Consideration of Tool-joint Effects for Annular Pressure Loss Calculation

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***Abstract* — Managed pressure drilling (MPD) is an innovative approach which can be used to solve the drilling problems caused by narrow safety pressure window. The precise wellbore flow model is not only premising to realize accurate wellbore pressure control, but also the key for safe and efficient drilling. In order to improve the prediction accuracy of wellbore pressure, annular pressure loss needs to be calculated accurately. Using dimensional analysis in conjunction with theoretical methods, the influence of tool joint and drill pipe rotation on annular pressure loss is studied in this paper. New annular pressure loss model has been developed to account for the contribution of tool-joints and pipe rotation to the total annular pressure loss, which enhanced wellbore pressure prediction accuracy. Model predictions show strong hydraulic resistance created by the tool-joint that increases the local annular pressure loss significantly as the flow rates increases. As well depth and flow rate increase, cumulative pressure loss of tool-joint increases. As pipe rotation increases, pressure loss may increase or decrease depending on the result of inertial effect and shear thinning. The new models are very useful to predict ECD and wellbore pressure accurately which is very important in hydraulic calculation for managed pressure drilling.**

Keywords - tool-joint, drill pipe rotation, annular pressure loss, dimensional analysis

I. INTRODUCTION

In recent years, with the increasing demands of the oil and gas, exploration and development are going deeper. Specially, in deep wells, the margin between pore and fracture pressures can be very narrow. Numerous facts [1-4] have proved that drilling problems in narrow safe density window is particularly prominent. In order to solve these problems, manage pressure drilling is presented. As a result, wellbore pressure and drilling fluid equivalent circulating density must be predicted accurately and maintained within the narrow margin to avoid kicks and circulation losses.

In the past years, a number of wellbore hydraulic studies[5-10]have been conducted to predict the annular pressure losses. The studies considered the effects of drillpipe rotation, borehole geometry, and pipe eccentricity on annular pressure loss.

However, very limited studies have been carried to investigate the effect of tool-joint on wellbore hydraulics. The presence of a tool-joint changes the annulus geometry between the drillpipe and casing/hole resulting in strong turbulence and fluid acceleration that generate additional viscous dissipation and pressure losses. Studies on a non-rotating tool-joint [11, 12] has indicated a significant increase in pressure loss due to the tool-joint. And field case verified that the cumulative error of pressure loss increase as well depth increases if tool-joint is ignored which endanger the safe of managed pressure drilling. To accurately predict wellbore pressure in narrow density window, the effect of tool-joint on wellbore hydraulics should be taken into account. Dimensional analysis was applied to research the effect of tool joint on annular pressure loss in the paper.

II. THEORETICAL MODEL OF ANNULUAR PRESSURE LOSS

The total annular friction pressure loss including:

i) pressure loss across the tool-joint that doesnot account for the contraction and expansion losses; and ii) pressure loss due to tool-joint contraction and expansion, as shown in Figure 1. Hence:

$$\Delta P_{\mathrm{f}} = \Delta P_{\mathrm{f1}} + \Delta P_{\mathrm{f2}} \quad (1)$$

The pressure loss ΔP_{f1} includes pressure losses in the narrow and wide regions of the tool joint. Therefore, ΔP_{f1} is calculated as the sum of these two components:

$$\Delta P_{\mathrm{f1}} = \Delta P_{\mathrm{N}} + \Delta P_{\mathrm{W}} = \frac{4\tau_{\mathrm{w,N}} L_{\mathrm{N}}}{D_{\mathrm{hyd,N}}} + \frac{4\tau_{\mathrm{w,W}} L_{\mathrm{W}}}{D_{\mathrm{hyd,W}}} \quad (2)$$

Under laminar flow condition, for power law fluids, the wall shear stress in the annulus can be estimated using the narrow slot approximation method as:

$$\tau_{\mathrm{w}} = K\left[\frac{12v}{D_{\mathrm{hyd}}}\left(\frac{2n+1}{3n}\right)\right]^{n} \quad (3)$$

For turbulent flow, wall shear stress is calculated as:

$$\tau_{\mathrm{w}} = \frac{1}{2} f \rho v^{2} \quad (4)$$

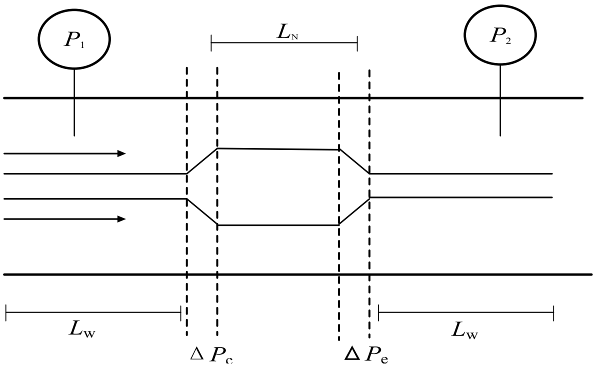

Figure 1. Schematic of tool-joint

Where f is the fanning friction factor. It can be estimated using the following correlation.

For smooth pipe, friction factorcan be calculated by Dodge and Metzner equation [13]:

$$\frac{1}{f^{0.5}} = \frac{4}{n^{0.75}} \log\left[\mathrm{Re} f^{\left(1-\frac{n}{2}\right)}\right] - \frac{0.4}{n^{1.2}} \quad (5)$$

For rough pipe, fanning friction factor is calculated as:

$$\frac{1}{\sqrt{f}} = -4\log_{10}\left(\frac{1.255}{\mathrm{Re}\sqrt{f}} + \frac{\varepsilon}{3.7d}\right) \quad (6)$$

The hydraulic diameters of the narrow and wide parts of the tool-joint are determined as:

$$D_{\mathrm{hyd,N}} = D_{\mathrm{ci}} - D_{\mathrm{TJ}}$$
$$D_{\mathrm{hyd,W}} = D_{\mathrm{ci}} - D_{\mathrm{po}} \quad (7)$$

The pressure loss ΔP_{f2} includes pressure losses due to tool-joint contraction and expansion. Hence:

$$\Delta P_{f2} = \Delta P_c + \Delta P_e \quad (8)$$

where,

D_{ci}--- the inner diameter of casing, m;

D_{po}, D_{TJ}--- the outer diameters of the drillpipeand tool-joint, respectively, m;

ΔP_c---the pressure loss due to tool-joint contraction and expansion, respectively, Pa;

Contraction and expansion effects of the tool-joint are modeled using the same definition as Jeong and Shah. Accordingly, the contraction pressure loss, ΔP_c, is:

$$\Delta P_c = \rho \times K_c \left(\frac{v_N^2}{2g}\right) \quad (9)$$

where, K_c is the contraction head loss coefficient.

For squared tool-joint, the contraction head loss coefficient is:

$$K_c = \left(1 - \frac{A_N}{A_W}\right)^2 \quad (10)$$

For tapered tool-joint, the contraction head loss coefficient is calculated as:

$$K_c = 0.5\sqrt{\sin\frac{\theta}{2}\left(1-k^2\right)} \quad (11)$$

Similarly, the expansion pressure loss ΔP_e can be defined as:

$$\Delta P_e = \rho \times K_e \left(\frac{v_W^2}{2g}\right) \quad (12)$$

where, K_e is the expansion head loss coefficient, which can be determined for both squared and tapered tool-joint as:

$$K_e = \left(\frac{A_W}{A_N} - 1\right)^2 \quad (13)$$

Applying the energy balance, the pressure difference between Point 1 and Point 2 (i.e. pressure loss) is expressed as:

$$\Delta P = \frac{\rho}{2g} v_N^2 \left\{K_c + K_e\left(\frac{A_N}{A_W}\right)^2\right\} + \Delta P_{f1} \quad (14)$$

where,

ρ--- density of the fluid, kg/m^3;

v_N--- the fluid mean velocity in the narrow area around the tool-joint, m/s.

A_N, A_W--- the areas of the narrow and wide sections of the tool joints, respectively, m^2.

III. DIMENSIONLESS ANALYSIS

Buckingham method is applied to analysis theoretical model. Seven independent variables are expected to influence the tool-joint pressure loss. The variables are flow velocity (v), viscosity (μ), density (ρ), pipe rotation speed (Ω), offset distance between the inner and outer cylinders (e), and wellbore geometric factors (hydraulic radius and inner pipe effective radius).

$$\frac{\mathrm{d}P}{\mathrm{d}L} = \mathrm{fun}\left(v, \mu, \rho, \Omega, e, \Delta R_h, R_{ih}\right) \quad (15)$$

The hydraulic radius, $\Delta R_h = R_o - R_{ih}$. The effective radius ($R_{ih}$) is the arithmetic average between the outer radiuses of inner pipe and the tool-joint that can be determined as:

$$R_{ih} = \frac{R_{po}L_p + R_{TJ}L_{TJ}}{L_p + L_{TJ}} \quad (16)$$

where,

R_{po},R_{TJ}--- the inner pipe and tool-joint outer radiuses, respectively, m;

L_p, L_{TJ}--- the inner pipe length in the tool zone and tool-joint length, respectively, m.

For straight annular section, $R_{po} = R_{TJ}$. Thus: $R_{ih} = R_{po}$, and $\Delta R_h = R_{ci} - R_{po}$.

v , ρ and ΔR_h are selected to be repeating variables that do not form dimensionless groups. After performing the dimensional analysis, five dimensionless groups have been obtained. Theoretical analysis of pipe and annular flow show that, in addition to the apparent viscosity function, the fluid behavior index and yield shear stress of the fluid affect the friction factor. Thus, dimensionless forms of these parameters is shown in Table I.

TABLEI. DIMENSIONS GROUPS

Dimensionless Group	Definition
Friction factor (*f*)	$\pi_1 = \dfrac{\Delta R_h \dfrac{dP}{dL}}{\rho v^2}$
Reynolds number (Re)	$\pi_2 = \dfrac{\Delta R_h \rho v}{\mu}$
Taylor number (Ta)	$\pi_3 = R_{ih} \Delta R_h^3 \left(\dfrac{\rho \Omega}{\mu}\right)^2$
annular eccentricity (ε)	$\pi_4 = \dfrac{e}{\Delta R_h}$
Ratio of the inner effective radius to the outer radius (κ)	$\pi_5 = \dfrac{1}{\kappa} - 1$
Dimensionless yield stress	$\pi_6 = \dfrac{\tau_y}{\rho v^2}$
Fluid behavior index	n

Dimensionless equation can be written as:

$$\text{fun}\left(f, \frac{\tau_y}{\rho v^2}, \varepsilon, n, T_a, \text{Re}, \frac{1}{\kappa} - 1\right) = 0 \quad (17)$$

Dimensionless groups that may affect the friction factor *f* or pressure loss ratio (PLR) are:

$$f \,/\, PLR = \text{fun}\left(\frac{\tau_y}{\rho v^2}, \varepsilon, n, T_a, \text{Re}, \frac{1}{\kappa} - 1\right) \quad (18)$$

The final formula that has been developed from the previous dimensionless analysis can be written as:

$$PLR = A \times \left(B + \frac{\tau_y}{\rho v^2}\right)^C \times \varepsilon^D \times n^E \times T_a^F \times \text{Re}_{\text{eff}}^G \times \left(\frac{1}{\kappa} - 1\right)^H \quad (19)$$

Or,

$$f.\text{Re}_{\text{eff}} = A \times \left(B + \frac{\tau_y}{\rho v^2}\right)^C \times \varepsilon^D \times n^E \times T_a^F \times \text{Re}_{\text{eff}}^G \times \left(\frac{1}{\kappa} - 1\right)^H$$

Therefore, the friction factor or pressure loss ratio is a function of the yield shear stress, eccentricity, flow behavior index, Taylor number, Reynolds number and annular diameter ratio.

IV. EMPIRICAL MODEL OF ANNULAR PRESSURE LOSS

Pressure loss in annular flow with pipe rotation is estimated as:

$$\left(\frac{\Delta P}{\Delta L}\right)_{\omega} = PLR \times \left(\frac{\Delta P}{\Delta L}\right)_{\omega=0} \quad (21)$$

Where, $(\Delta P/\Delta L)_{w=0}$ is the pressure loss without rotation. *PLR* is the annular pressure loss ratio, which is predicted using empirical correlations developed from the experimental measurements using dimensional analysis.

According to experimental data ofMajed [14], semi-empirical models have been developedto account for the effect of pipe rotation on the pressure loss for straight section without tool-joint.

The following correlation has been developed to compute *PLR* for Newtonian fluids.

$$PLR = 0.237 \times \varepsilon^{0.01} \times T_a^{0.04} \times \text{Re}^{0.02} \times \left(\frac{1}{\kappa} - 1\right) \quad (22)$$

Equation (22) is valid for Taylor number ranges from 8,700 to 5,500,000 and Reynolds number between 5,000 and 100,000. Eccentricity and diameter ratio values were varied between 0.5 and 0.58 and 0.57 and 0.71, respectively.

For non-Newtonian fluids, a similar correlation has been developed to predict the pressure loss ratio.

$$PLR = \left(1 + \frac{\tau_y}{\tau_w}\right)^{0.07} \times \varepsilon^{0.15} \times n^{0.01} \times T_a^{0.04} \times \text{Re}^{0.01} \times \left(\frac{1}{\kappa} - 1\right)^{-0.15}$$

Equation (23) is valid for fluid behavior index from 0.3 to 0.6, Taylor number from 42 to 464,000, Reynolds number between 28 and 7,500, eccentricity values of 0.5 and 0.58, and diameter ratio values of 0.57 and 0.71.

Empirical models have been developed to account for the effect of pipe rotation on the tool joint pressure loss.

The following correlation has been developed to determine the *PLR* for Newtonian fluid under turbulent flow conditions (between 2,600 and 100,000).

$$PLR = 0.55 \times \varepsilon^{0.03} \times T_a^{0.02} \times \text{Re}^{0.04} \times \left(\frac{1}{\kappa} - 1\right)^{-0.05} \quad (24)$$

Equation (24) is valid for Taylor number ranging from 6,500 to 1,000,000. Two eccentricity (0.5 and 0.58) and diameter ratio (0.61 and 0.75) values have been used in the development of the model.

For non-Newtonian fluids, a separate equation has been developed to determine the *PLR*.

$$PLR = 0.773 \times \left(0.64 + \frac{\tau_y}{\rho v^2}\right)^{1.83} \times \varepsilon^{1.06} \times n^{0.183} \times T_a^{0.024} \times \text{Re}^{0.022}$$

$$\times \left(\frac{1}{\kappa} - 1\right)^{-0.231} \quad (20) \quad (25)$$

Equation (25) is valid for Taylor and Reynolds numbers ranging from 40 to 478,000 and 30 to 8,600, respectively. The correlation is developed using two different eccentricity (0.5 and 0.58) and diameter ratio (0.61 and 0.75) values.

V. SENSITIVITY ANALYSIS

Simulated well consists of a 304.8mm long section (2.875' ×5.5' annulus) with tool-joint (60.96 mm long and 38.1 mm OD). Drilling fluid density is 1000 kg/m^3, flow pattern index is 0.6, consistency coefficient is 0.48Pa•S^n. Annulus friction pressure loss with and without tool-joint is calculated respectively using the model in this paper. And the effect of tool-joint on annular pressure loss is analyzed.

A. Tool-joint Effect on the Annular Pressure Loss

Pressure loss from the sections with and without tool-joint are plotted in Fig.2. Results show strong hydraulic resistance created by the tool-joint that increases the local annular pressure loss significantly as the flow rates increases. Annular pressure loss with tool-joint increased by 61% at 14 l/min and 100% at 120 l/min.

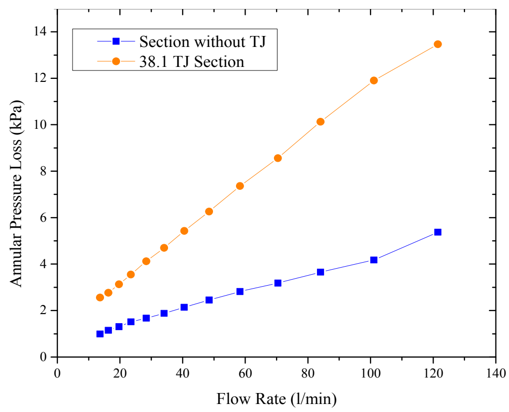

Figure 2. Comparison of annular pressure loss with and without tool-joint for different flow rates

Fig.3 presents fanning friction factor as a function of Reynolds number for annular sections with and without tool-joint. Results from the section with tool-joint show very high friction factor indicating the strong hydraulic resistance of the tool-joint.

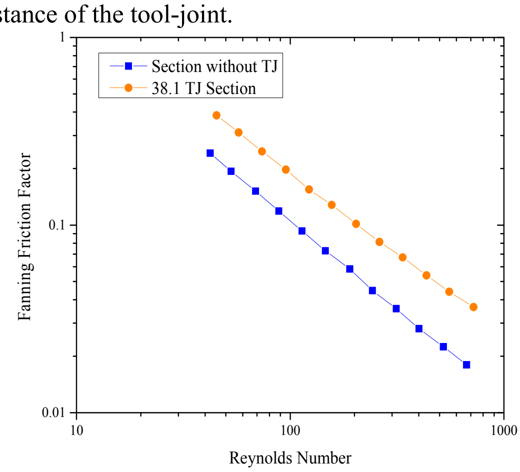

Figure 3. Comparison of fanning friction factor with and without tool-joint for different Reynolds numbers

To study the global effect of the tool-joint on the annular pressure loss, the contribution of the tool-joint to the total pressure loss is calculated by assuming one tool-joint in every 9.4m of drillstring.

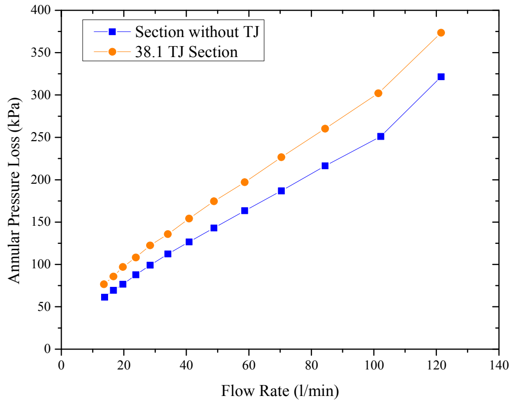

Figure 4. Comparison of annular pressure loss for one stand of drillpipe with one joint at different flow rates

As shown in Fig.4, annular pressure loss with tool-joint increased by 11% at 14 l/min and 16% at 120 l/min. In contrast to the tendency in Figure 3, the effect of tool-joint on annular pressure loss is not significant. This is because that even though the localized hydraulic effects of a tool-joint can be substantial, the overall effect could be minimal due to its short length.However, as well depth and flow rate increase, cumulative pressure loss of tool-joint increases. The effect of tool-joint on annular pressure loss should be considered.

B. Effects of Drillpipe Rotation on the Annular Pressure Loss

The effects of pipe rotation on the annular and tool-joint pressure losses were calculated using five drill pipe rotation speeds (0, 60, 120, 180 and 240 RPM), as shown in Fig. 5 and Fig.6.

Fig. 5 shows the pressure loss slightly decreases as pipe rotation speed increases at low flow rates. However, at high flow rates, Fig. 5shows an increase in the annular pressure loss as pipe rotation increases. The increase in the annular pressure loss could be due to the inertial effects resulting from the eccentricity of the pipe and/or the formation of Taylor vortices that intensify the viscous losses.

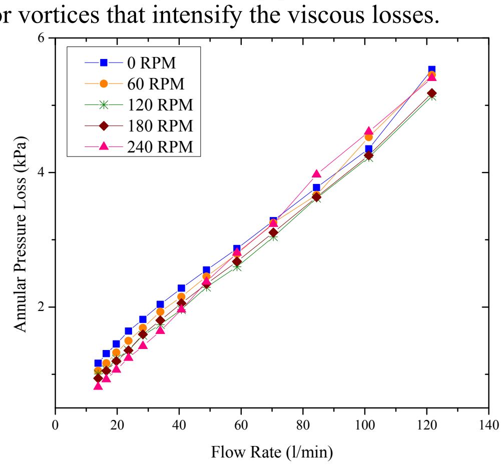

Figure 5. Annular pressure loss with flow rate for different rotation speeds

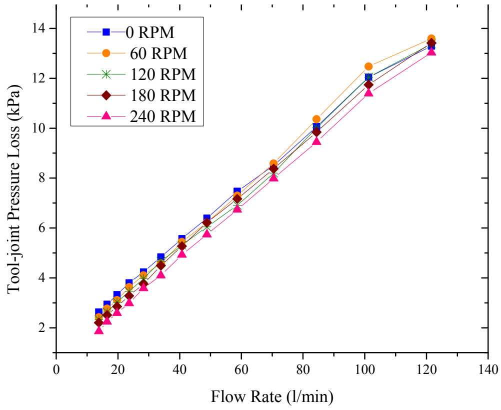

Figure 6. Tool-joint pressure loss with flow rate for different rotation speeds

Fig.6 shows there is no apparent trend as pipe rotation increases at low flow rates. At high flow rates, the trend shows slight but consistent decrease in tool-joint pressure loss.This is because that the rotation of drillpipe complicates the flow around tool-joints. The presence of strong inertial effects such flow disturbance and fluctuations at a rotating tool-joint that generate substantial viscous resistance and dissipation. Simultaneously, the rotation increases the resultant shear rate (i.e. combined shear rate of tangential and axial flows) and causes shear thinning that reduces the pressure loss. The overall effect is the result of these two opposing factors. The decrease in the annular pressure loss could be due to the effect of shear thinning, which might be dominated by the inertial effect that has the opposite consequence.

C. Tool-joint Contraction and Expansion Effects

Tool-joint contraction and expansion zones generate strong hydraulic resistance and substantial pressure loss. Total annular pressure loss and contraction and expansion zone pressure losses with different flow rate were presented in Fig. 7.

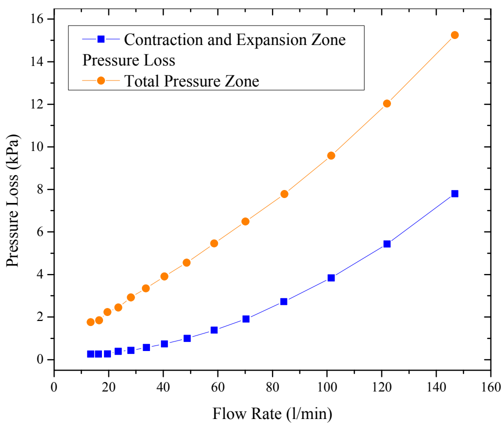

Figure 7. Tool-joint total and contraction and expansion zone pressure losses with flow rate

Fig.7 shows that at approximately 40 l/min, the pressure loss caused by contraction and expansion effects represents about 15% of the total pressure loss. However, at high flow rates (i.e. greater than 150 l/min), the contribution of contraction and expansion effects increases to 50% of the total pressure loss. The pressure loss generated by contraction flow is higher as flow rate increases. The effect of tool-joint need to be considered in calculating annular pressure loss.

VI. CONCLUSIONS

In this study, the effects of tool-joint on annular pressure loss were performed using theoretical and empirical models. The following conclusions can be drawn as follows:

1.As flow rate increases, flow regime from laminar flow condition becomes unstable and turbulent flow condition. Strong hydraulic resistance created by the tool-joint that increases the local annular pressure loss significantly. Due to short length of a tool-joint, the overall effect could be minimal. However, cumulative pressure loss of tool-joint increases as well depth and flow rate increase.

2. As pipe rotation increases, annular pressure loss slightly decreases at low flow rates. However, at high flow rates, the annular pressure loss increase.

3. As pipe rotation increases, there is no apparent trend at low flow rates in tool-joint pressure loss. At high flow rates, the pressure loss may increase or decrease depending on the result of inertial effect and shear thinning.

4. As flow rate increases, the contraction and expansion parts of the tool-joint create strong flow disturbances and turbulent flow conditions that cause the pressure loss to increase.

5. In order to accurately predict ECD and maintain wellbore pressure within the narrow margin to avoid kicks and circulation losses, the effect of tool-joint on wellbore hydraulics should be considered.

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REFERENCES

[1] Beltran J.C., Gabaldon O.R.,"Case Studies - Proactive Managed Pressure Drilling and Underbalanced Drilling Application in San Joaquin Wells", SPE Annual Technical Conference and Exhibition, San Antonio, 24-27 Sep., 2006,doi:10.2118/100927-MS.

[2] Driedger D.J., Kelly S.P.,"Managed Pressure Drilling Technique Applied in a Kurdistan Exploration Well", SPE Middle East Oil and Gas Show and Conference, Bahrain, 10-13 March, 2013,doi:10.2118/164403-MS.

[3] Solvang S. A., Leuchtenberg C.,"Managed pressure drilling resolves pressure depletion related problems in the development of the HTHP Kristin Field", SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, Abu Dhabi,28-29 Jan., 2008,doi:10.2118/113672-MS.

[4] Syltoy S., Eide S. E., "Highly advanced multitechnical MPD concept

extends achievable HTHP targets in the North Sea",SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, Abu Dhabi, 28-29 Jan., 2008,doi:10.2118/114484-MS.

[5] Ahmed R. M., Miska S. Z.,"Experimental Study and Modeling of Yield Power-Law Fluid Flow in Annuli with Drillpipe Rotation",IADC/SPE Drilling Conference, Florida, 4-6 March, 2008, doi:10.2118/112604-MS.

[6] Ahmed R. M., Enfis M. S.,"The Effect of Drillstring Rotation on Equivalent Circulation Density: Modeling and Analysis of Field Measurements", SPE Annual Technical Conference and Exhibition, Italy, 19-22 Sep., 2010, doi:10.2118/135587-MS.

[7] Hemphill T., Bern P.,"Field Validation of Drillpipe Rotation Effects on Equivalent Circulating Density",SPE Annual Conference and Technical Exhibition, California, 11-14 Nov., 2007, doi:10.2118/110470-MS.

[8] Jeong Y., Shah S.,"Analysis of Tool Joint Effects for Accurate Friction Pressure Loss Calculations",IADC/SPE Drilling Conference,Texas,2-4 March, 2004, doi:10.2118/87182-MS.

[9] Scheid C.M, Calcada L.A.,"Prediction of Pressure Losses in Drilling Fluid Flows in Circular and Annular Pipes and Accessories", SPE Latin American and Caribbean Petroleum Engineering Conference,Colombia,31 May-3 June, 2009,doi:10.2118/122072-MS.

[10] Simoes S.,"The Effect of Tool Joints on ECD while Drilling with Power Law Fluids", M.S Thesis, U. of Tulsa, 2007.

[11] Fang P, Manglik R.M,"The Influence of Inner Cylinder Rotation on Laminar Axial Flows in Eccentric Annuli of Drilling Bore Wells",Int. J. of Tran. Phenomena,vol.4,2002, pp. 257-274,

[12] Ooms G, Kampman-Reinhartz B.E,"Influence of Drillpipe Rotation and Eccentricity on Pressure Drop over Borehole with Newtonian Liquid during Drilling". J. SPE Drill and Completion, vol.15,pp. 249-253, 2000, doi:10.2118/67618-PA.

[13] Dodge D.W, Metzner A.B,"Turbulent Flow of Non-Newtonian Systems". AIChE Journal, vol.5, 1959, pp.189-204.

[14] Majed Sadeg Enfis,"The Effects of Tool-joint on Annular Pressure Loss", M. S Thesis, U. of Oklahoma, 2011.