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Investigation of the viscous fluid effect on torque and drag modeling in highly deviated wells

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In this work, the effects of the viscous flow of fluids on torque and drag simulation results were investigated for down-hole strings. Torque and drag simulations were performed with and without the inclusion of viscous fluid effects, the influence viscous fluid effects inclusion had on torque and drag simulation results were determined and the consequence this margin of influence would pose to drilling operation. Well plan software was used for the simulation; two cases were considered. Case 1 considered the torque and drag simulation without the inclusion of viscous fluid effects. Case 2 considered the torque and drag simulation with the inclusion of viscous fluid effects. Simulations were run for open hole friction factors (OHFF) of 0.15, 0.2 and 0.25 and cased-hole friction factors (CHFF) of 0.2. From the results, it was realized that the maximum effective tension and maximum hookeload decreased by approximately 2.1 kilopounds (kips) for tripping in operation and by approximately 3.3 kips for tripping out operation, and sliding and drilling (rotating-on-bottom) operations remained unchanged due to the inclusion of viscous effects of fluid flow. Analyses of drag and torque revealed that the maximum drag decreased by 2.1 kips for tripping in (slack-off drag) and by 3.3 kips for tripping out (Pickup drag) operations and maximum torque during drilling operation increased by approximately 310.3 ft-lbs due to the inclusion of the viscous effect of fluid flow.

Key words: Well trajectory, downhole forces, tripping operation, well drilling, operational cost, friction factors.

INTRODUCTION

Highly deviated wells pose great challenges during drilling and completions (Kerunwa, 2020a) in the earlier days of the oil and gas industry. Then it was nearly impossible to achieve complex well architectures because the drilling technology was immature and the technique for complex well drilling was not well understood. However, breakthroughs in well engineering have enabled the development of drilling and completion technologies and well design philosophies which altogether have given rise to effective well engineering design protocols thus ensuring reliable, sustainable, economical and safer drilling of complex and challenging wells and lithologies (Neamah and Alrazzaq, 2018). Drilling and completion operations are now executed

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much easier, faster, and at optimally reduced operational costs. Operators have given more interest to complex wells such as extended reach wells, horizontal wells (Kerunwa, 2020b), multilateral wells, etc., because of their advantages over conventional vertical wells. These wells have increased well-reservoir contacts which translate to higher productivity, higher sweep efficiency, and more drainage. The production capacity achievable by drilling many conventional wells is surpassed by drilling a few complex highly deviated maximum reservoir contact wells (MRC) at comparably lower costs thereby helping to reduce the cost per barrel of oil produced (Al-haj et al., 2015; Neamah and Alrazzaq, 2018). Thus, adopting an effective well design protocol pays off by greatly reducing the operational cost of developing a well. Nonetheless, rigorous or complex wells have their inherent problems and challenges which are not akin to conventional wells. As a result of the increase in the complexity of the well geometry, greater frictional and normal force interactions abound due to increased areas of contact between the downhole strings and the borehole walls (Leonard and Seitassanov, 2017).

Friction and normal forces depend on the well operations and the nature of contacting surfaces during the well operation. The consequence of these frictional and normal forces in opposition to the direction and movement of string in the borehole leads to higher possibilities of well problems such as torque and drag, casing wear, etc (Fazaelizadeh, 2013). Torque and drag is a major challenge in complex well engineering operations. Torque and drag represent one of the fundamental problems experienced in the well during drilling, completions, and work over operations. Torque and drag comprise the downhole forces acting on the down hole strings and tubular during these operations. The risks and consequences of torque and drag become more profound as the well trajectory becomes more complex. Thus, great caution is needed during the design and the operational phases of complex wells to reduce the impact of torque and drag. Proper methods as well are required to estimate these crucial down hole forces to maintain well integrity and reduce the operational cost of well operations while maintaining a safe engineering practice. These would also help in the planning, design, and all operational activities to be conducted around the well as proper evaluations and management decisions are fostered by an accurate estimate of down hole interactions of the down hole equipment. Torque and drag in wells have been known to cause buckling, string wear (such as casing wear), stuck pipe, pipe failures, lockup, and costly fishing jobs which ultimately increase the overall operational cost of the well (Mason and Chen, 2007). It is proper to define torque and drag individually and how they both impact the wellbore during downhole operations (Zhang et al., 2015). Torque can be conveniently defined as the product of force and rotation. In the wellbore, torque is the rotational force experienced due to the rotation of downhole strings and tubular in the well. During drilling, torque is generated from the surface of the top drive and transmitted downhole to the bits via the drill pipe and other drilling accessories. The torque transmitted to the bit is utilized in crushing the rock/formation during drilling operations. However, because of so many factors in the well, the amount of torque generated by the top drive at the surface does not get fully transmitted to the bits as there are torque losses along the wellbore. The degree of losses is a function of so many factors like the geometry of the well, the doglegs and tortuosity of the wellpath, the fluid weight, the friction factors in the well, the stiffness and bending parameters of the string, the radial clearance between the string and the borehole, the degree of eccentricity of the string in the borehole, etc (Wang and Yao, 2017; Ohia et al., 2021). The deviated sections of the borehole generate greater torque losses than straight sections because of the greater contact between the string and the walls of the well in these curved well sections. It is important to identify the several types of torque prevalent in boreholes during well operations such as drilling; these can be conveniently categorized as mechanical torque, frictional torque, bit torque, and viscous (hydrodynamic) torque. The sum of all the torque should be equal to the torque generated at the surface (surface torque) by the top drive. The frictional torque is the torque used to overcome the frictional forces in the wellbore; they are usually lost in the wellbore due to friction. The mechanical torque is that torque generated by cutting beds, centralizers and stabilizer effects. The viscous torque is the torque generated as a result of the movement between the drillstring and the drilling fluid in the wellbore. In most torque evaluations and, torque and drag evaluations this viscous torque is erroneously neglected. The bit torque represents the net torque transfer from the surface to the bits after torque losses have been incurred in the wellbore (Wang and Yao, 2018). Drag on the other hand is the sum of the axial force acting on the downhole string. Drag resists the motion of the string and acts in opposite direction to the axial movement of the string in the borehole. Technically, drag can be regarded as the force that inhibits the motion of an object in a straight line. In the wellbore, it is more conveniently explained as the force required in lowering or pulling the string in and out of the well (Ihaddoudènea et al., 2018). When tripping in (lowering the string into the hole), the string moves downward into the well while the drag acts upwards against the direction of the string movement. In this case, since the drag acts upwards against gravity, the drag force is subtracted from the buoyed weight of the string and the string weight recorded will be less than its buoyed weight in the well. Contrarily, when tripping out (pulling the string out of the hole), the string moves upwards out of the well while the drag force acts downwards. Drag forces are classified as upward drag and downward drag. Upward drag is also called pickup drag and is the drag experienced when the string is pulled out of the hole. On the other hand, downward drag also called slack-off drag is the drag experienced when the drill string is lowered into the hole. Pickup drag is usually greater than slack-off drag during well operations (Smith and Rasouli, 2012).

From the literature, there are two schools of thought prevalent in the development of governing equations and principles for torque and drag determination in wellbores. These are the soft string and stiff string torque and drag models. These models have their peculiar assumptions and applicability (Nwonodi et al., 2017; Neufeldt et al., 2018). The soft string torque and drag model gained popularity as the standard torque and drag model in the industry. Its popularity stems from its simplicity and elegance and the fact that it has proven to be accurate in a wide range of field applications. In the soft string model also called the cable model, the drill string is assumed to entirely lie at the path of the wellbore such that there is continuous contact between the drill string and the borehole wall (Ren et al., 2017). This model is simplistic and does not account for the effects of stiffness or bending parameters in the string and also entirely neglects the effect of borehole clearance (Samuel and Zhang, 2018). This model has been observed to predict torque and drag with good accuracy in wells with smooth trajectory, however, for complex wells with highly tortuous wellpaths and micro-irregularities soft string models may introduce errors and significant differences may arise between simulated and actual field results. Soft string models have been recognized to over-estimate the contact forces in the wellbore and also cannot predict the string positioning in the wellbore (Al-haj et al., 2015). Conversely, stiff string model accounts for the bending and stiffness parameters in the wellbore and also takes into account the effect of radial clearance in the hole. This model assumes that not all the string length lies on the wellpath as there are unknown sections of the wellbore that are not in contact with the wellbore wall (Mason and Chen, 2007). This model is intended to produce a more realistic and accurate analysis of the configuration, stresses, and loads acting on the string and wellbore wall. Both soft string and stiff string models have both been applied with relative degrees of accuracy and there are notable areas where it is wholly necessary to use stiff string model. These include: wells that has highly tortuous trajectories, well paths with high dogleg severity, and well designed with narrow radial clearances. Soft string model was first introduced by Johancsik et al. (1984), he modeled and provided the basic equations for soft string torque and drag model by treating the drill string as a cable that lies entirely on the wellbore wall. Their model presented the first generally accepted torque and drag model in the industry. Later, Sheppard et al. (1987) modified the work of Johancsik et al. (1984) by introducing differential parameters and bringing in the effect of mud pressures which replaces the true tension with effective tension. Sheppard et al. (1987) model is considered the standard model for use in the industry for torque and drag analysis. Ho (1988) conducted a study that combines both soft string and stiff string models. He aimed to determine the effect of well tortuosity on torque and drag results. He concluded that torque and drag increase at an exponential rate with the depth of the well. Mason and Chen (2007) conducted a study on soft string model. They assumed the loads on the strings result from the gravity effects and frictional drag that occurs due to contact force between the string and the wellbore. Their model includes the effect of hydrodynamic viscous force and the effect of tortuosity. Mitchell (2007) was the first to conduct comprehensive research on stiff string torque and drag. He included the effect of shear forces in his modeling and also bending moments. Mitchell (2008), went further to replace the minimum curvature method that was conventional at that time with a trajectory model that uses spline functions derived from stiff string dynamics. His model produced more accurate and realistic results, especially for high build rates. However, the model was complex and expensive to use by engineers. Mirhaj et al. (2016) in their work made a comparison of soft string and stiff string models identifying their strengths and lapses. They concluded that the two models can be used with good accuracy as long as they are applied to their respective applicable areas. Zhang and Samuel (2019) considered in their work when to use the soft string or stiff string model. They highlighted the difference between the two models and developed appropriate criteria on the application of the models.

Ohia et al. (2021) conducted an extensive study on the comparative analyses of stiff string and soft string models on standard survey data. They defined standard survey data to be the conventional deviational data done every 90-95 ft intervals. They maintained that standard survey data are unable to reveal the micro-irregularities in the wellpath such as micro-doglegs and micro-tortuosities. They conducted their simulation using both soft string and stiff sting models on standard deviational survey data.

Their result revealed that there is no appreciable difference between soft string model results and stiff string model results on standard deviational survey data and recommended that soft string model be used when there is standard deviational survey data since it is simpler and easier to use. From the literatures reviewed, no significant attention was paid on the viscous fluid effect on torque and drag modeling in highly deviated wellbores. In this work, the impacts of viscous fluid on torque and drag in highly deviated boreholes were investigated. Simulations were conducted using Wellplan software for a case with viscous fluid effect and a case without viscous fluid effect. The study seeks to substantiate the operational dangers prevalent with the neglect of viscous fluid flow effects in torque and drag simulations.

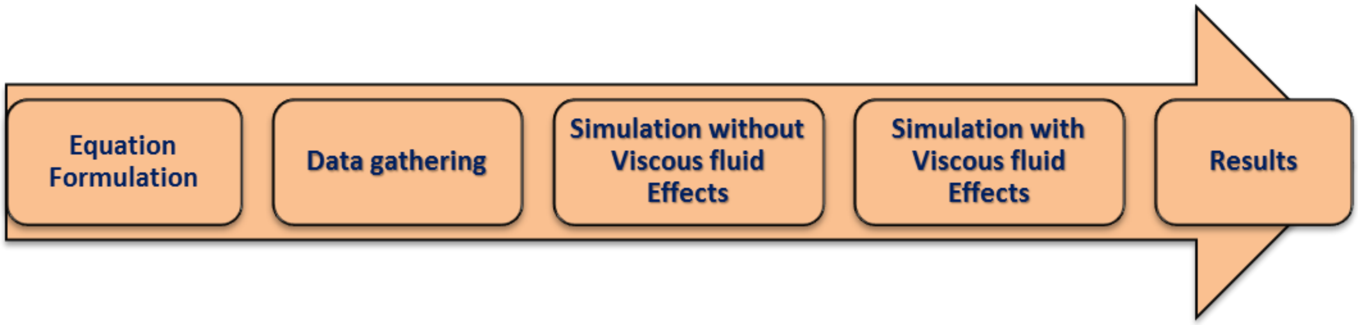

Figure 1. Methodology workflow.
Source: generated by authors

METHODOLOGY

The methods used in this study comprised: Equation formulation; Data gathering and case study; and Simulation. The block diagram depicted in Figure 1 summarizes the methodology of this study.

Equation formulation

The equations shall be presented for the following parameters: Effective tension, Hookeload, Side force/Normalization length, drag and torque.

Equation for tension

The equation for true tension change is given as Samuel (2010):

$$\Delta F_e = \sum\left[Lw_{air}\cos\theta \pm F_D + \Delta F_{area}\right] - F_{bottom} + WOB + F_{bs} \quad (1)$$

where ΔF_e - change in effective tension (lb/ft), w_{air} - weight per foot of the drill string in the air (lb/ft), L - length of drill string hanging below point (feet), θ - inclination (degrees), F_{bottom} - bottom pressure force, F_{bs} - buckling stability force, ΔF_{area} - the change in force due to a change in area, $F_d - \text{Drag force (lbs)}$, $WOB - \text{weight on bit}$, and $F_{bs} - \text{buckling stability force}$.

The effective tension is determined from the bottom of the hole upwards. It starts from the target depth (TD) and is computed upwards. If the string is on-bottom, that is, the bits are making contact with the formation rock, then the bit is in compression and the first effective tension to be computed is negative (that is, compression) and equal to the weight-on-bit. If the bit is off-bottom (that is, the bit is not making contact with the formation), then the tension at the bit is equal to zero.

The equation for normal force or side force

The equation for the normal force is given as (Ohia et al., 2021):

$$F_n = \sqrt{\left(F_e\Delta\phi\sin\,\theta_{avg}\right)^2 + \left(F_e\Delta\theta + W_b\sin\,\theta_{avg}\right)^2} \quad (2)$$

where F_e - the effective tension at the bottom of the section, lbs, W_b - buoyed weight of the string for the section, lbs, $\Delta\phi$ - the change in azimuth over the section length, rads, $\Delta\theta$ - change in inclination, degrees, θ_{avg} – average inclination, degrees.

The normal force is computed per section. Each hole section has its length. Usually, the hole is divided into sections of say 100 ft. The normal force is calculated per section of the hole and summed from the bottom of the hole to the surface. There is a greater degree of contact for curved and horizontal hole section and the normal force in these hole sections are expected to be significantly high.

Equation for frictional drag

The equation for frictional drag is given as (Mitchell and Miska, 2011):

$$F_{dl} = \mu F_n\left[\frac{V_t}{V_r}\right] \quad (3)$$

where $V_t - \text{trip speed, in/sec}$, $V_r - \text{resultant speed, in/s}$, and μ - friction factor.

The trip speed is the axial speed which acts vertically. This is because during the trip there is only an axial movement of the drill string in and out of the borehole. The resultant speed is the vector sum of the trip speed (axial speed) and the angular speed. The angular speed has a tangential component along the radial axis of the string. When there is a pure axial movement of the drill string, the angular speed is zero and the resultant speed would be equal to the trip or axial speed, otherwise, the trip speed is a fraction of the resultant speed.

The Drag in total length of string is given as:

$$F_d = \sum\nolimits_{i=1}^{n} F_d \quad (4)$$

where n is the number of sections in the borehole.

From Equation 4, the drag force is computed from the bottom of the hole to the surface of the hole. It is computed per section.

The equation for viscous drag

Due to viscous fluid effects, additional drag force is computed. The drag force caused by a viscous force called viscous drag is given as (Smith and Rasouli, 2012):

$$\Delta F_{vd} = \frac{\pi \Delta P_{loss}\left(D_h^2 - D_{bo}^2\right)D_{bo}}{4\left(D_h - D_{bo}\right)} \tag{5}$$

where ΔF_{vd} – additional drag force due to fluid drag, lbf, ΔP_{loss} – change in pressure loss, psi, D_h – Hole diameter, inch, and D_{bo} – Outer diameter of the pipe body, in.

The total drag section of drill string is the sum of the drag force computed in Equation 5 and the viscous drag force (F_{td}) given in Equation 6:

$$F_{td} = F_d + \Delta F_{vd} \tag{6}$$

Equation for frictional torque

The equation for torque is given as (Samuel, 2010):

$$\Delta T = \mu r F_n \left[\frac{V_a}{V_r}\right] \tag{7}$$

where V_a = angular speed, in/s, V_r = resultant speed, in/s, μ = friction coefficient.

$$T_2 = T_1 + \Delta T \tag{8}$$

where T_2 = is the torque at the upper string section, T_1 = Torque at the lower string section.

Also, the torque is computed from the bottom to the top. If the bit is on bottom and rotating, then the first torque to be computed at the bottom of the last string is equal to the torque-at-bit. The torque at the top of the string for that section of string is given by Equation 8. The torques for each string section is then summed up to the surface of the hole. The torque at the surface represents the torque required to be supplied at the surface by the top drive and rotary system to enable the drilling of the hole by crushing the formation rocks.

Equation for viscous torque

The equation for viscous torque is given as (Smith and Rasouli, 2012):

$$T_v = (1.355748) * \tau_t 2\pi l \left(\frac{D_p^2}{2}\right) \tag{9}$$

where T_v - viscous torque, ft-lbs, τ_t - stress, psi, l - pipe length, ft, and Dp - diameter of the pipe, inches.

The total toque is the sum of the frictional torque and the viscous torque:

$$T_t = T + T_v \tag{10}$$

where T_t is the total torque, T is the frictional torque, and T_v is the viscous torque.

Equations for Hookeload

The equation for Hookeload is given as (Mitchell and Miska, 2011):

$$HL = W_b \pm F_d - WOB \tag{11}$$

where W_b – Bouyed wight of string for that section, lbs, F_d – Drag force, and WOB – Weight on bit.

The total Hookeload is given as:

$$HL_t = \sum_{i=1}^{n} (W_b \pm F_d) - WOB \tag{12}$$

The Hookeload is the load recorded at the load measurement device at the surface. The Hooke load is the sum of the weight of the hook plus every weight attached to the hook reduced by the force in the fluid in which they are immersed. Hookeload is calculated from the surface to the bottom of the string. This is because weight acts downwards and increases as strings are added to the bottomhole assembly.

Case study

The case study used in this study is well BUX3 of reservoir MUK2 in the Niger Delta area of Nigeria. It is utilized for prediction of torque and drag for a drilled section of the well before further commencement of drilling. The well has cased and open-hole sections. The well depth is 11249.4 ft. The cased region is from surface to 9280 ft and cased with a casing - OD 9 5/8 in and ID 8.535 in with weight 53.5 ppf. The openhole section starts from 9280 to 11249.4 ft. Additional data for the well required for simulation are shown in Table 1.

From Table 1, the cased-hole friction factor is the friction factor of the wellbore cased with a casing of OD 9 5/8 in and ID 8.535 in with weight 53.5 ppf. The friction factor for this section of the well is 0.15. The friction factor for the open hole section (OHFF) is given as 0.2, 0.25, and 0.3. The open-hole section is the region of higher friction due to the possibilities of drill cuttings accumulation, tortuosities, doglegs, and even tools that might have fallen into the hole. All of these increase the friction factor in the open-hole section, thus it is ideal to investigate several friction factors in the open-hole section of the well. Fluid (mud) weight of 10.8 ppg is used. For cases 1 and 2, water base-mud is used. The drill string data is shown in Table 2.

From the drillstring data given in Table 2, the hole depth is 11,249.4 ft. Strings made of carbon steel (CS) are used throughout, the length, internal diameter (ID), outer diameter (OD), tool-joint parameters, weight, grade, material makeup, and a class of the strings are all shown in Table 2.

Other simulation parameters are: Tripping in at 60 ft/min and 0 rpm; Tripping out at 60 ft/min and 0 rpm; Rotating on-bottom (drilling) with 20 kips WOB and 5,000 ft-lbf torque at bit; and Sliding with 25 kips WOB and 2,400t-lbf torque at bit.

Simulation and model overview

Simulations were conducted for this study using Wellplan. Wellplan is a drilling software owned by Halliburton. It is the software of choice by drilling engineers for drillstring design and analyses of the

Table 1. Well data.

Parameter	Value
Cased-hole friction factor (CHFF)	0.15
Open hole friction factor (OHFF)	0.2 to 0.3
Fluid weight	10.8 ppg (water-based mud, oil-base mud for sensitivity)
block weight	50 kips

Source: Well BUX3 data accessed through company Rep of a company operating in the Niger Delta area

Table 2. Drillstring data.

Type	Length		Body		Stb/Tool joint			Linear weight		Grade	Material	Class
	Pipe	Total	OD	ID	OD	ID	Length	NOM	Actual			
	[ft]	[ft]	[in]	[in]	[in]	[in]	[in]	[lb/ft]	[lb/ft]	[psi]		
Pipe	6780.94	6780.9	5	4.28	6.312	2.75	28.9	19.5	19.5	135000	CS	P
Hevi-Wate DP	370.73	7151.7	5	3	6.5	3	20	49.7	49.7	55000	CS	
Hevi-Wate DP	1010.14	8161.8	3.5	2.25	4.75	2.313	20	23.2	23.2	55000	CS	
Jar	12.5	8174.3	4.75	2.06	-	-	20	37.5	37.5	110000	CS	
Hevi-Wate DP	367.29	8541.6	3.5	2.25	4.75	2.313	20	23.2	23.2	55000	CS	
Pipe	2577.76	11119.4	3.5	2.76	4.812	2.125	29.9	13.3	13.3	135000	CS	P
Hevi-Wate DP	30.51	11149.9	3.5	2.06	4.75	2.125	20	25	25	55000	CS	
MWD	61.35	11211.2	4.75	1.92	-	-	29.9	50	50	110000	SS	
Hevi-Wate DP	10.17	11221.4	3.5	2.25	4.75	2.188	20	25	25	55000	CS	
Stabilizer	1.15	11222.5	4.75	2.25	5.75	2.19	3.3	40	40	110000	CS	
PDM	26.25	11248.8	4.75	2	-	-	29.9	42.91	42.91	110000	CS	
BIT	0.66	11249.4	6	0	-	-		0	0	0	CS	

Source: Drillstring data of well BUX3 accessed through company Rep of a company operating in the Niger Delta area

well for pre-planning and post-operation programs. The Wellplan is one of the Halliburton's Engineer's DesktopTM (EDTTM) software. EDTTM is a comprehensive and integrated well construction software suite developed by Landmark and owned by Halliburton. It has the reputation of being the preferred standard software by many E&P companies. Wellplan as part of the EDTTM suit is a drilling and completion analysis software designed for use both for office and at rig site. It provides both well planning and operational analyses to improve well designs, prevent well engineering problems such as stuck pipe, BHA failures, buckling, lockup, casing wear, etc., and reduce operational cost of drilling and completion while maintaining efficiency and standards. The design process achieved in Wellpan helps operators in better decision making as regards the sizes of drillstring and tubulars that will safely and most economically be deployed to target depth. Wellplan has several modules which include Torque and Drag, Surge and Swab, Hydraulics, Cementing, Well Control, etc. The Torque and Drag module can be used to predict the measured weights and torques that can be expected while drilling or completing the well. Torque and drag simulation of this was done using soft string model since the wellbore path is not too complex and can be better approximated by soft string model. Two cases were considered in the simulation. Case 1 which is the base case comprised torque and drag simulations without the inclusion of the effects of viscous torque and drag. Case 2 is torque and drag simulation with the inclusion of viscous torque and drag. Figure 2 shows the string schematics starting from the surface to the depth of the well. The open-hole and cased-hole sections were also revealed with their respective sizes. The various types of strings at each depth were given with their respective sizes and weight.

RESULTS AND DISCUSSION

In each of these operations, necessary parameters for the evaluation of the impact of viscous fluid effects on torque and drag such as effective tension, Hookeload, buckling, torque, drag, viscous drag, and stretch from the simulations conducted are presented.

Case 1 (Base Case): Simulations results

The base case simulation constitutes the torque and drag simulation with the exclusion of the effects of the viscous fluid. Thus the effect of the dynamics of the fluid movement with the strings was neglected. This is a peculiar example of a traditional torque and drag simulation performed by many engineers. For each of the well operations the effective tension, Hookeload, Torque, Drag (both Pickup and slack-off drag), side force, and Buckling (both sinusoidal and Helical) are given for openhole friction factor (OHFF) of 0.2, 0.25, and 0.3 and cased-hole friction factor (CHFF) of 0.2.

Effective tension

The effective tension for tripping in, tripping out, drilling

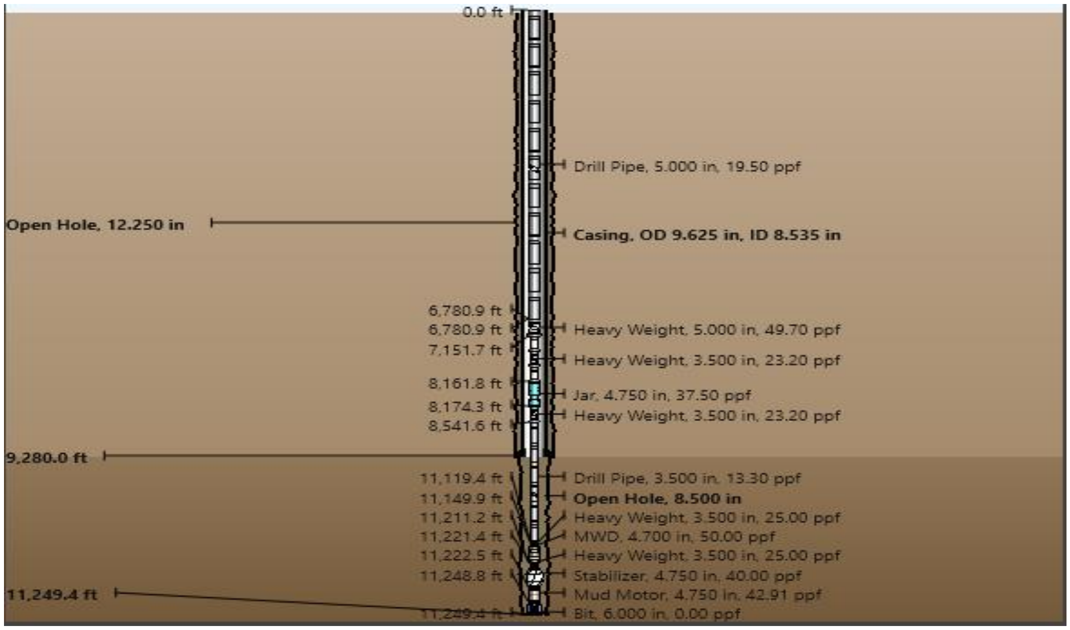

Figure 2. String Schematics of the Wellbore.
Source - String Schematics generated by Well plan software

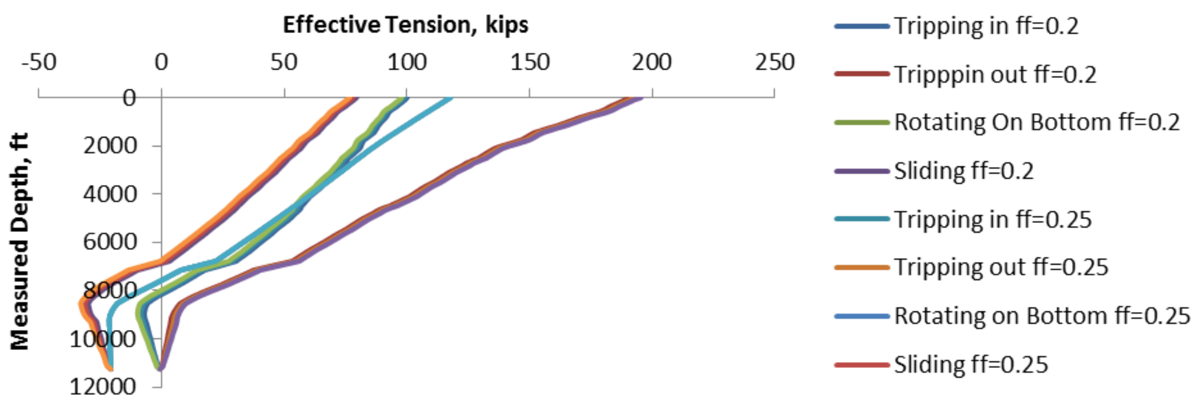

Figure 3. Effective tension plot for case 1 (without viscous fluid effect).
Source - Plot generated by Well plan software

sliding for OHFF of 0.2, 0.25, and 0.3 and CHFF of 0.2 for case 1 is as shown in Figure 3. Critical observation of Figure 3 reveals that different rates of accumulation of the effective tension for the different operations are encountered during drilling of the well. The maximum effective tension was observed for tripping out operation while the lowest effective tension was observed for sliding operations. Tripping out operation had the highest effective tension because of the orientation of the drag force relative to the direction of movement of the string. The drag force for tripping is positive and is added to the force acting at the lower string thereby increasing the effective force experienced while summing the forces in the string from bottom to surface. However, for tripping out, the orientation of the drag force is negative. Thus, the drag force is subtracted from the force calculated at the bottom string as the calculation proceeds from the bottomhole to the surface. In sliding, the weight-on-bit (WOB) adds a compressive load to the string that reduces the effective tension. Also, it can be observed that increasing the friction factor lowers the effective tension for tripping in and sliding operations while increasing the friction factor increases the effective tension for tripping out operations. The effective tension for drilling operations remained constant irrespective of the value of the friction factor and this is visible in Table

Table 3. Effective tension for case 1.

S/N	Operation	Open hole friction factors (OHFF)			Difference	Difference	Average difference
		0.2	0.25	0.3	[0.2-0.25]	[0.25-0.3]	
1	Tripping in, kips	100.2	99.1	97.9	1.1	1.2	1.15
2	Tripping out, kips	191.7	193.6	195.5	-1.9	-1.9	-1.9
3	Drilling, kips	117.8	117.8	117.8	0	0	0
4	Sliding, kips	79.6	78.1	76.7	1.5	1.4	1.45

Source - Table generated by Well plan software

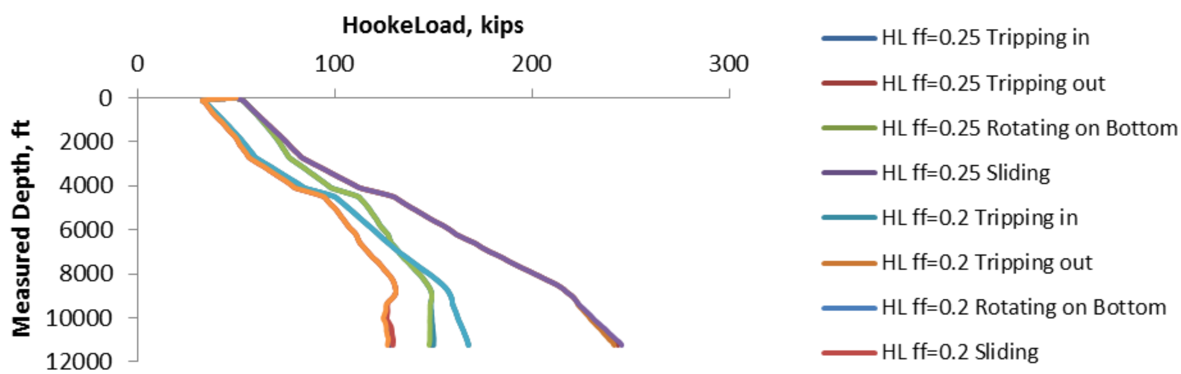

Figure 4. Hookeloads plot for case 1.
Source - Table generated by Well plan software

3. Increased effective tension as a result of the increase in friction factor is explained by extra drag force added to the tension during tripping out because of the direction of movement of the drillstring. When tripping out, the drill string is pulled out of the hole, frictional drag acts and in the opposite direction to string movement which acts downwards 'into' the hole and thus is positive because it is in the same direction with gravity. Thus, the effective tension is the summation of the tension in the string and the extra force due to drag pointing downwards. The reverse is the case during tripping in, here the string moves downwards while frictional drag points upwards. Since the frictional drag acts against gravity, it has a negative sign and is subtracted from the tension when computing the effective tension for tripping in. Sliding is similar to tripping except that a compressive load (slack-off weight) is added and there is slight rotation at specific points along the string especially when it is intended to kick off on a tangent. However, rotation is not from the surface as the case in drilling (rotating-on-bottom). Changes in the Friction factor have negligible effects on the effective tension when drilling, thus the effective tension is constant for the entire friction factor considered. This is because the rotation of the strings during drilling breaks friction and renders negligible the effect of friction relative to the effective tension. The effect of the friction factor is more profound in tripping out than in all the operations considered. Thus, for tripping out, an increase in friction of 0.05 led to an average increase in effective tension of 1.9 kips. For tripping in, an increase in friction factor of 0.05 led to an average decrease in effective tension of 1.15 kips. For sliding, an increase in friction factor of 0.05 led to an average decrease in effective tension of 1.45 kips.

Hookeload

Depicted in Figure 4 is the Hookeloads plot for case 1. Hookeload is measured from the top (surface) to bottom. The Hookeload is measured using special measuring equipment called the Martin Decker. The Hookeload indicated by the measuring tool is the net sum of the loads acting on the Hooke at that point. Figure 4 reveals that the Hookeload varies with the drilling operation. It can be seen that the Hookeload for tripping out is highest, while the Hookeload for sliding is lowest as depicted in Table 4. The Hookeload for tripping out is higher than that of drilling from the surface till 7000 ft depth afterward the Hookeload for drilling surpassed that of tripping out operation. The reason for the differences in loads for the different operations is due to the magnitude and direction of the frictional forces as well as drag force encountered in those operations. Figure 4 also reveals

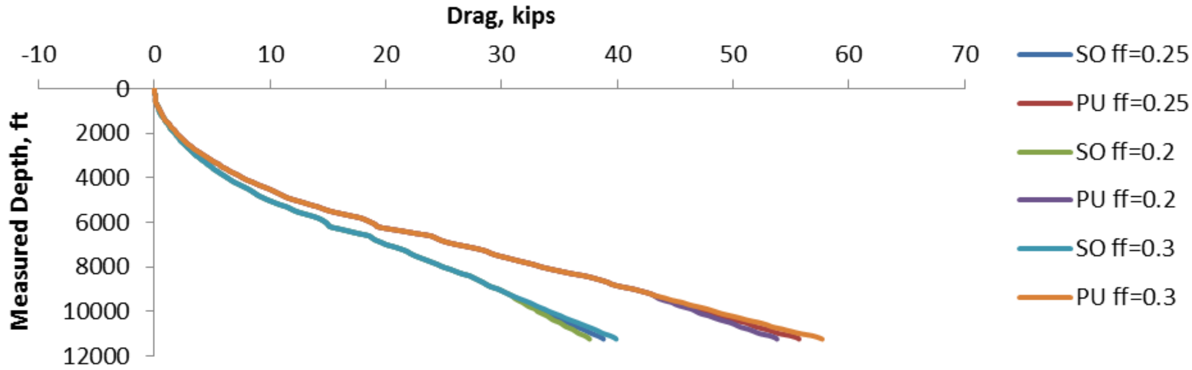

Figure 5. Drag plot for case 1.
Source - Plot generated by Well plan software

Table 4. Hookeload at the bottom (maximum hookload) for case 1.

S/N	Operation	Open hole friction factors (OHFF)			Difference	Difference	Average difference
		0.2	0.25	0.3	[0.2-0.25]	[0.25-0.3]	
1	Tripping in, kips	150.2	149.1	147.9	1.1	1.2	1.15
2	Tripping out, kips	241.7	243.6	245.5	-1.9	-1.9	-1.9
3	Drilling, kips	167.8	167.8	167.8	0	0	0
4	Sliding, kips	129.6	128.1	126.7	1.5	1.4	1.45

Source - Table generated by Well plan software

the bottom Hookeloads for all the operations considered at various friction factors. As is the case with effective tension, increasing the friction factor reduces the Hookeload for tripping in, and sliding operations and increases the Hookeload for tripping out operations. However, the Hookeload for drilling operation remains constant irrespective of the increase in OHFF. The reason for this is the same as the reason given earlier for the effect of friction factors on effective tension.

Drag

The frictional drag result for case 1 is given in this section. Both pickup drag and slack-off drag are considered. Pickup drag is encountered when the string is pulled out of hole while slack-off drag is encountered when running-into-the hole and adding strings to the BHA. Figure 5 shows the drag force for case 1. It can be observed that the pickup drag is higher than the slack-off drag. This is consistent with literature and the equations developed in section two. The effect of gravity creates additional drag when pulling out of hole than when running into the hole. Drag is not experienced for rotational movement because the axial component of the velocity is zero. The Pickup and slack off drag for the entire drillstring at bottom of the hole measured the surface is shown in Table 5. From Table 5, it can be observed that the pickup drag is higher than the slack-off drag for all the openhole friction factors considered. Furthermore, analyses of the effects of friction factor on drag force reveal that drag force increases with increase in friction factor. This is in agreement with the equation developed by Johanscisk et al (1984). The drag force is a product of the friction factor and the normal/side force between the drillstring and the wellbore wall. The magnitude of the difference in drag due to variation in friction factor is more profound for pickup than for slack-off. As can be seen in Table 5, friction factor increase of 0.05 led to an average increase in drag of 1.95 kips for pickup drag and 1.15 kips for slack-off drag, respectively.

Torque

Torque is only experienced for drilling operation. The torque for tripping and sliding operations is zero. The torque for drilling operation for case 1 is as shown in Figure 6. As can be observed from Figure 6, the torque begins to accumulate from the bit (bottom of the hole) to the surface of the hole. With bit-torque of 5000 ft-lbs, the surface torque to be applied by the top drive at the surface must be able to compensate for all the torque losses to be encountered in the borehole from the

Table 5. Bottom (Maximum) drag for case 1.

S/N	Operation	Open hole friction factors (OHFF)			Difference 0.25	Difference	Average difference
		0.2	0.25	0.3	0.2-0.25	0.25-0.3	
1	Slack-off, kips	37.6	38.8	39.9	-1.2	-1.1	-1.15
2	Pickup, kips	53.8	55.7	57.7	-1.9	-2	-1.95

Source - Table generated by Well plan software

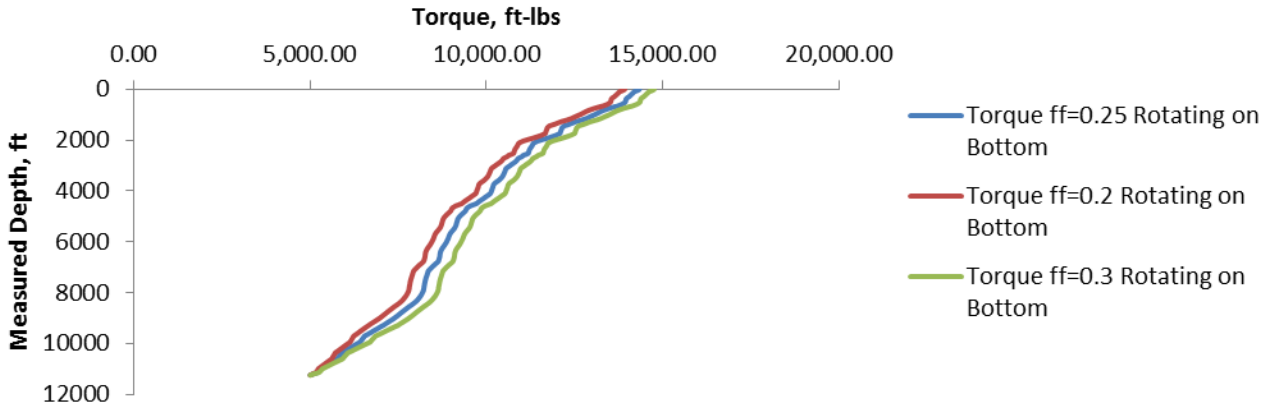

Figure 6. Drilling torque plot with no viscous fluid effects.
Source - Plot generated by Well plan software

necessary to turn the bit and achieve the crushing of the underlying formation rocks. The surface torque required to achieve 5000 ft-lbs torque on bit for OHFF of 0.2, 0.25 and 0.3 are 13,925.6, 14342.3 and 14,759 ft-lbs, respectively. It can be seen that the higher the friction factor, the higher the surface torque required for equivalent torque at the bit. This is because the higher the friction factors the more torques are lost in the wellbore. Worthy of note, is that the drillstring needs more force to overcome the larger frictional resistance created. An average increase in surface torque requirement of 416.7 ft-lbs is realized for 0.05 increases in OHFF used.

Side force/Normalization length

Figure 7 depicts the side force/normalization length for case 1. From Figure 7, the side force increase in the following order: tripping out, drilling (rotating on bottom), tripping in, and sliding. Thus, the side force for tripping out is highest while the side force for sliding is lowest. The variations of inside force for the various operations explain the differences in effective tension accumulation wherein side force is added for upward movement of the drillstring and subtracted from downward movement of the drillstring. Side force is dependent on friction factor and varies with well operations. Consequently, the side force/normalization lengths for tripping in decreases with an increase in the value of the openhole friction factor (OHFF) while the side force/normalization length for tripping out increases with increase in friction factor. For drilling operation, the side force is independent of the friction factor while for sliding operation, the side force decreases with an increase in friction factor.

Case 2: Simulation with viscous fluid effects

Case 2 considers the simulation of torque and drag for a downhole string with the inclusion of viscous fluid effects. Afterward, a comparison was made between the result from case 2 and the result from case 1to determine the impact of the fluid viscous forces when added and the consequence of neglecting fluid viscous force on the torque and drag result during the planning and operational phases in well operations.

Effective tension for tripping in

The effective tensions for torque and drag simulation with and without viscous fluid effects are as shown in Figure 8. Figure 8 reveals that the viscous force of the fluid decreases the effective tension for tripping-in operation. Similarly, from Table 6, it can be observed that the inclusion of viscous fluid effect to the torque and drag

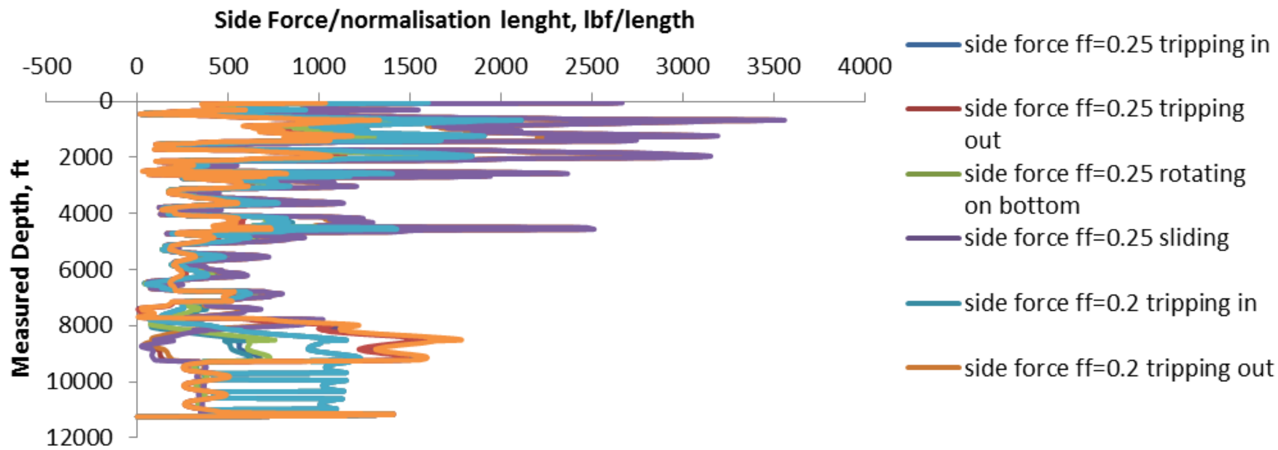

Figure 7. Side force/normalization length for case 1.
Source - Plot generated by Well plan software

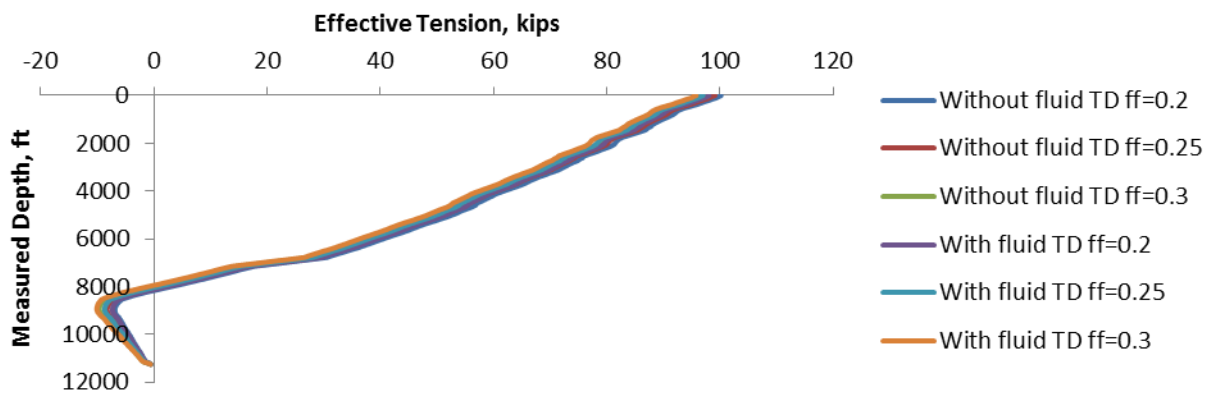

Figure 8. Tripping in effective tension plot for simulation with and without viscous fluid effects.
Source: Plot generated by Well plan software

Table 6. Maximum tripping in effective tension results for simulation with and without viscous fluid effects.

Condition	Open Hole Friction Factors (OHFF)		
	0.2	**0.25**	**0.3**
Without viscous fluid effect, kips	100.2	99.1	97.9
With viscous fluid effect, kips	98.1	97	95.8
Difference, kips	2.1	2.1	2.1

Source: Table generated by Well plan software

simulation decreases the effective tension by 2.1 kips for tripping-in operation for OHFF of 0.2, 0.25 and 0.3, and the inclusion also decreases the maximum effective tension for tripping in operation; this is because the additional drag calculated due to viscous fluid effects increased the total drag in the system. Since drag force is always subtracted for tripping in due to the fact that trip is in the same direction with the load (gravity which points downwards), the maximum effective tension would decrease as expected. While high effective tension value indicates safe operation without risk of bucking occurrence, the reduction of the effective tension beyond some critical value may increase the chances of the drill string being in compression and prone to buckling. While

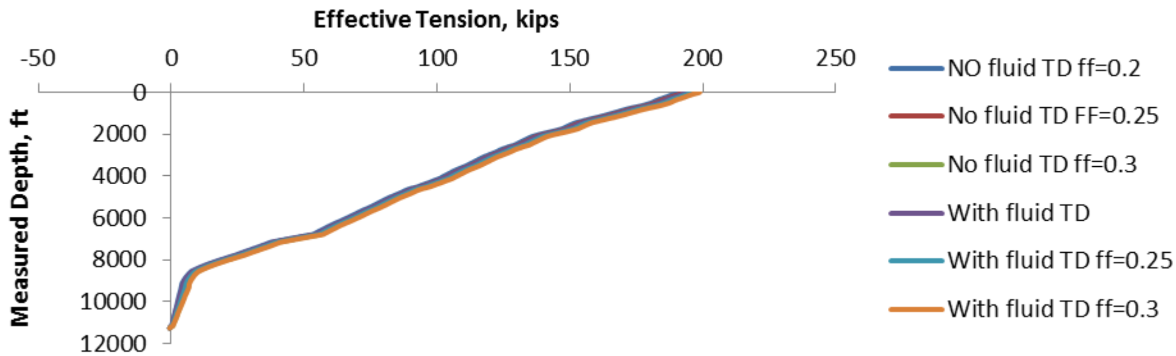

Figure 9. Tripping out effective tension plot for simulation with and without viscous fluid effects.
Source: Plot generated by Well plan software

Table 7. Maximum tripping out effective tension for simulation with and without viscous fluid effects.

Condition	Open hole friction factors (OHFF)		
	0.2	0.25	0.3
Without viscous fluid effect, kips	191.7	193.6	195.5
With viscous fluid effect, kips	194.9	196.8	198.8
Difference, kips	+3.2	+3.2	+3.3

Source: Table generated by Well plan software

tripping in, care must be taken to ensure that the viscous fluid effect is considered in the simulation to avoid erroneous results that may compromise the well when operation is initiated.

Effective tension for tripping out

Tripping out effective tension for case 2 is given in this section; the result of the tripping out effective tension for simulation with viscous fluid effect is compared with the result for case 1, that is, without the inclusion of viscous fluid effects. Critical analyses of Figure 9 reveal that the tripping out effective tension for torque and drag simulation with viscous fluid effect is higher than that for simulation without viscous fluid effects, although the margin is not profound. From the tripping out results for simulation with and without viscous fluid effect given in Table 7, it can be observed that the inclusion of viscous fluid effects to the torque and drag simulation increased the effective tension by 3.2 kips for tripping-out operation for all friction factors considered (OHFF of 0.2, 0.25 and 0.3). Thus, the inclusion of the viscous effects of the fluid to torque and drag simulation increases the maximum effective tension for tripping-out operation; this is because the additional drag calculated due to viscous effects of the fluid increased the total drag in the system. Since drag force is always added to the effective tension for tripping out due to the fact that the tripping out is in reversed direction with the load (gravity force which points downwards), the maximum effective tension would increase as expected.

Effective tension for drilling

The effective tension for case 2 is presented in Figure 10 with comparison made with case 1. The effective tension for drilling is the same for simulation with and without viscous fluid effects. The difference in effective tension due to the inclusion of viscous fluid effects is zero for drilling. This is because during drilling, no additional drag is experienced since there is no axial movement of the drill string. Thus, viscous drag is zero for drilling operation.

From Figure 10, it can be observed that there is a single line for all the cases (with and without viscous fluid effects). This is because irrespective of the friction factor or simulation with or without viscous fluid effects, the effective tension during drilling (rotating-on-bottom) remains the same.

Effective tension for sliding

The effective tension for sliding operation for simulation with and without viscous fluid effects is as shown in Figure 11. The effective tension for Sliding is the same for simulation with and without viscous fluid effects. The

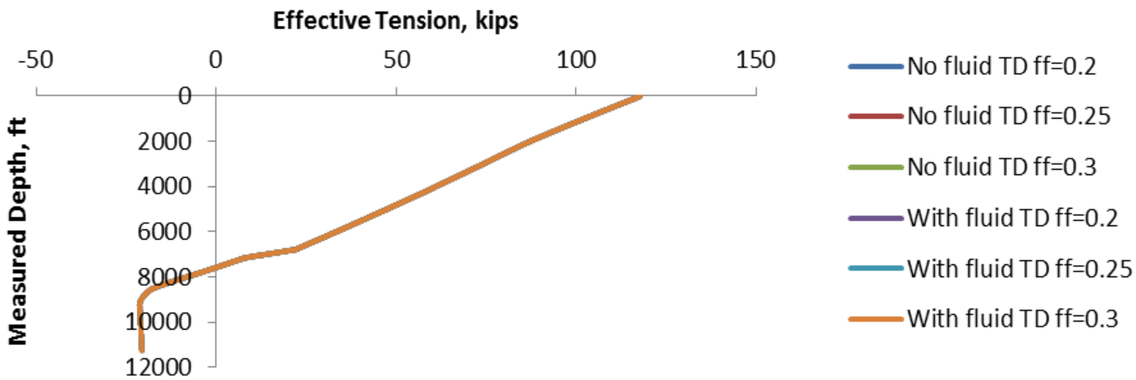

Figure 10. Drilling effective tension plot for simulation with and without viscous fluid effects.
Source: Plot generated by Well plan software

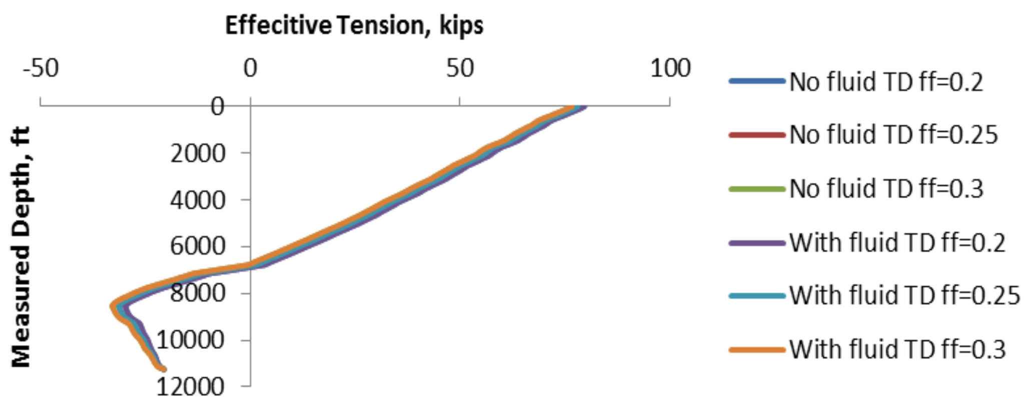

Figure 11. Sliding effective tension plot for simulation with and without viscous fluid effects.
Source: Plot generated by Well plan software

difference in effective tension due to the inclusion of viscous fluid effect is zero for sliding. Viscous fluid effect did not affect the effective tension for sliding. This is because during sliding, no additional drag is experienced since there is no axial movement of the drillstring. Thus, viscous drag is zero for sliding operation. However, sliding effective tension is dependent on the friction factor of the hole section.

Hookeloads

The maximum Hookeload (that is, Hookeload at the bottom) for simulation with and without viscous fluid effects for all operations and friction factors are shown in Table 8. From Table 8, it can be observed that the inclusion of viscous fluid effects on the torque and drag simulation decreased the Hookeload for tripping-in operation by 2.1 kips and increased the Hookeload for tripping-out by 3.2 kips for 0.2 and 0.25 OHFF and 3.3 kips for OHFF of 0.3. For drilling and sliding operations, the difference in Hookeload is zero. This means that the inclusion of viscous fluid effects did not have any influence on the Hookeloads for drilling and sliding operations.

Torque

The maximum torque for simulation with and without viscous fluid effects for all operations and friction factors are shown in Table 9. Torque is only important for drilling operation because there is a rotation of the entire drillstring. From Table 9, it can be seen that maximum torque for drilling operation increases due to the inclusion of viscous fluid effects in the torque and drag during simulation. There was a torque increase of 310.4 ft-lbs for 0.2OHFF and 310.3 ft-lbs for 0.25 OHFF and 0.3 OHFF, respectively. The maximum torque for sliding operation for simulation without viscous fluid effects is the same as that for simulation with viscous fluid effects, so the difference in the result is zero. It can be noted that the

Table 8. Maximum Hookeload results for simulation with and without viscous fluid effects.

Operations	Friction factors	Hookeloads		Differences
		Without viscous fluid effect, kips	With viscous fluid effect, kips	
Tripping In	0.2	150.2	148.1	-2.1
	0.25	149.1	147	-2.1
	0.3	147.9	145.8	-2.1
Tripping Out	0.2	241.7	244.9	3.2
	0.25	243.6	246.8	3.2
	0.3	245.5	248.8	3.3
Drilling	0.2	167.8	167.8	0
	0.25	167.8	167.8	0
	0.3	167.8	167.8	0
Sliding	0.2	129.6	129.6	0
	0.25	128.1	128.1	0
	0.3	126.7	126.7	0

Source: Table generated by Wellplan software

Table 9. Maximum torque for simulation with and without viscous fluid effects.

Operations	Friction factors	Maximum torque, ft-lbs		Differences, ft-lbs
		Without Viscous fluid Effect	With Viscous fluid Effect	
Tripping In	0.2	0	0	0
	0.25	0	0	0
	0.3	0	0	0
Tripping Out	0.2	0	0	0
	0.25	0	0	0
	0.3	0	0	0
Drilling	0.2	13,925.60	14,236.00	310.40
	0.25	14,342.30	14,652.60	310.30
	0.3	14,759.00	15,069.30	310.30
Sliding	0.2	2400	2400	0
	0.25	2400	2400	0
	0.3	2400	2400	0

Source: Table generated by Wellplan software

torque result for tripping in and out is zero as the drillstring is not subjected to rotational movement.

Drag

Results for pickup and slack-off drag simulations with and without the effects of fluid viscous forces are presented Table 10. From Table 10, it can be observed that the inclusion of fluid viscous force in the torque and drag simulation increased the slack-off drag and the pickup drag by 2.1 and 3.3 kips, respectively. The drag force given in the table is the total calculated drag which is the sum of the frictional drag and the viscous drag. Due to the inclusion of the viscous fluid effects in the torque and drag simulation, the total drag increased as expected and predicted.

Side force/Normalization length

The side force/normalization length for simulation with

Table 10. Maximum drag results for simulation with and without viscous fluid effects.

Friction factors	Drag				Differences, kips	
	Without Viscous fluid effect, kips		With Viscous fluid effect, kips			
	Slack-off	Pickup	Slack-off	Pickup	Slack-off	Pickup
0.2	37.6	53.8	39.7	57.1	2.1	3.3
0.25	38.8	55.7	40.9	59	2.1	3.3
0.3	39.9	57.7	42	61	2.1	3.3

Source: Table generated by Wellplan software

Table 11. bottom Side force/Normalization Length results for simulation with and without viscous fluid effects.

Operations	Friction factors	Side force/Normalization length		Differences
		Without viscous fluid effect, kips	With viscous fluid effect, kips	
	0.2	647	634	-13
Tripping In, lbf/length	0.25	640	626	-14
	0.3	632	618	-14
	0.2	1250	1271	21
Tripping Out, lbf/length	0.25	1262	1284	22
	0.3	1275	1297	22
	0.2	511	511	0
Drilling, lbf/length	0.25	502	502	0
	0.3	492	492	0
	0.2	763	763	0
Sliding, lbf/length	0.25	763	763	0
	0.3	763	763	0

Source: Table generated by Wellplan software

and without viscous fluid effects is shown in Table 11. From Table 11, it can be observed that torque and drag simulation with viscous fluid effects decreased the bottom side force/Normalization length by an average value of 13.67 lbs/length for tripping in operation while tripping out operation increased by an average value of 21.67 lbf/length. The difference in the side force/normalization length due to viscous fluid effects was zero for drilling (rotating-on-bottom) and sliding operations. Note that for drilling operation, the increase in friction factor did not have any impact on the side force/normalization length. This was because the rotation of the drillstring helped to break off friction.

Conclusion

Viscous fluid effects on torque and drag modeling have been comprehensively evaluated. Simulation has been carried out taking into account and without taking into account viscous fluid effects. From the conducted study, the following conclusions are drawn:

(1) Maximum effective tension and maximum Hookeload decreased by approximately 2.1 kips for tripping-in operation and by approximately 3.3 kips for tripping-out operation, sliding and drilling operations remained unchanged due to inclusion of viscous effects of fluid flow
(2) Maximum drag decreased by 2.1 kips for tripping-in (slack-off drag) and by 3.3 kips for tripping-out (Pickup drag) operations. Since there was no axial movement of the drillstring, the drag remained unchanged during drilling and sliding operations.
(3) Maximum torque increased by approximately 310.3 ft-lbs during drilling, but the torque for sliding, tripping-out, and tripping-in remained unchanged.
(4) The side force/normalization length decreased by approximately 14 lbs/length during tripping-in and 22 lbs/length during tripping-out operations while the side force/normalization length for drilling and sliding

remained unchanged.

(5) Thus, viscous effects of fluid flow have minimal impact on the torque and drag and downhole problems are not expected to occur by neglecting the inclusion of viscous effect of fluid flow during torque and drag simulations and modeling. However, adequate care must be observed in high buckling-risk areas where small variation in torque and drag simulation results could initiate buckling regime or transition from one buckling mode to another such as from sinusoidal to helical or even to lockup.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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