$$

For laminar flow ($Re < 3000$), pressure loss is calculated via standard approaches, as in equation (5) for power-law fluids and pipe flow,

$$\Delta p_L = \left(\frac{L * K * v^n}{144000 * ID^{1+n}} \right) + \left(\frac{3 + \frac{1}{n}}{0.0416} \right)^n \quad (5)$$

If the Reynolds number is higher than 3000, the pressure drop for the turbulent flow regime is calculated making use of the friction factor concept. For e.g. for pipe flow,

$$\Delta p_T = \frac{f * \rho * v^2 * L}{25.8 * ID} \quad (6)$$

where, we make use of correlations for friction factor derived from data analysis and matching with published data. Similar approach is followed for the annulus space.

Pressure drop at the drill bit is calculated as follows,

$$\Delta p_{bit} = \frac{8.311 * \rho * Q^2}{100000 * C_d^2 * A_t^2} \quad (7)$$

Initial Simulation

In order to correctly simulate a section of a drilled well, the user must follow the BHA design that was used to drill the actual well. For purposes of simulation, only a specific BHA design can be selected.

The drill collar length was fixed at 400 ft, which was chosen based on the bit diameter. The user can select the size of the drillpipe by changing the outside (OD) and inside (ID) diameter in the editor. In addition to that, the user can change the nozzles' size and numbers according to the actual drill bit to calculate the pressure losses at the bit. The possible configuration of drill collar sizes is presented in the table below (Table 2).

Table 2. Drill collars sizes in relation to the selected bit size

Bit Size [in]	Collar OD [in]	Collar ID [in]
30	12	4
24	12	4
17 ½	10	3 ½
13 ¼	8	3
8 ½	6 ¼	2 ½
6	5	2 ¼

Initially, the software was tested on a simple BHA design. The results of the software were compared with commercially available drilling software (Software 2) to investigate the differences in terms of pressure losses and equivalent circulation density (ECD) for a 2000 ft open-hole vertical well. The drilling fluid has a density of 8.40 lbm/gal. The rheological properties by Fann viscometer dial reading at 3, 6 and 300 RPM (Allahviridzadeh et al., 2016) are presented in the table below (Table 3).

Table 3 Fann measurement inputs

Speed [RPM]	Dial Reading
Fann300	4.9
Fann6	1.2
Fann3	1

For the simulation, the following BHA design was selected:

Table 4 BHA design

Type	Length [ft]	OD [in]	ID [in]
PDC bit	-	-	17 ½
Drill collar	400	10	3 ½
Drillpipe	1600	5	4.276

A 17 ½ -in. drill bit with 4x15 and 3x13 nozzles was selected. In addition, surface facilities have to be included. Software 1 contains a surface pipe facility with a length of 300 ft and inside diameter of 5 in. The entire simulation was completed with a constant flow rate of 1000 gpm. It should be mentioned that the simulator doesn't take into consideration the tool joints outside and inside diameter, thus an additional deviation in pressure losses is expected. The results (Figure 1) show good matching, proving the validity of the hydraulics model that the software provides. For both simulations, the compared value is the

standpipe pressure and the ECD at the target depth. From the ECD perspective the results were 8.42 and 8.41 lbm/gal at 2000 ft accordingly.

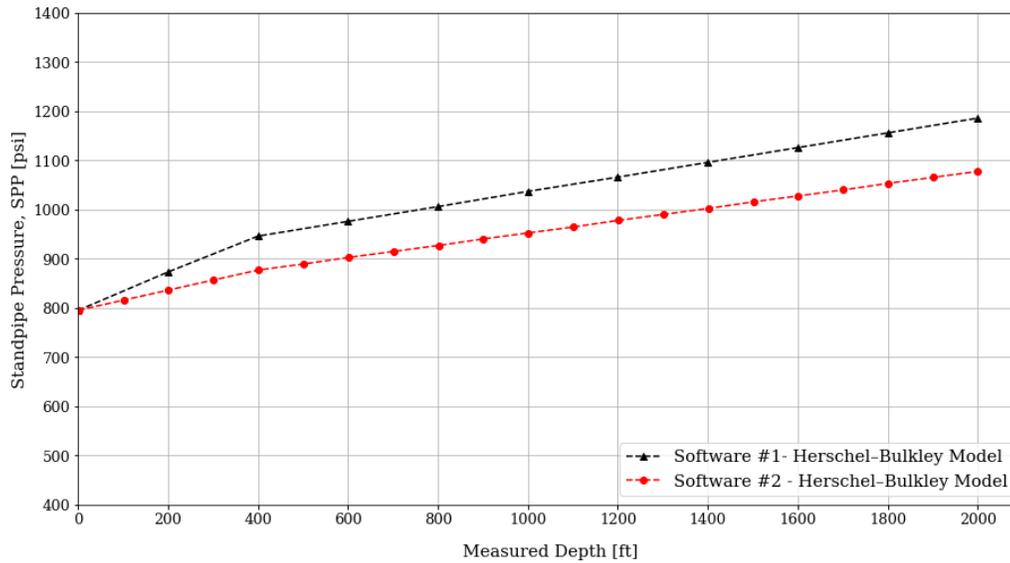


Figure 1 Simulation results

The output value of SPP of the simulator (Software 1) shows a higher value with respect to the output from Software 2, and that can be correlated with overestimation or underestimation of the actual pressure. The pressure losses inside the drill string were higher by approximately 60 psi for the drillpipe and 40 psi for the drill collars.

Figure 2 shows the distribution of pressure losses in the drilling system (well) for the Herschel-Bulkley model. The biggest losses tend to be at the drill bit, as expected, followed by losses in the drillpipe and drill collars, the surface and the finally the losses in the wellbore annulus space.

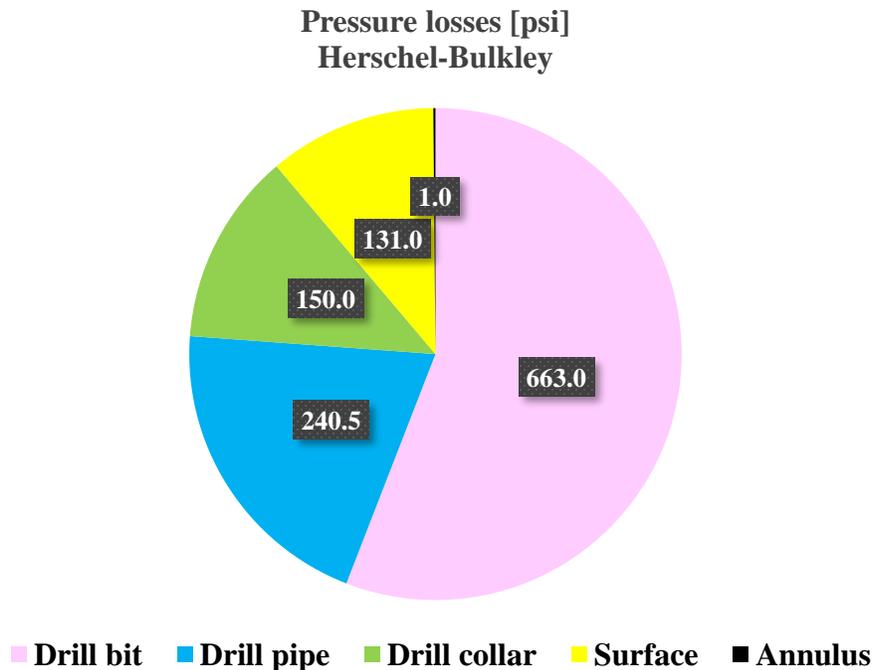


Figure 2 Pressure losses distribution in drillstring and annulus, Herschel-Bulkley rheological model

Following, the distribution of pressure losses in the drilling assembly for the Bingham plastic model is shown in Figure 3. It is important to highlight/notice overestimation of annular pressure losses that is in accordance with literature review (Langlinais et al., 1983; Hacıislamoglu, 1994; Simon, 2004). For this case, the annular pressure losses are very low, but in an actual complex well with a possible narrow pressure window, accurate estimation of annulus pressure losses is essential in order to prevent a kick or fracturing of the formation.

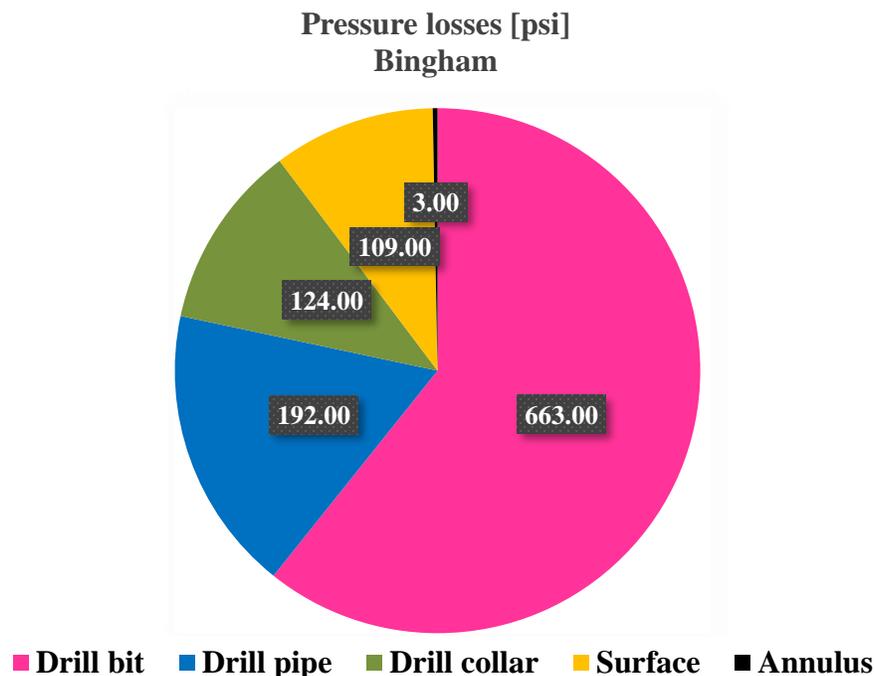


Figure 3 Pressure losses distribution in drillstring and annulus, Bingham plastic rheological model

Actual Well Simulation-Case Study and Results

We try to compare the simulation results versus field data from an actual drilled well. A vertical well of 17 ½ -in. size was drilled from 40 ft to a target depth of 2000 ft. A PDC bit was used to drill the section with 7x13/32 nozzles. Regarding the drilling fluid properties, the density was approximately 9.6 lbm/gal and 9.7 lbm/gal from approximately 1400 ft to target depth, with a plastic viscosity of 14 cP and yield point of 34 lbf/100 ft². Since plastic viscosity and yield point refer to Bingham plastic, and the simulator requires the values of 300, 6 and 3 RPM, a better fitting approach was used in order to derive those values and the resulted output values are illustrated in Table 5. The produced values that were used for the Herschel-Bulkley rheological model were:

Table 5: Herschel-Bulkley rheological model data

Parameter	Value	Units
Yield Stress	5.674	lbf/100ft ²
n	0.4381	[]
K	2.963	lbf s ⁿ /100ft ²

The output values of the simulator will be compared with the actual SPP and ECD. The actual drilling data were given as depth-based with an interval of 1 ft. The pressure losses from surface facilities can be

easily estimated by assuming that at the depth of 1 ft, the value of SPP is the pressure losses at the bit and the surface facilities. Thus, by calculating the pressure drop at the bit and then subtracting it from the current SPP, the pressure losses at the surface facilities can be estimated. The data were averaged every 25-30 ft to reduce the required time for the simulation.

To compare the actual well data with the simulated results, the standpipe pressure and equivalent circulation density are the main parameters to investigate, shown in Figures 4 and 5 respectively.

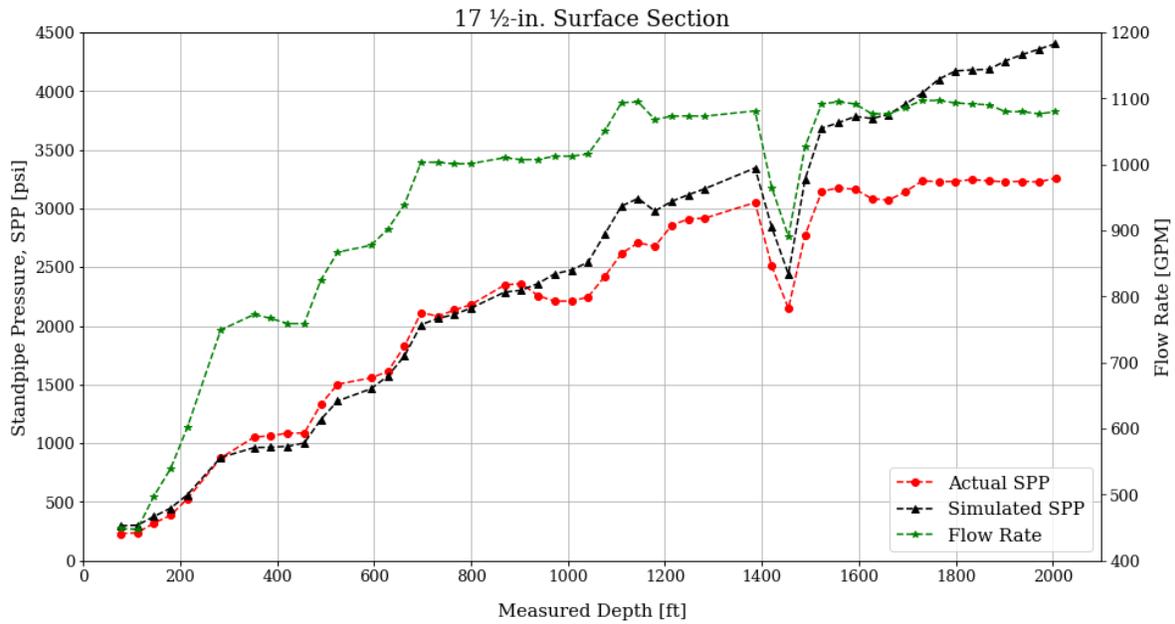


Figure 4 SPP from simulated and actual drilling data versus depth, together with flow rate

The simulated results show excellent matching until approximately 1500 ft. A small difference can be expected through some losses during the actual process. The software outputs change instantly in any change of flow rate or BHA design passing from drill collars to drillpipe, which allows real-time interaction between the user and the software. This enables the user to understand the physics behind the calculations and act accordingly in any challenge that occurs while drilling.

At the deeper part of the section, the results start to deviate from the actual SPP. Because the flow rate is steady from 1500 to 2000 ft, a linear increase of the SPP is expected both for the field results and in the simulator. The actual data show a steady trend with a minor SPP increase for the last 500 ft, hence the almost constant pressure at the deeper section could be attributed to possible flow losses. Thus, a difference of the simulated and actual SPP is expected, since partial fluid losses is a very common phenomenon while drilling surface sections.

Figure 5 below illustrates the output value of ECD while drilling the section. In the actual drilling process, in order to reduce the risk of fracturing the formation, an accurate value of ECD is crucial, especially in narrow pressure windows. The actual ECD at the depth of 2000 ft was 9.74 lb/gal. The slight difference between the actual and simulated ECD indicates and verify the validity of the simulator. As it was mentioned in the paragraph above, the resulted SPP has as a result the decrease of the actual ECD.

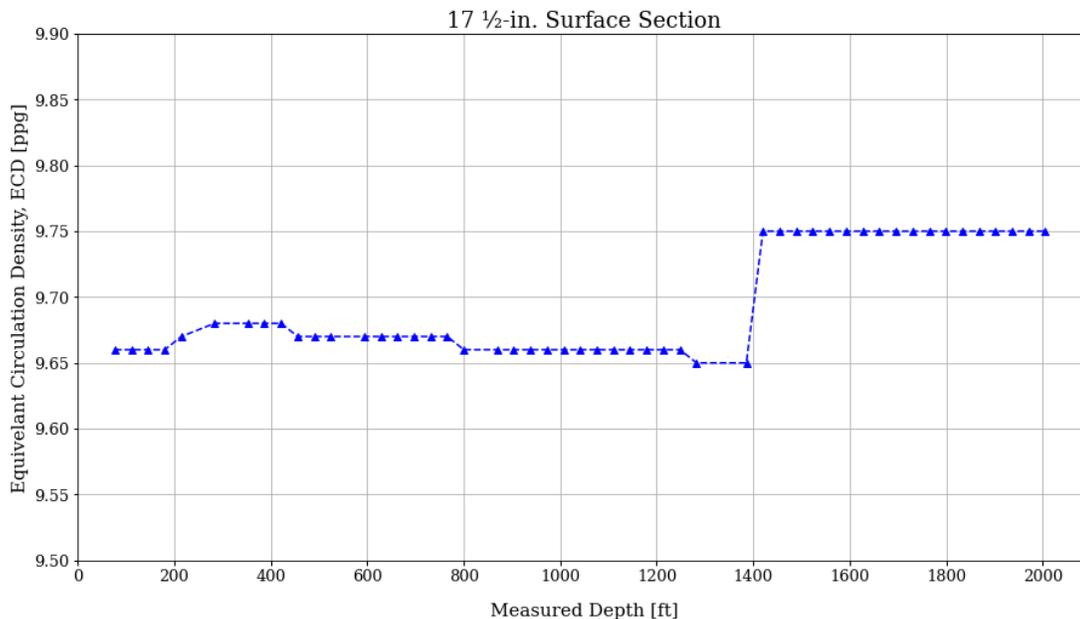


Figure 5: Actual ECD in real-time while simulating the actual well

Conclusions

We have provided an approach which allows for the prediction of pressure losses in the entire drilling system. The hydraulic model used can capture the effect on non-Newtonian fluids by utilizing the appropriate measurements for the drilling fluid from laboratory tests or field data. The results show that, for the case studied, the difference between the simulated and the actual field data is small and differences are possibly due to losses that may have occurred during the drilling process. The comparison of actual and simulated data indicates valid correspondence for a range of flow rates.

A combination of an accurate hydraulic model and a real-time simulator can assist in training students or professionals to drill a well in the most effective way prior to the actual drilling process. Intervals that have a narrow pressure window can create an additional challenge, since ECD should always be kept lower than fracture pressure but higher than pore pressure. Thus, recreating the actual drilling environment in a simulator enables the possibility to have several drilling scenarios for that specific interval to find the optimum way to drill it faster and safer.

Current limitations make difficult to introduce complex BHA designs because the simulation results become less accurate. Future work will focus on further software validation using additional real-time data considering also hole cleaning as a necessary element of the drilling process for drilling more complex wells like horizontal and deviated.

Nomenclature

A_t	Total nozzle area [in ²]
C_d	Correction factor, 0.95 [-]
d	Diameter [in]
f	Friction factor [-]
f_f	Friction factor assuming smooth pipe [-]
$Fann$ 3/6/300	Fann viscometer dial reading at 3,6 or 300 RPM
ID	Inside diameter [in]
K	Consistency index [lbf s ⁿ /100ft ²]
L	Length [ft]
n	Flow behavior index [-]
OD	Outside diameter [in]
Δp	Pressure drop [psi]
Q	Flow rate [gpm]
Re	Reynolds number [-]
v	Velocity [ft/s]

Greek symbols

$\dot{\gamma}$	Shear rate [s ⁻¹]
μ	Viscosity [cP]
μ_p	Plastic viscosity [cP]
ρ	Density [lbm/gal]
τ	Shear stress [lbf/100ft ²]
τ_0	Yield point [lbf/100ft ²]

Abbreviations

API	American Petroleum Institute
BHA	Bottomhole Assembly
ECD	Equivalent Circulation Density [lbm/gal]
PDC	Polycrystalline Diamond Compact Cutter
RPM	Revolutions per minute
SPP	Standpipe pressure [psi]

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