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Real-Time ECD Management by Accounting for Effects of Drillpipe Rotation and Eccentricity in the Wellbore

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Abstract

Drillpipe (tubular) rotation operation and eccentricity of the pipe in the wellbore significantly affect dynamic equivalent circulating densities (ECD). This paper presents a method to help accurately estimate pipe eccentricity in high-angled wells and determine its contribution to changes in annular pressure loss. Additionally, the method more accurately predicts complex variations in annular pressure loss as pipe rotates at various speeds during circulation.

Pipe location invariably shifts from a concentric position based on the wellbore/drillstring configuration. For varying eccentricities, non-Newtonian wellbore fluids have significantly different velocity/viscosity profiles and flow rate vs. pressure drop relationships.

Various drilling operations require pipe rotation at speeds that could enhance the effective shearing experienced by circulated fluids. At certain pipe rotation speeds, a fluid instability effect can contribute to additional pressure loss in the axial direction.

Analytical models were developed to capture the effects of drillpipe rotation and eccentricity on ECD. The models were studied and validated with actual well data for a range of annulus gaps, flow rates, and fluid characteristics.

The model results show that annular pressure losses are considerably smaller for eccentric pipe positions compared to concentric pipe positions; pressure drop reductions up to 50% were predicted for fully eccentric scenarios. This reduction is particularly applicable for high-angle well sections where pipe is significantly eccentric.

For pipe rotation, the models indicate strong flow-rate-dependent behavior; at low flow rates, the models show pressure loss (or ECD) decreases with increasing pipe rotation speeds; however, for high flow rates, pressure loss (or ECD) increases with increasing pipe rotation speeds.

The models were validated on several wellbores with different inclinations by comparing the ECD predictions with pressure-while-drilling (PWD) measurements as the pipe rotated at various speeds.

Accurately determining the effect of pipe rotation and eccentricity on wellbore pressures helps provide more efficient methods to manage the ECD between the formation's fracture and pore pressure gradients during a wellbore operation and enables fluid formulation optimization and improved operating conditions for real-time ECD management.

Introduction

The axial flow of non-Newtonian fluids through eccentric annuli has been studied extensively using analytical and numerical methods[1,2]. The non-Newtonian nature of the fluids was incorporated based on power-law and Bingham-plastic models. The studies demonstrated that annular pressure loss decreases with increasing eccentricity of the inner shaft.

The axial-rotational flow in the annulus as the inner shaft rotates has been researched experimentally for Newtonian fluids in laminar and turbulent regimes[3,4]. The experiments demonstrated that the flow resistance increases beyond a certain rotation speed of the inner shaft. Numerical models were applied to simulate the velocity profiles and vortices in the laminar and turbulent flows of the Newtonian fluids through annuli with inner shaft rotation[5,6]; the simulations showed an increase in the friction factor as a result of the inner shaft rotation.

With regard to the drilling scenario, the drilling fluid is pumped down the drillpipe and returned to the surface mud pit through the annulus between the drillpipe and the wellbore wall/casing. The drilling fluids are non-Newtonian with a significant degree of shear thinning and yield-stress behavior. Drillpipe is often rotated to facilitate cuttings transport. The drillpipe rotation results in the axial-rotational flow of the drilling fluids in the wellbore annulus. Experimental studies have shown that the impact of the drillstring rotation on annular pressure loss is significant (Δ ECD $\approx$ 1 to 2 lbm/gal) in slimhole (narrow annulus) wells[7]. It was observed that for low-circulation flow rates, annular pressure loss decreased with an increase in the pipe rotation speed. To the contrary, for high-circulation flow rates, the pressure loss increased with an increase in the pipe rotation speed.

Finite element-based numerical simulations have shown decrease in annular pressure loss resulting from drillpipe rotation in the wellbore, which agrees with laboratory experiments but disagrees with field observations at high-circulation flow rates[8]. Conversely, modeling of the helical flow behavior using the empirical methods described that the pressure drop increases with an increase in pipe rotation speed[9,10].

Overall, there have been conflicting observations concerning the effect of pipe rotation on ECD in the wellbore. The discrepancy is addressed in this paper by accounting for two opposing physical phenomenon operating simultaneously: shear thinning and increased dissipation resulting from drillpipe rotation. The development and validation of the analytical models for the effect of drillpipe rotation and eccentricity on ECD is presented.

Theory

Fluid rheological behavior was characterized based on the Herschel-Bulkley model as follows:

$$\tau = \tau_0 + k * (\dot{\gamma})^n \quad \text{....... Eq. 1}$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate, τ_0 is the yield stress, k is the consistency index, and n is the flow index. The drilling fluids are shear thinning; hence, n < 1.

Effect of Pipe Eccentricity on the Annular Pressure Loss: For a concentric annulus, the eccentricity $\varepsilon = 0$; for a fully eccentric annulus, $\varepsilon = 1$. The annular pressure loss in an eccentric annulus is lower compared to that in the concentric case; the decrease is a function of the drillpipe eccentricity (ε), the radius ratio of drillpipe to the wellbore (r_i/r_o), and the fluid rheological parameters (n, k, τ_0), as presented in Eq. 2:

$$(\frac{\Delta P}{\Delta L})_{ecc} = g_1(\varepsilon, r_i / r_o, n, k, \tau_0) * (\frac{\Delta P}{\Delta L})_{conc} \quad \text{....... Eq. 2}$$

where the annular pressure loss in the concentric annulus was determined based on standard API methods[11].

Effect of Pipe Rotation on the Annular Pressure Loss: The combined axial-rotational flow of the drilling fluid in the annulus as a result of the drillpipe rotation produces a revised friction factor (f) compared to that from axial flow alone (f_{ax}).

The ratio of the friction factors is a function of the fluid rheological parameters (n, k, τ_0), axial and rotational shear rates, and Reynolds numbers ($\dot{\gamma}_{ax}, \dot{\gamma}_{rot}$, Re_{ax}, Re_{rot}), as presented in Eq. 3:

$$\frac{f}{f_{ax}} = g_2(n, k, \tau_0, \dot{\gamma}_{ax}, \dot{\gamma}_{rot}, Re_{ax}, Re_{rot}) \quad \text{....... Eq. 3}$$

Eq. 3 accounts for rotational effects in terms of two competing effects that include the fluids' shear thinning and flow dissipation. The model shows that depending on the details of the experiment or the wellbore (geometry, fluid properties, and the operating conditions), either an increase or decrease can be observed in the ECD when the drillpipe is rotated.

Results

The predictions from the drillpipe eccentricity and rotation (E&R) models are demonstrated in simplistic single annular section scenarios. The rheological parameters of the representative fluid are defined by the Herschel-Bulkley model as $\tau_0 = 12$ lbf/100 ft^2, k = 0.33 lbf/100 ft^2, and n = 0.83.

Fig. 1 shows predictions from the drillpipe eccentricity model for a 5 1/2-in. drillpipe in an 8 1/2-in. hole for the representative fluid. The fluid was circulated at an axial flow rate of 200 gal/min. The model results show that annular pressure loss was considerably smaller for an eccentric annulus compared to the concentric annulus; pressure loss reductions up to 50% were predicted for fully eccentric scenarios.

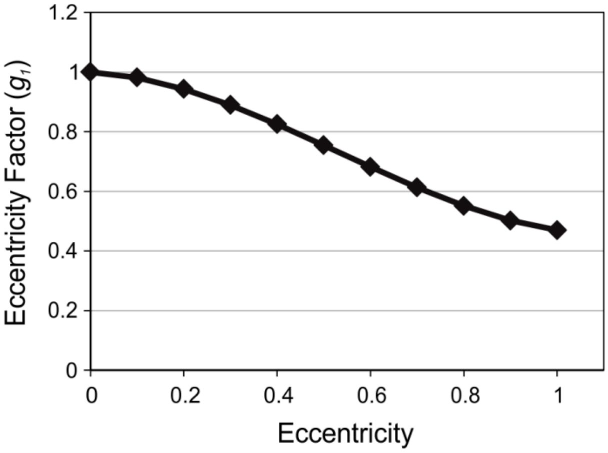

Fig. 1—The eccentricity factor g_1 as a function of the drillpipe eccentricity for a 5 1/2-in. drillpipe in the 8 1/2-in. hole for the representative fluid circulation.

Fig. 2 shows results from the drillpipe rotation model for a 5 1/2-in. drillpipe in three different hole sizes: 8 1/2-, 12 1/4-, and 17 1/2-in. in diameter, respectively. The normalized pressure drop, P/P_{ax}, represents the prediction of the ratio of annular pressure loss under axial-rotational flow (P) to that under axial flow alone (P_{ax}) obtained using Eq. 3. The parameter in each plot is the axial flow rate in gal/min.

The model predicts that the effect of rotation is non-trivial in the sense that it could lead to either an increase or decrease in pressure loss (or, equivalently, ECD) depending on the rotation rate, geometry, rheology, and the axial flow rate. For the smallest hole size considered (Fig. 2a), pressure loss slightly increased before decreasing slightly at the lowest axial flow rate of 100 gal/min. At the higher flow rate, the pressure loss increased monotonically. For the other two hole sizes considered (Figs. 2b and 2c), the rotation led to a decrease in ECD at a 100 gal/min flow rate and an increase in ECD at the highest flow rates. There was an intermediate flow rate at which the impact on ECD was non-monotonic (i.e., ECD initially increased with a small amount of rotation but then decreased at higher rotation rates).

In general, it was observed that for relatively narrow annulus or high-axial flow rates, the ECD increased as a result of rotation, while a larger annulus or low axial flow rates could lead to a decrease in ECD as a result of rotation.

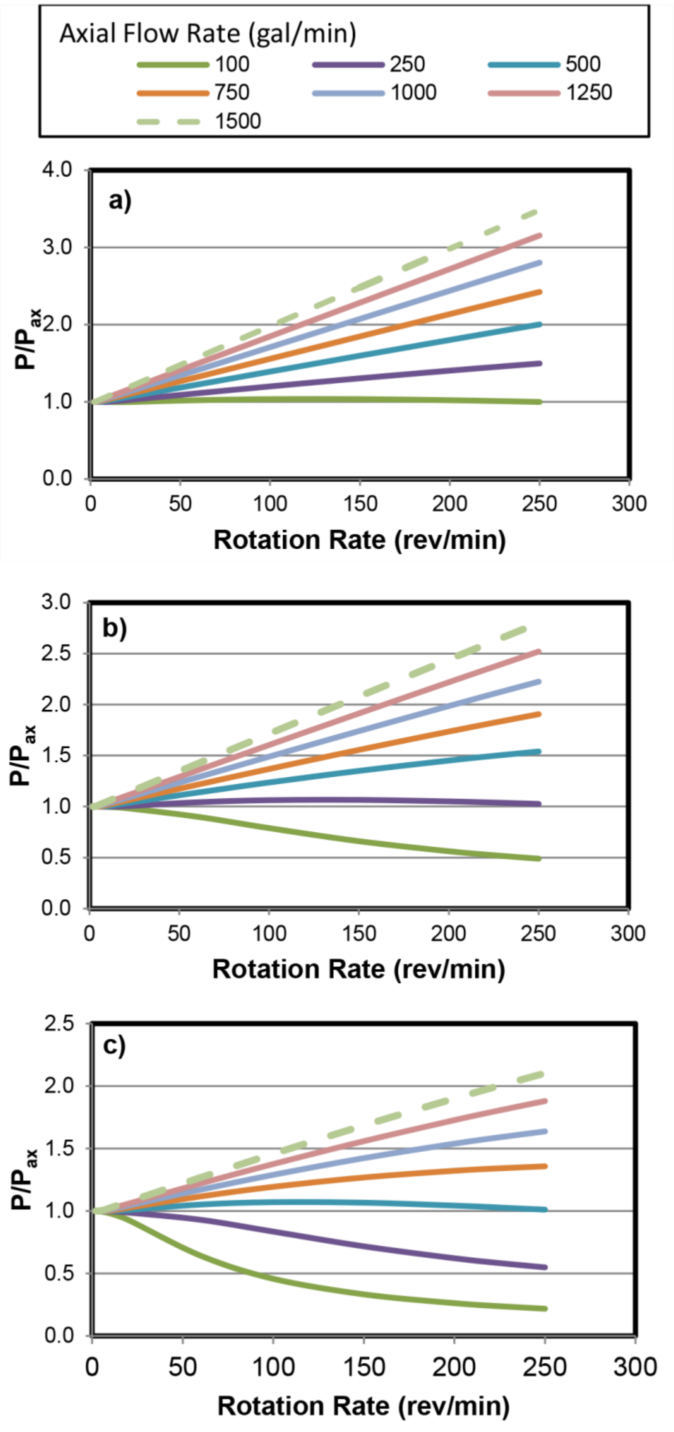

Fig. 2—Normalized pressure drop as a function of the rotation rate, as predicted by the drillpipe rotation model for a) 8 1/2-in., b) 12 1/4-in., and c) 17 1/2-in. hole with 5 1/2-in. drillpipe for the representative fluid. The parameter is the axial flow rate given in gal/min.

Field Validation

The drillpipe E&R models were validated for field scenarios by studying their impact on hydraulic calculations for a given set of wellbore geometry, fluid properties, and operational conditions. **Fig. 3** illustrates the wellbore configuration where the well measured depth (MD) was ~13,800 ft and true vertical depth (TVD) was ~10,300 ft. Inclinations along the wellbore path varied significantly, reaching values as high as 72° and resulting in a highly eccentric annulus. The casing outer diameter (OD) was 9 5/8 in., and the pipe OD was 5 1/2 in.

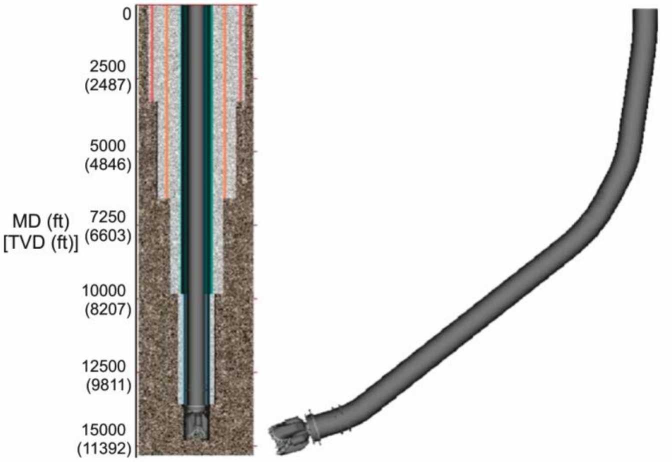

Fig. 3—Schematic of the wellbore used for field validation of the drillpipe E&R models.

The drilling fluid circulating through the wellbore was an 11.5 lbm/gal oil-based mud (OBM) with an oil/water ratio of 67:33. The surface temperature was ~85°F, while the bottom hole temperature (BHT) was ~200°F. **Table 1** presents additional drilling fluid properties at the surface. Downhole temperature and pressure corrections were applied to the fluid properties to help improve the accuracy of the hydraulic calculations.

Table 1—Composition and properties of the field mud.

Property	Composition
Mud weight (lbm/gal)	11.5
High-pressure/high-temperature (HP/HT) (mL/30 min)	0.5
Oil/water ratio	67/33
Emulsion stability (volts)	1053
Viscometer Data	
600 rev/min (lbf/100 ft^2)	111
300 rev/min (lbf/100 ft^2)	71
200 rev/min (lbf/100 ft^2)	57
100 rev/min (lbf/100 ft^2)	41
6 rev/min (lbf/100 ft^2)	17
3 rev/min (lbf/100 ft^2)	15
10 sec gel (lbf/100 ft^2)	17
10 min gel (lbf/100 ft^2)	27

Flow rate during the drilling process **(Fig. 4)** was steady at 560 gal/min, while pipe rotation speed varied from 0 to 150 rev/min for a 360-second duration (the variable rev/min was plotted using the secondary y-axis). For this duration, the field data with regards to PWD obtained from the downhole tools is shown on the ECD (primary y-axis) vs. time plot (red data points).

For this field scenario, the ECD model prediction without considering the drillpipe E&R effect remained unchanged at 14.44 lbm/gal, irrespective of the rev/min changes shown in Fig. 4 (dotted black line). This predicted ECD differed considerably from the PWD measurements, especially at no or low pipe rotation speeds (difference >0.3 lbm/gal). To the contrary, the ECD model prediction that accounted for E&R effects based on Eqs. 2 and 3 (solid black line) tracked the PWD behavior well as the rev/min varied (difference <0.1 lbm/gal). Because the strong inclination of the present wellbore resulted in significantly eccentric drillpipe, application of the drillpipe eccentricity model lowered the ECD prediction to 14.1 lbm/gal (no rotation condition). As the drillpipe rotation speed increased, the dominating flow dissipation resulted in the predicted ECD increasing from 14.1 to 14.4 lbm/gal.

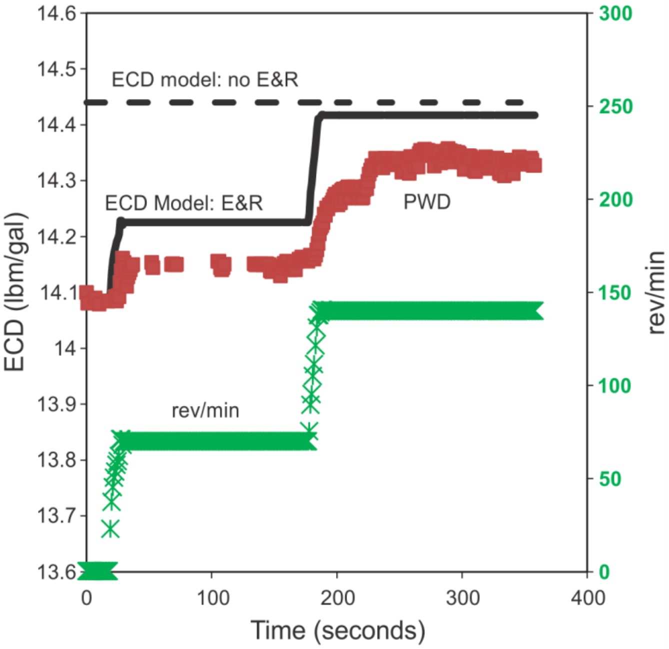

Fig. 4—Real-time ECD obtained from (a) PWD measurements (red data points); (b) ECD model without considering the drillpipe E&R effects (dotted black line); and (c) ECD model accounting for the E&R effects (solid black line). The secondary y-axis was used to show the corresponding pipe rotation speed (rev/min) vs. time (green data points). The axial flow rate was fixed at 560 gal/min.

Fig. 5 shows a snapshot of the real-time ECD software representing a 2-hour log of the data recorded at 5-second intervals. The software uses real-time inputs for rate of penetration (ROP), wellbore geometry, fluid properties, circulation flow rate, and drillpipe rotation speed. As output, the software predicts real-time ECD, which is compared to the corresponding PWD measurements. For the current geometry and operating conditions, it was observed that the real-time ECD predictions (accounting for the drillpipe E&R effects) were in agreement with the corresponding PWD response (third column of Fig. 5).

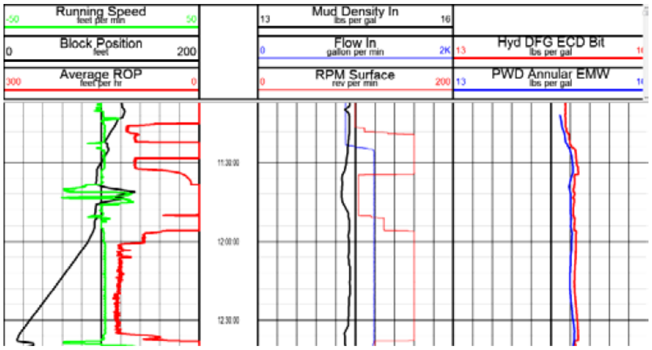

Fig. 5—Snapshot of the real-time ECD software for 2-hour log data: the left column shows software input of real-time ROP; the middle column shows real-time inputs of real-time fluid density, circulation flow rate, and drillpipe rotation speed; and the right column shows the software output in terms of predicted ECD compared to the PWD measurements.

Fig. 6 shows quantitatively that real-time ECD predictions accounting for drillpipe E&R effects are significantly more accurate compared to those predicted without considering the E&R effects. The data was obtained from the real-time ECD software performed on the present well for several hours. The plot shows normal distribution of Δ ECD, which is defined as the difference between real-time predicted ECD and corresponding PWD. For the ECD model accounting for the E&R effect, the Δ ECD values remained in the narrow margin of 0 to 0.1 lbm/gal, emphasizing its enhanced ability to track/predict the PWD response.

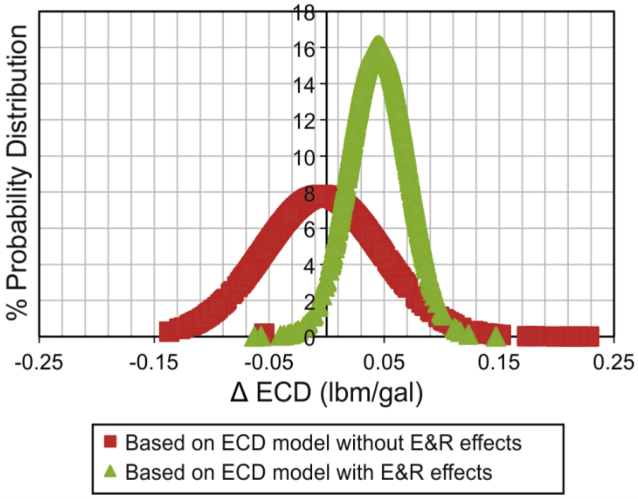

Fig. 6—Normal distribution of the Δ ECD (the difference between real-time predicted ECD and corresponding PWD) presented for ECD models without and with consideration of the drillpipe E&R effects.

Conclusions

The following conclusions are a result of this work:

- Drillpipe eccentricity leads to a reduction in the annular pressure loss (or ECD); pressure loss reductions up to 50% were predicted for fully eccentric scenarios.
- Drillpipe rotation could lead to either an increase or decrease in annular pressure loss based on the details of the experiment or the wellbore geometry, fluid properties, and the operating conditions.
- The drillpipe rotation model predicted that for a relatively narrow annular region or high axial flow rates, an increase in ECD results from the rotation, while a larger annulus or low axial flow rates could lead to a decrease in ECD resulting from the rotation.
- Based on PWD measurements in the field, it was validated that real-time ECD predictions accounting for drillpipe E&R effects are significantly more accurate than those predicted without considering these effects.

Acknowledgments

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Nomenclature

ECD = *equivalent circulating density*
gal/min = *gallons per minute*
lbm/gal = *pounds per gallon*
PWD = *pressure while drilling*
rev/min = *revolutions per minute*

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