A Review of Effects of Oil-Well Parameters in Estimating Annular Pressure Losses

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ABSTRACT:

Good hydraulics plays a vital role in the drilling of oil wells. Important aspects of drilling hydraulics include prediction of downhole circulating pressures and equivalent circulation densities. Such predictions become more essential as drilling operations complicated. Horizontal, extended reach, slim hole and deep offshore drilling pose extra difficulties for safe drilling operations because of the narrower window between formation pore/fracture pressures. Demand for excellent predictions of annular frictional pressure losses and equivalent circulation densities become ever greater. Unfortunately current pressure loss predictions are not accurate and reliable. Many wellbore parameters that are pertinent downhole are ignored in these relations which hamper excellent pressure loss estimations. The main purpose of this paper is to shed the light on the effect of these parameters on annular pressure loss and equivalent circulation densities during drilling with incompressible drilling fluids.

Keywords: Drilling Fluid, Annular Pressure Loss, Tool Joint, Drillpipe Eccentricity, Pipe Rotation, Cuttings Accumulations, Rheology.

1. Introduction

Drilling fluids are generally aimed at many functions during drilling an oil-well. The most common functions are to clean the wellbore bottom from drill-cuttings, removing these cuttings out of wellbore, ensuring the stability of the borehole walls, maintaining bottom hole pressure at higher values than formation pressures, maintaining cuttings in a state of suspension during circulation breaks, cleaning teeth of drilling bits, lubricating drill-bit bearings, supplying energy to several bottom hole assemblies during directional drilling, ensuring high rate of penetrations for cost effective drilling operations. Most of these functions are optimized through hydraulic optimization during well planning.

Annular frictional pressure loss is, however, a complicated phenomenon because it is affected by many factors such as flow rate, flow regime, drilling fluid density/rheology, wellbore geometry (tool joint, drillpipe eccentricity, ratio of drillpipe outside diameter to wellbore diameter), cuttings content, drillpipe roughness, drillpipe rotation, high temperature and high pressure effect on rheology. However, the majority of these effects are not considered in conventional pressure loss calculations and are believed to be the principle reason for imperfect predictions of such calculation methods. These effects are the possible errors of why the current correlations do not give excellent predictions of standpipe pressure, SPP, or equivalent circulation density, ECD.

In conventional drilling, annular pressure loss rarely exceeds 15% of the pump pressure and large errors in calculating annular pressure loss in conventional well occasionally have serious consequences [1]. However, in slim boreholes or in wells with long reach, circulation of the drilling fluid can cause significant frictional pressure drop in the annulus. In a slim hole well, up to 90% of the pump pressure is due to pressure loss in the annulus [1, 2, 3]. This results in an increase in BHP and ECD which may exceed the formation fracture pressure and loss of circulation and creating a potentially dangerous situation due to the resulting loss of hydrostatic head. Hence, accurate predictions of annular pressure loss leads to excellent estimations of the BHP and ECD that prevents kicks and circulations losses.

Rheological models are equations that relate shear stress with shear rate. Drilling fluid models and their derived parameters are used for fluid hydraulics calculations. However, there are issues related to selection of appropriate models, how they are matched to measured data, and how they are used for pressure-loss calculations [4]. The assumptions made, considering the application of these models to represent the flow of a drilling fluid in a drilling well, are: (1) the drilling fluid is incompressible; (2) the rheology of the drilling fluid is constant versus pressure and temperature. Based on these models, expressions to calculate average velocity, Reynolds number and pressure drops, both in circular and annular sections, has been developed. Those expressions have been obtained solving simultaneously the equations of momentum and mass conservation [5]. The assumptions made in developing such expressions are: (1) steady state flow; (2) axial flow; (3) concentric annular and circular sections; (4) annular sections has been considered as a rectangular slot; (5) laminar and turbulent flow are only considered. In reality, none of these assumptions are completely valid, and the resulting system of equations will not perfectly describe the flow of drilling fluids. Recently, several research has been conducted toward removing these assumptions but the additional computational complexity required to remove the assumptions above has not been justified in practice.

Several studies investigated the effect of tool joint restrictions, drillpipe rotation, drillpipe eccentricity and cuttings beds accumulations at the low side of the well on annular frictional pressure losses and equivalent circulation densities as well as the effect of high temperature and pressure on drilling fluid properties. Therefore, a critical review on the effect of such factors on frictional pressure loss of drilling fluid is a mandatory endeavour before incorporating such effects in applied mathematical modelling. In this paper in-depth review of these effects are presented and discussed.

2. Effect of Tool Joint Restrictions

The tool joint is a necessary part to extend the drillpipe. These components are fabricated separately from the pipe body and welded onto the pipe at a manufacturing facility. The tool joint provide high-strength, high pressure threaded connections that are sufficiently robust to survive the heavy duty and extreme loads at the rig. Tool joints have smaller inside diameters than the drillpipe body and larger outside diameter.

The presence of tool joints causes restriction against flow in pipes with contraction and expansion of the fluid as it enters and exits the tool joint [6, 7]. The pressure loss caused by entry into the tool joint is small compared with the exit losses [8]. On the other hand, tool joints have larger outside diameter that changes the annulus geometry between the drillpipe and the casing/hole resulting in strong turbulence and fluid acceleration that generates additional viscous dissipations and pressure losses [9, 8]. This effect is assumed minimal because fluid velocity is so low in the annulus [9].

Jeong and Shah [7] performed tool joint tests with water and polymeric fluids to investigate the effect of tool joint on the annular friction pressure. It was found that the effect of the tool joint on the annular friction pressure was significant. This effect resulted in 29% increase in friction pressure at 5 bbl/min and up to 75% increase at 8.5 bbl/min for the flow of fluid in 5 1/2-in - 2 1/2-in annulus (Figure 1). Smaller pressure losses were reported by Hemphill et al. [10] where the results show that the tool-joint can increase the annular loss up to 12%.

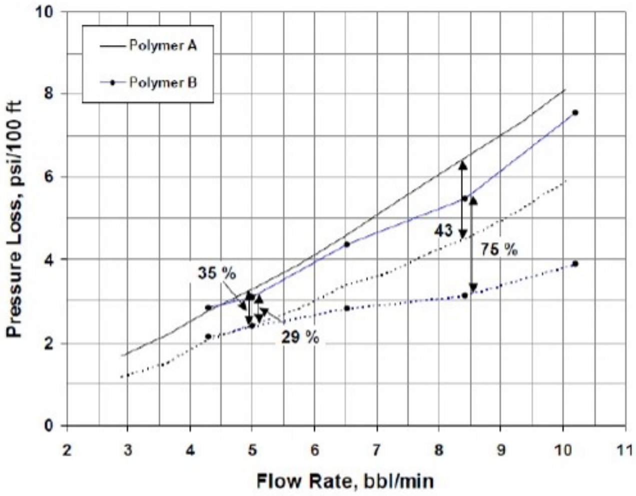

Figure 1: Effect of Tool-Joint on frictional pressure loss [7]

Similarly, Enfis [11] conducted theoretical and experimental work to investigate the hydraulic effects of both rotating and non-rotating tool-joints on annular pressure losses. Annular flow experiments were carried out for different flow rate, fluid rheology, annular geometry, rotation speed of the inner pipe. Experimental results show substantial increase in pressure loss gradient around the tool-joints. The pressure loss increases strongly depending on fluid properties and flow geometries. The overall effect of tool-joint on the annular pressure ranged from 11% to 31%. The contraction and expansion parts of the tool-joint create strong flow disturbances and turbulent flow conditions that cause the pressure loss to increase. The fluid velocity in the narrow annulus of a tool-joint is high and results in increased friction pressure loss. Therefore, ignoring the tool joint effect causes considerable error in pressure loss calculations [6-9, 11-12]

3. Effect of Drillstring Rotation

Pipe rotation is mandatory to rotary drilling as it is responsible for many functions. Generally, drilling community believes that pipe rotation helps hole cleaning particularly in horizontal and highly deviated wellbores [13-15]. However, there has been a lack of studies to describe effect of pipe rotation in frictional pressure loss. Lately, it has been shown that the drillstring rotation affects the pressure loss significantly, particularly, for slim hole, extended reach, horizontal and highly deviated drilling applications. The influence of drillpipe rotation can be substantially depending on rotation speed, fluid properties, flow regimes, diameter ratio and eccentricity. Drillpipe rotation even for fairly small rotation rates, creates unstable flow and promotes transition from laminar to turbulent flow [9, 12]. Saasen [12] argues that turbulences may take place because of pipe rotation, even without axial flow and the transversal motion of the drillstring, creates vortices that destabilize the flow. Consequently, the annular frictional pressure loss is increased even though the drilling fluid becomes thinner because of added shear rate. However, mixed effect of drill pipe rotation has been reported by several studies.

McCann et al. [1] conducted flow experiments in narrow annuli to provide data on the effects of pipe rotation, flow regime, fluid properties and eccentricity on pressure loss in narrow annuli. They concluded that the pressure loss for Power Law (PL) fluids increases with increasing pipe rotation in turbulent flow and decreases with increasing pipe rotation in laminar flow. In line with these observations, other researchers reported reduction of annular pressure loss with the increase in the rotation speed with PL fluids at low flow rates, however, at high flow rates, annular pressure losses increased with the increase in pipe rotation [16-17]. However, Hansen and Sterri [18] results show that for laminar flows when Taylor number is greater than the critical Taylor number (i.e. Taylor number of a flow at the onset of Taylor vortices), the friction pressure loss increases with rotation speed. Otherwise, the pressure loss decreases with increasing pipe rotation speed. Opposite observations has been reported by Ozbayoglu and Sorgun [19-20] particularly at low Reynolds number, annular pressure loss increased as the rotation increases. However, as flow rate increases, the effect of pipe rotation on the annular pressure loss diminishes and eventually becomes negligible.

Based on numerical simulations, Ooms et al. [21] pointed out, that in the case of a concentric drillpipe, rotation does not influence the axial pressure drop for a stationary, fully developed laminar flow of a Newtonian liquid. However, when the drillpipe is placed in an eccentric position, the axial pressure drop increases with increasing rotation speed. These results have been reproduced later on by Wei et al. [22] for non-Newtonian fluids using the full scale Tulsa university drilling research project (TUDRP) flow loop. Wei et al. reported an increase in annular frictional pressure loss with increasing inner pipe rotation, particularly for tests without centralizers. This was in contrary to the result of their theoretical model. This effect was attributed to the drillpipe lateral motion during rotation which creates lateral flow in the annulus and hence the laminar flow is disrupted. Flow tests were run with centralizers to ensure axial rotation of the drillpipe without lateral motion. The results show a reduction in annular frictional pressure loss with increasing pipe rotation. Shear thinning effect and reduction in apparent viscosity of PL fluids are considered the main reason behind this effect. This effect was not dominant in flow tests without centralizers since the shear thinning effect induced by pipe rotation is smaller than the effect of pipe lateral motion. The effect of drillpipe rotation on annular pressure loss is affected by mud properties, flow rate, wellbore geometry, and drillpipe rotary speed.

The increase in annular pressure loss is more pronounced in thin mud with high pipe rotary speed in an eccentric pipe configuration. The TUDRP flow loop is designed to approximate real drilling situation with 41/2-in drillpipe and 8-in transparent acrylic outer pipe with a total length of 85 ft. The tested polymeric fluids have follow the PL model with "n" values range from 0.4228 to 0.7582 and "K" values range from 0.007 to 0.039 $lb.s^n/ft^2$. Drillpipe rotary speeds range from 0 to 120 revolution per minute (rpm). Eccentricities range from 0 to 0.5 and flow rates range from 150 to 350 gallon per minute (gpm). Laminar flow is maintained in all tests.

A number of field studies have been undertaken for the purpose of evaluating the effect of pipe rotation on annular friction pressure losses. In separate studies conducted at drilling sites in the North Sea [1, 23-24], the effects of drillpipe rotation were studied while circulating and rotating at various rates inside casing (without cuttings), and results were analysed in terms of changes in ECD as calculated from downhole pressure tool data. In general, results show an increase in pressure losses with increasing the rotary speed. Pando #1 slim hole well was drilled by Mobil in the Madre de Dios region of Bolivia. Hydraulic testing of at this well confirmed that standpipe pressure is sensitive to annular geometry, pipe rotation, and fluid properties [1]. Figure 2 shows that standpipe pressure in Pando #1 increased significantly with increase in pipe rotations.

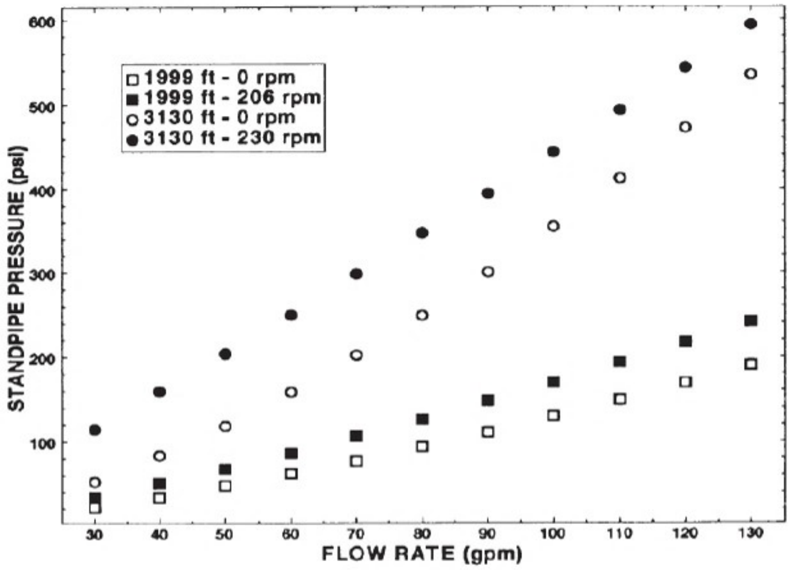

Figure 2: Effect of pipe rotation on standpipe pressure, Pando #1 slim hole well [1]

Wei et al. [20] analysed pressure while drilling data from three extended reach wells drilled in Europe. The annular pressure loss increased by 66% to 147% due to pipe rotation. Furthermore, the effect of drillpipe rotation on increasing ECD is greater in cases when the axial flow is reduced and this effect decreases as the axial flow increases. This effect is more pronounced as the gaps become narrower (increasing D_p/D_h), and can be quite dramatic in slim hole drilling operations [2, 8, 23-30].

Moreover, the effect of drillpipe rotation on annular pressure and ECD has been dealt with theoretically. Computer simulations indicate that the shear-thinning effect induced by pipe rotation on PL fluids results in reduction of annular frictional pressure loss in both concentric and eccentric pipe configurations. The pressure reduction is most significant for concentric pipe configuration [20]. However, Hemphill et al. [27] noticed that the effect of increasing drillpipe rotation speed at a constant annular velocity produced a non-linear increase in ECD. The ratio of the outer diameter of the drillpipe to the internal diameter of the hole or casing (D_p/D_h) was found to be a meaningful modelling parameter instead of eccentricity. This is because, while drilling, drillpipe eccentricity is not known with any level of confidence at any one time. Calculation errors obviously result if the incorrect level of drillpipe eccentricity is used, as this can change the local velocity distribution in the annulus. A potential solution to this problem is to gauge all calculations based on diameter ratios (D_p/D_h) [11, 15, 29-32].

4. Effect of Drillstring Eccentricity

The annular frictional pressure losses of vertical or near vertical well sections differ from the highly inclined and horizontal wellbores. This is because of natural tendency of the drillstring to lay down on the low side of the wellbore due to gravity. This configuration forms eccentric annulus and generally referred to as drillstring eccentricity. Hence, the assumption of a concentric annulus is often not realistic, particularly, for horizontal and highly deviated wellbores. Moreover, the drillstring is elastic and has the possibility to wobble in the hole during rotation. It can be positioned differently in the wellbore cross section at different depths, depending on inclination and hook load [33]. The pressure losses depend on the annulus eccentricity. Moving the drillstring to the wall of the wellbore generates a wider flow channel in part of the annulus which change the direction and acceleration of the annular flow and reduces the frictional pressure losses significantly (Figure 3) [1, 9, 12].

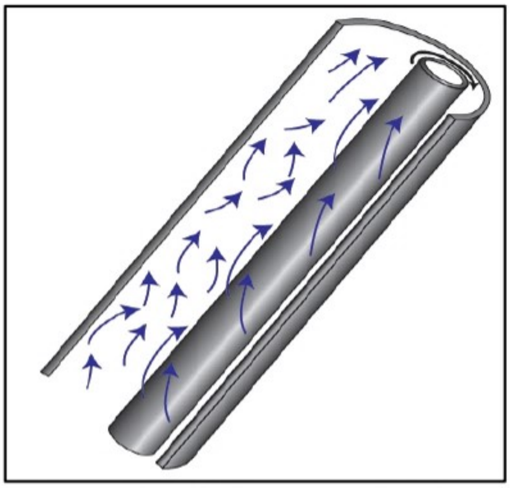

Figure (3): Drillstring eccentricity [33]

Several experimental studies on hydraulics of eccentric annuli have been conducted [3, 16–18, 34-37]. Reported results show decrease in the pressure loss as eccentricity increases. Pressure losses in the range of 18 to 40% less than that of the concentric annulus were reported [36]. Eccentricity can reduce the annular pressure losses significantly as much as 40%, while dependence on fluid rheology and diameter ratio is less pronounced [34]. The effect of eccentricity on fully developed laminar flow of a Newtonian fluid through an annulus without inner cylinder rotation is to produce a flow in which the peak velocity increases progressively with azimuthal location from the narrowest to widest part of the annulus [31]. If the inner cylinder rotates effects of eccentricity vanish and significant increases due to pipe rotation in eccentric narrow annuli were reported.

5. Effect of Pipe Roughness

The effect of pipe roughness can be neglected under laminar flow condition but it is significant in turbulent flow. Friction losses are higher in rough pipes for both Newtonian and non-Newtonian fluids [7]. However because of the chaotic nature and eddies during turbulent flow, it is extremely difficult to arrive at an exact analytical method for determining pressure losses in turbulent flow [38]. Therefore, simplification of friction factor equation becomes necessary. One common form of these simplifications is the use of the Blasius equation [39]. This equation ignores pipe roughness and is applicable only for the calculation of pressure drop in smooth pipes. However, drillpipes are sometimes rather old and have rough interior surfaces [9]. This equation depends only on the Reynolds number and has been used by many textbooks [38, 40-47]. Different researchers use different coefficients for the equation which therefore, represent a considerable source of error during pressure loss estimations in turbulent flow [6].

The equation for the pressure losses in turbulent flow of a Newtonian fluid in pipe is known as the Fanning Equation (Eq. 1) and the friction factor "*f*" defined by this equation is called the Fanning friction factor. All the terms in this equation, except for the friction factor, can be determined from the operating parameters. The friction factor in turbulent flow is a function of the Reynolds number and pipe roughness.

$$\frac{dp}{dL} = \frac{4fV^2\rho}{2D} \quad \text{…….. Eq. 1}$$

An empirical correlation (Eq. 2) for the determination of friction factors for fully developed turbulent flow in circular pipes has been presented by Colebrook [48]. The

Colebrook equation is a referential standard for its estimation of friction factor [49]. This equation, though accurate, is an implicit equation. This means friction factor appears both inside and outside the log term of Colebrook's equation. The friction factor hence, is either solved by numerical/iterative solution or one finds "f" from a graph. A plot of friction factor against Reynolds number on log-log paper is called Moody/Fanning/Stanton chart [42].

$$\frac{1}{\sqrt{f}} = -4log\left[0.269\frac{\epsilon}{D} + \frac{1.255}{N_{Re}\sqrt{f}}\right] \text{ ....Eq. 2}$$

Where: f is the friction factor; ϵ/D is the relative roughness; ϵ is the equivalent sand-grain roughness; D is the hydraulic diameter of the pipe; N_{Re} is the Reynolds number.

Colebrook and White provided another implicit equation which have been widely accepted (Eq. 3) by combining the Prandtl's formula (Eq. 4) for the smooth pipes and von Karman's formula for the fully rough regime (Eq. 5) [50]. However, many explicit equations have been proposed so far, but they are either not accurate, or they are accurate but not simple.

$$\frac{1}{\sqrt{f}} = -2log\left[\frac{\epsilon}{3.7D} + \frac{2.51}{N_{Re}\sqrt{f}}\right] \text{ ....Eq. 3}$$

$$\frac{1}{\sqrt{f}} = 2log\left[\frac{N_{Re}\sqrt{f}}{2.51}\right] \text{ ....Eq. 4}$$

$$\frac{1}{\sqrt{f}} = log\left[\frac{3.7D}{\epsilon}\right] \text{ ....Eq. 5}$$

One simple form of explicit equations found in drilling literature is the modified Moody [51] friction-factor. This equation provides a broader perspective in that laminar, transitional, and turbulent regimes are easily identified and compared regardless of geometry [52]. The original Moody correlation was developed in 1947 and is valid for all ranges of the Reynolds numbers and the relative roughness. Moody original friction factor relationship is shown in equation (6). The Modified friction factor uses a roughness of 0.00001 can be expressed as in equation (7).

$$f_t = 5.5 \times 10^{-3}\left[1 + \left(2 \times 10^4\frac{\varepsilon}{D} + \frac{10^6}{N_{Rep}}\right)^{1/3}\right] \text{ .... Eq. 6}$$

$$f_t = 0.001375\left[1 + \left(2 \times 10^4\frac{0.00001}{D} + \frac{10^6}{N_{Rep}}\right)^{1/3}\right] \text{ .... Eq. 7}$$

Another explicit equation is the Churchill equation (Eq. 8) first proposed by Churchill [53] in 1973. This equation is valid only for the turbulent regime [54]. Chen's [55] correlation (Eq. 9) is also an explicit form of Colebrook-White equation and give similar accuracy to the Colebrook-White equation that was employed for generating the friction factor chart widely used in the petroleum industry [46]. Haaland [50] explicit equation (Eq. 10) is also used in drilling industry. Haaland equation is one of the fastest and accurate correlation among the other correlations [56]. The application range as the Colebrook equation: $0 < \varepsilon/D < 0.05$ by $3000 < N_{RE} < 10^8$.

$$\frac{1}{\sqrt{f}} = -2log\left[\frac{\epsilon}{3.71D} + \left(\frac{7}{N_{Re}}\right)^{0.9}\right] \text{ ....Eq. 8}$$

$$f = \left[-4log\left[\frac{\in}{3.7065} - \frac{5.0452}{N_{Re}} log\left[\frac{\varepsilon^{1.1098}}{2.8257} + \left(\frac{7.149}{N_{Re}}\right)^{0.8981}\right]\right]\right]^{-2} \text{ .... Eq. 9}$$

$$\frac{1}{\sqrt{f}} = -1.8log\left[\left(\frac{\epsilon}{3.7D}\right)^{1.11} + \frac{6.9}{N_{Re}}\right] \text{ ....Eq. 10}$$

For Power-Law fluids, the Colebrook correlation does not give accurate results and the Dodge and Metzner [57] correlation is used instead [42]. Equation (11) depicts Dodge and Metzner correlation. Dodge and Metzner offered an exhaustive experimental and theoretical study on flow of turbulent flow in non-Newtonian in smooth pipes. They extended von Karman's work on turbulent flow friction factors to include the Power -Law fluids. This correlation has found wide application in the oil and gas industry but tends to over predict the frictional pressure loss [42, 58].

$$\sqrt{\frac{1}{f}} = \frac{4}{n_p^{0.75}} log\left[N_{Re} f^{\left(1-\frac{n_p}{2}\right)}\right] - \frac{0.395}{n_p^{1.2}} \text{ - ....Eq. 11}$$

In practice it would be extremely difficult to routinely measure pipe wall roughness while the pipe is in service [38]. However, drilling fluids are relatively viscos and the Reynolds number seldom exceeds 100,000. Also for most wellbore geometries, the relative roughness is usually less than 0.0004 [42]. For smooth pipe and Reynolds number range of 2100 to 100,000, a straight-line approximation on a log-log plot of of the Colebrook function is made possible. This approximation is first presented by Blasius [39] and is given by equation (12).

$$f = \frac{0.0791}{{N_{Re}}^{0.25}} \text{ ....Eq. 12}$$

Because of this, most researchers use empirical relations to calculate the friction factor. Moore, Adams, Rabia, Bourgoyne et al. and Carden et al. [38, 40-42, 45] treat the turbulent flow of PL and Bingham Plastics (BP) similarly. However, resulting turbulent flow equations are slightly different because they used different relationships between friction factor and Reynolds number. Moore used a different linear relationship between the friction factor and the Reynolds number ($f = 0.046/Re^{0.2}$) than those used by Adams, Bourgoyne et al. ($f = 0.0791/Re^{0.25}$) and Rabia ($f = 0.057/Re^{0.2}$). Similarly, Carden et al. used different linear relationships ($f = 0.0458/Re^{0.19}$ & $f=0.058/Re^{0.22}$). The Blasius form of the turbulent-flow friction factor for non-Newtonian fluids is a function of Reynolds number N_{Re} (Eq, 13 and Eq. 14) and the PL rheological parameter "n_p". The expressions for "a" (Eq, 15) and "b" (Eq, 16) are based on curve fits of data taken on PL fluids [52, 59]. API [60] adopted these values to be used in the Blasius equation for turbulent flow friction factor estimations in API RP 13D recommended practice.

$$f_t = \frac{a}{{N_{Re_p}}^{b}} \text{ ....Eq. 13}$$

$$N_{Re_G} = \frac{\rho V^2}{19.36\tau_w};\ N_{Re_p} = \frac{928\rho D V_p}{\mu_{ep}} \text{ ....Eq. 14}$$

$$a = \frac{log n_p + 3.93}{50} \text{ ....Eq. 15}$$

$$b = \frac{1.75 - log n_p}{7} \text{ ....Eq. 16}$$

Laminar flow friction factor for pipes and concentric annuli are usually defined in equation (17) while for transitional flow the commonly accepted expression for critical number can be used to approximate the transitional flow friction factor (Eq.18). Equation (17) is first suggested by Metzner and Reed [61] for non-Newtonian pseudo-plastic fluids in laminar flow in smooth pipes

$$Laminar\ flow: f_l = \frac{16}{N_{\mathrm{Re_G}}} \quad \text{……..Eq. 17}$$

$$Transitional\ flow: f_{tr} = \frac{16 N_{Re_G}}{(3470-1370n)^2} \quad \text{……..Eq. 18}$$

Where: N_{ReG} is the generalized Reynolds Number defined previously (Eq. 14).

It is clear therefore that different frictional factors will be generated for every single flow rate according to the method selected to predict the turbulent frictional pressure losses. Accordingly, different estimates of turbulent frictional pressure losses are expected.

6. Effect of Simplified Hydraulic Diameter

During annular flow, shear forces will act between the fluid and the outside of the drillpipe and the inside diameter of the wellbore. For concentric annuli, the geometry of conduit can be expressed by the equivalent diameter. Pipe flow equations are extended to annular geometry and the same equations which are used for pipe flow are used to calculate the Fanning friction factor for annulus flow by simply replacing the pipe diameter with an equivalent diameter. Many studies have been undertaken to transform annular flow to pipe flow by developing an effective equivalent diameter.

Several equivalent diameter definitions are proposed, however, two equations are widely used [7, 42]. The first equation (Eq. 19) is based upon the definition of hydraulic radius, which is the ratio of the cross sectional area to the wetted perimeter of the flow channel. The equivalent diameter is equal to four times the hydraulic radius and for concentric annulus it is the difference between the internal diameter of the inner conduit, i.e. D_{hyd} = (D_h-D_p). If there is no inner pipe, D_p = 0, the equivalent hydraulic diameter correctly reduces to the inner diameter of the outer pipe, D_h. This definition is adopted by API in its recommended practice RP 13D and used in major drilling text books [38, 40-43, 60, 62]. Bourgoyne et al. argue that the wider use of this definition is probably due to the simplicity of the method rather than a superior accuracy. The second most popular equivalent diameter equation (Eq. 20) used is the slot flow approximation for annulus [42]. The second equivalent diameter equation, D_{hyd} = 0.816(D_h-D_p), is adopted by Society of Petroleum Engineers (SPE). This definition has been found by comparing different friction pressure loss estimation methods by representing annulus as a circular and rectangular slot. Obviously, the annular friction factors calculated with the first definition are higher than those calculated with the second definition. That is why, if everything else is similar, friction pressure losses calculated by methods that adopt the first definition (API for example) will differ from those calculated by methods that adopt the second definition (SPE/Burgoyne et al. 1986).

$$D_{hyd} = \frac{4\,A_{ann}}{P_{wet}} = 4\frac{\frac{\pi}{d}\left(D_h^2 - D_p^2\right)}{\pi\left(D_h + D_p\right)} = D_h - D_p \quad \text{……..Eq. 19}$$

$$D_{slot} = 0.816\left(D_h - D_p\right) \quad \text{……..Eq. 20}$$

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Where: A_{ann} is the cross sectional area of the annulus; P_{wet} is the wetted perimeter of the annulus; D_h is the inner diameter of the wellbore; D_p is the outer diameter of the drillpipe.

Several other hydraulic diameter approximations are found in literature and have been used in practice. One expression for the equivalent diameter is presented by Lamb [63] and shown in equation (Eq. 21) by considering the flow system as shell of fluid having radius r. Another equation was developed empirically by Crittendon and is shown in equation (22) [64]. Langlinais et al. [65] studied the effect of "hydraulic diameter", "slot approximation" and "Crittendon criteria" on pressure losses of Bingham Plastics (BP) and Power Law (PL). Results show that the Crittendon criteria used with BP model gave the most accurate pressure loss prediction for all fluid samples. Jensen and Sharma [66] evaluated different friction factor and equivalent diameter definitions and found that for BP the "hydraulic diameter" used with Chen correlation gave the best fit to experimental pressure loss data. For PL, the "hydraulic diameter" used with the Blasius correlation gave the best estimate. Demirdal and Cunha [67] commenced comparative analysis of pressure losses using the previous four diameter definitions. Annular pressure losses are determined using BP, PL, Dual Power Law (DPL) and Yield Power Law (YPL) rheological models. BP based pressure losses were higher than PL for all the four equivalent diameters used. Narrow Slot and Lamb's equivalent diameter based pressure losses are identical for all rheological models and at the flow rates investigated (200 gpm to 1000 gpm). Furthermore, these two approaches yield pressure losses that are higher than those obtained using the "hydraulic diameter" and the "Crittendon diameter". Dosunmu and Shah [58] showed that the "hydraulic diameter" definition of equivalent diameter for an eccentric annulus provided the best annular definition for friction pressure prediction.

$$D_{Lamb} = \sqrt{D_h^2 + D_p^2 - \frac{D_h^2 - D_p^2}{ln\left(D_h/D_p\right)}} \quad \text{……..Eq. 21}$$

$$D_{Crittendon} = \frac{\sqrt[4]{D_h^4 - D_p^4 - \frac{\left(D_h^2 - D_p^2\right)^2}{ln\left(D_h/D_p\right)}} + \sqrt{D_h^2 - D_p^2}}{2} \quad \text{……..Eq. 22}$$

There are also less popular equivalent diameters which have been developed either analytically or empirically such as the Petroleum Engineering method (Eq. 23), Meter and Bird (Eq. 24), Reed and Pilehvari (Eq. 25) and Jones and Leung (Eq. 26) definitions [68]. The Petroleum Engineering definition was derived using gas flow equations but gives reasonable values when applied to liquids and often gives effective diameter that is 40% greater than the "hydraulic diameter". Meter and Bird definition is applicable to laminar and turbulent flow of Newtonian fluids in concentric annulus. Reed and Pilehvari definition is a function of annular geometry and rheology of the fluid. The model gives good results for YPL fluids. Jones and Leung definition is the product of the "hydraulic diameter" and a shape factor defined in the Meter and Bird equation. Anifowoshe and Osisanya [68] have investigated the effect of these less popular definitions as well as the most popular ones on pressure loss estimations. They concluded that pressure estimation is significantly affected by the equivalent diameter definition used. The "hydraulic diameter" definition gave the best estimate of pressure loss for PL fluids under laminar flow conditions.

$$D_{Pet\ Eng} = \sqrt[5]{\left(D_h^2 + D_p^2\right)^2 \times \left(D_h^2 - D_p^2\right)^3} \quad \text{……..Eq. 23}$$

$$D_{Meter-Bird} = D_h(1-K)\emptyset;\ \emptyset = \frac{1}{1-K^2}\left[(1+K^2) - \frac{1-K^2}{ln(1/K)}\right];\ K = {D_p}/{D_h} \quad \text{..Eq. 24}$$

$$D_{Reed-Pilehvari} = \frac{D_h - D_p}{G};\ G = \left(\frac{1+Z}{2}\right)\frac{[n(3-Z)+1]}{[n(4-Z)]} \quad \text{……..Eq. 25}$$

$$Z = 1 - \left[1 - \left({D_p}/{D_h}\right)^Y\right]^{1/Y};\ Y = 0.37n^{-0.14}$$

$$D_{Jones-Leung} = \emptyset D_e \quad \text{……..Eq. 26}$$

7. Effect of Cuttings Accumulations

Cuttings are generated by the bit are transported by the drilling fluid along the annulus. This affect the drilling fluid density and causes greater annular pressure losses than calculated. Furthermore, solid content increases the PV of BP fluids which included in pressure loss equations for BP fluids. Greater rate of penetrations, lower carrying capacity of the mud and inefficient solid control resulted in a higher concentration of these solids in the annulus and a greater effect on mud density and rheology. Cuttings accumulation are dominant at highly deviated wellbores. These cuttings are found as stationary or moving beds at the lower side of the wellbore [13-14]. Cuttings bedding causes a reduction in hydraulic diameter and flow area and increases the friction pressure loss. Therefore, in real drilling conditions the annular pressure loss will be affected by cuttings content as well as the other factors.

Equivalent circulation densities (ECD) are normally predicted using the hydrostatic pressure and frictional pressure drop in annulus, without considering the cuttings concentration in the annulus. This could lead to under estimations of ECD values. Correct ECD are predicted if cuttings concentrations together with slip velocity of cuttings are taking into consideration particularly for vertical and near vertical annuli [69]. Figure 4 shows equivalent circulation densities with and without cuttings. Kummen and Wold [33] studied the correlation between rapid alterations in cuttings concentration and the corresponding change in pressure loss, using standpipe pressure as pressure indicator. Drilling data were collected from two wells in the North Sea. A correlation between change in rate of penetration (ROP) and the response in standpipe pressure was found. However, calculations indicate that the change in pressure loss cannot be solely be explained by cuttings bedding, viscosity and density changes or weight of suspended cuttings in wellbore.

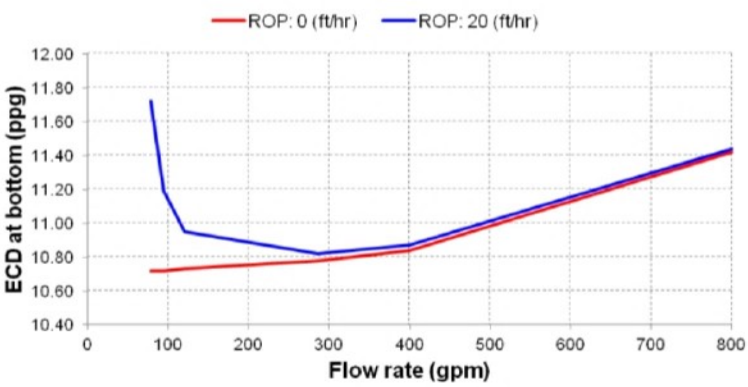

Figure 4: ECD at bottom hole with/without cuttings [69]

8. Effect of Temperature and Pressure

Drilling fluids are complex heterogeneous mixtures of various types of base fluids and chemical additives that must remain stable over a range of temperature and pressure. It is often assumed that drilling fluid properties are constant throughout the duration of drilling activities. This assumption is quite wrong in cases where there is a large variation in pressure and temperature conditions [70]. As the fluid flows in the wellbore, it absorbs heat from the formation, causing a rise in temperature. The temperature in the formation at an adequate distance from the wellbore is undisturbed and maintains the natural geothermal gradient. Increase in temperature will cause changes in the volumetric and rheological behaviour of the fluid. The fluid within the drillpipe receives heat from the annulus via convection on the inner and outer walls of the drillpipe and conduction through the drillpipe itself. There is also heat flow in and out of the differential elements within the drillpipe and annulus due to the bulk fluid flow. Temperature in the drillpipe and annulus are equal at the bottom of the hole [70].

During drilling operations, the drilling fluid is subjected to its own hydrostatic pressure and formation temperature. Drilling fluid rheological properties are typically measured at ambient pressure and temperature. These properties as well as the drilling fluid density are used in hydraulic calculations. In many cases the rheological variations with temperature are small, particularly for shallow wells as the temperature changes are not so large. Furthermore, many wells have a large window between pore pressure and fracture pressure, so errors in estimation of annular pressure loss have no dangerous consequences for well integrity and kick probability [71]. However, these properties are affected by the high temperatures and pressure sustained in real deep-well environments. The pressure and temperature differences between the hole and the surface are considerable, particularly in high pressure and high temperature wells (HPHT) and at low circulation rates [70]. Reliable prediction of equivalent circulation density (ECD) in HPHT wells require the use of pressure and temperature dependent rheology and density. These can be obtained directly from laboratory measurements at HPHT conditions of actual mud system, or from a model that is developed based on data from similar mud systems.

Higher well temperature lowers the drilling fluid density and affect its rheology. White et al. [6] performed downhole measurement of synthetic-based mud (SBM) in an offshore well. Results show sensitivity of the SBM rheology and density to temperature and pressure. High temperature conditions cause the drilling fluid to expand thermally, accordingly density and rheology decrease (Figure 5). While greater bottom hole pressure causes slight fluid compression and increases mud density and rheology (Figure 6). These are two opposing effects and failure to take such effects into account can lead to errors in the estimation of bottom hole pressure [9, 70].

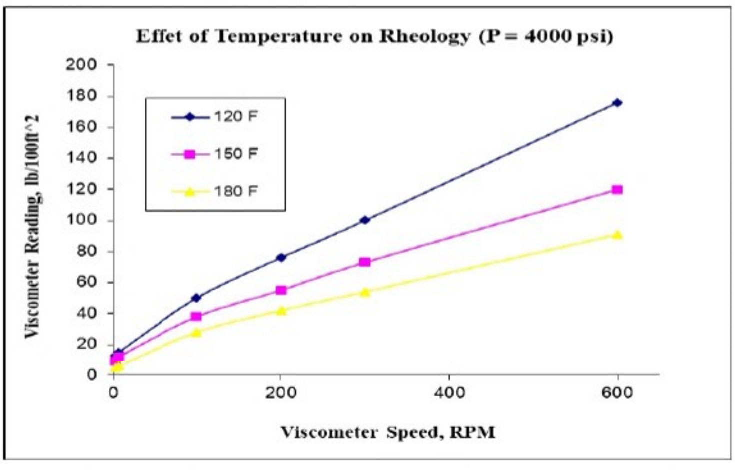

Figure 5: Effect of temperature on SBM rheology - reproduced from [6]

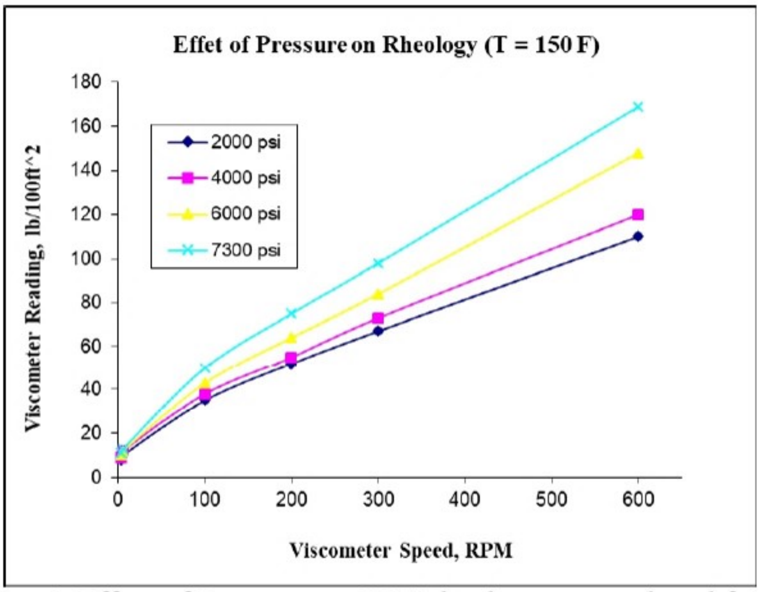

Figure 6: Effect of Pressure on SBM rheology - reproduced from [6]

Lately, Guracy et al. [72] experimentally investigated the effect of temperature on friction pressure loss through vertical concentric annulus using water and polymer based drilling fluid. The effect of temperature on consistency index "K" of PL model and yield point "YP" of BP model were more dominant than the effect of temperature on flow behaviour index "n" of PL model. Similar results have been reported earlier by White et al. [6]. The apparent viscosity decreased exponentially with increasing temperature and this decrease was more obvious in low shear rate values. Temperature also affect flow regime as earlier regime transition was observed with increasing temperature. Result of HPHT rheology experiments show that the effect of temperature is much larger than the effect of pressure particularly for water based muds [71, 73]. For oil-based muds in vertical wells the effect of temperature and pressure cancel out each other [9, 71].

Based on simulations that were performed by Hariss and Osisanya [70], results show that "the effect of temperature and pressure on the volumetric and rheological behaviour of drilling fluids play an important role in the bottom-hole pressure that will occur in deep hot wells. Generally, higher geothermal gradients lead to lower bottom-hole pressure and the inlet pipe temperature does not have a significant effect on the bottom-hole pressure. Higher circulation rates result in lower bottom-hole temperature and higher bottom-hole pressure. This is because the drilling fluid spends less time in the wellbore to absorb heat and thus undergoes a lesser degree of thermal expansion". These effects are not considered in normal hydraulic calculations and are considered a source of error, particularly in HPHT wells [9]. In order to accurately estimate the fluid density and frictional pressure loss in the wellbore, it is thus necessary to evaluate the temperature profile in the wellbore over time. And this require analysing the flow of heat in the wellbore.

9. Conclusion

- Pressure drop relations most commonly used are based on a number of simplifying assumptions, such as concentric annular and circular sections, non-rotating drillstring, isothermal conditions in the borehole and steady state axial flow. These assumptions are not valid in real life.
- Pipe eccentricity, pipe rotation, high temperature, tool-joint, cuttings accumulations, pipe roughness can have significant effect on frictional pressure loss. Transportation and accumulation of cuttings cause an additional pressure loss in the well. If the rate

of penetration is too high, or during drilling highly deviated wellbore, cuttings may accumulate in the annulus causing pressure build up.

- Different friction factor correlations for turbulent flow are in practice use which may rise the questions about which is the most accurate.
- Several simplified hydraulic diameters are used to approximate annular flow. Pressure loss predictions are affected by the used equivalent diameter definition.

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مراجعة تأثيرات ظروف بئر النفط في حسابات فارق الضغط لسائل الحفر

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الملخص:

تؤدي هيدروليكا البئر المصممة بشكل جيد دورًا حيويًا ومهمًا في عملية حفر آبار النفط، وأهم مكونات هيدروليكا البئر تشمل التنبؤ بضغط تدوير سائل الحفر، وكثافة سائل الحفر المكافئة في أثناء التدوير. هذه التنبؤات تصبح ملحة وأكثر أهمية في عمليات الحفر المعقدة التي تشمل الحفر الأفقي، والحفر الممتد لمسافات طويلة، والحفر في أعالي البحار، وحفر الآبار التي تتسم بأقطار صغيرة، إذ يصاحب هذه العمليات الكثير من الصعوبات في الغالب بسبب الفارق اليسير بين ضغط سائل الطبقة وضغط كسرها وصعوبة المحافظة على ضغط سائل الحفر بين هذين الضغطين. لذلك تبدو الحاجة هنا ملحة جدًا لأن تكون التنبؤات لضغط تدوير سائل الحفر دقيقة جدًا لتجنب مشاكل الحفر المصاحبة. إنَّ طرق التنبؤ الحالية غير دقيقة وتفتقر للمصداقية إذ إنَّ كثيرًا من ظروف البئر يتم إهمالها بغرض التيسير، مما يعوق الحصول على تنبؤات دقيقة. إنَّ الهدف الرئيس لهذه الورقة هو تسليط الضوء على تأثيرات هذه الظروف، التي عادة ما تهمل في أثناء إجراء حسابات التنبؤ بضغط تدوير سائل الحفر وبخاصةٍ في حالة سوائل الحفر غير الانضغاطية.

الكلمات المفتاحية: سائل الحفر، فقدان الضغط في الفراغ الحلقي، أداة ربط أنابيب الحفر، حيود أنابيب الحفر، دوران أنابيب الحفر، تجمعات نواتج الحفر.