Utilizing Managed Pressure Drilling Technique to Prevent Rock Failure and Maintain Wellbore Stability

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Abstract. Rock failure is one of the major concerns of drilling operation, especially in the formation with narrow drilling window, which may lead to several technical issues and even endanger the operation safety, such as wellbore collapse, stuck pipe, formation breakdown, lost circulation, etc. A new technology is proposed in this paper to prevent rock failure and maintain wellbore stability through controlling the annular pressure profile. A new managed pressure drilling equipment named pressure control drilling system (PCDS) is developed which combines the constant bottom hole pressure technique and micro-flux control technique to quickly create overbalanced, near-balanced and underbalanced wellbore condition in the whole process of drilling operation. Based on the proposed MPD equipment, a novel technology is developed to maintain the annular pressure within the range of formation fracture pressure and formation collapse pressure, ensuring the formation rock to be neither shear failure nor tensile failure. Hydraulic calculation is performed before and during the drilling operation to predict the pressure profiles inside and outside the drill pipe, frictional pressure and equivalent circulating density, providing reference to the maintenance of wellbore stability. Real-time monitoring of multiple parameters such as properties of drilling fluid, bottom hole pressure and circulating flow rate as well as logging data is conducted to detect any minor change of down hole circulating system, minimizing the potential of wellbore collapse and formation breakdown.

The proposed technology has been applied in several onshore and offshore wells with a great success. Generally, a relatively low density of drilling fluid is used to cooperate the application of this new technology, due to its advantage of fast response to down hole conditions, minimizing the possibility of formation breakdown and formation damage as well as enhancing the rate of penetration. The easily collapsed formation is successfully drilled through with the assistance of the proposed technology by maintaining the annular pressure profile to be constant as pre-designed and eliminating the pressure fluctuations. Several incidences of early phase lost circulation are detected in time, and the annular pressure would be modified, avoiding the failure of the borehole wall rock, therefore prevent the serious losses. On the basis of specific MPD equipment, this new technology gives drilling engineers a fast and effective way to ensure the borehole wall stability, thus eliminate the potential of multiple technical issues due to shear and tensile failure of borehole wall rock. Application of this technology could significantly improve the operation efficiency and enhance the economic benefits of drilling operation.

1. Introduction

Wellbore instability refers to a condition that the downhole section does not keep gauge size and shape and structural integrity, which is one of the most rigorous and frequent issue in drilling oil and gas wells. Wellbore instability can take several forms including hole size reduction, hole enlargement, collapse and fracturing¹, and results in different problems such as increase of torque and drag, pipe
sticking, difficulty of casing landing, wellbore deviation, lost circulation, etc. Multiple factors are responsible for wellbore instability and can be generally classified into uncontrollable factors, which attribute the natural characteristics of formation, such as naturally fractured or faulted formations, high in-situ stresses, mobile formations, unconsolidated formations, and controllable factors, which can be manually controlled during the process of drilling operation including bottom hole pressure, well inclination and azimuth, transient wellbore pressure, physical/chemical rock-fluid interaction, drill string vibrations, downhole erosion and drilling fluid temperature. As the development of research techniques, Diverse factors and their corresponding mechanisms are further explored. Kiran, et al. analyzed the effects of irregular shape and wellbore breakout on pressure loss, velocity profile, and geo-mechanical stresses based on CFD modelling method. They indicated that the elliptical profile would resulted in a higher annular pressure losses and the hoop stress profile reversed from increasing to decreasing. Dessouki, et al. proposed elastoplastic models to calibrate Thick-wall cylinder (TWC) laboratory tests using the Modified Cam Clay (MCC) material model and further combined with finite element analysis to investigate failure mechanisms. It was observed that failure occurs in thick-walled cylinder tests when a particular near cavity displacement gradient is achieved for each rock type, this displacement gradient is constant for each rock type independent of wall thickness. Due to the serious consequences of wellbore instability, considerable efforts had been exerted and numerous wellbore Wellbore-stability analyses and borehole-instability prevention measures were proposed. An analytical wellbore stability model was proposed by Wang and Weijermars based on Green and Taylor equations and Jaeger’s Weak-bedding Plane failure criterion, which can be applied to determine the stress concentrations and trajectories near the wellbore, and determination of safe drilling window. Sidelnik, et al. developed an approach for multivariate calculation of wellbore stability to reduce drilling risks in a narrow window of a safe mud density. Gao, et al. performed indoor mechanics experiments to analyze the deformation characteristics of tight sandy conglomerate formation in Bohai Oilfield and developed a finite element numerical model to simulate the development of the plastic zone in the near-wellbore formation, which can be used in determining the safety pressure difference during the well test. Murgas and Tovarb used cavings analysis to enhance the performance of wellbore stability 1D models in forecasting the wellbore stability in real time operations of a well, which is lack of sonic and density well logs information. Hajer, et al. proposed a pre-drill wellbore stability model based on well bore stability analysis of offset wells in Kuwait area. Application of the proposed model and real-time geo-mechanical monitoring had resulted in very good wellbore stability. Zhou, et al. implemented a systematic experimental work to demonstrate that the nanoparticles added to drilling fluids could improve wellbore stability of shale formations. Petrie and Doll introduced the successful application of continuous circulation systems in improving drilling performance and reduce NPT related to wellbore stability in a number of geothermal projects. In the recent years, manged pressure drilling technique was introduced as an innovative way to enhance the wellbore stability, which has a great potential in preventing wellbore instability issues and remediate thier consequenses. Sadlier et al. introduced a case study of a real-time automated pressure management and wellbore stability alarms to reduce the potential of kick, loss, and wellbore instability issues, based on a series of inputs data from both the pre - drill planning and execution stages of drilling. The constant bottomhole pressure variant of managed pressure drilling technique was utilized to mitigate bottom hole pressure fluctuations and cyclic stress, assisting dynamic and static wellbore strengthening operation through sequences of unstable shale and depleted sand packages with no drilling windows. Zein, et al. introduced the pioneering application of managed pressure drilling technique to minimize the potential of bore hole instability and even wellbore collapse by maintaining the down hole pressure profile within the window between wellbore stability gradient and the mud loss gradient during drilling and making connection in East Java Province of Indonesia. This paper introduced a new managed pressure drilling equipment, which is named as pressure control drilling system and its application in preventing rock failure and maintaining wellbore stability. The root principle of the MPD technique and the major element of the MPD equipment are introduced. The process of how the MPD equipment dealing with the wellbore instability issue are introduced in detail. The results of MPD applications are discussed.
2. Principles of MPD in Wellbore Stability Maintenance

2.1 Mud Weight Window
The density of drilling fluid is of vital in maintaining wellbore stability during drilling operation. The drill mud density should be limited within a range to remain the wellbore pressure stable during drilling, which is defined as mud weight window. If the mud weight is smaller than the lower bound of mud weight window, the shear failure is encountered, which probably lead to wellbore shrinkage and collapse. While tensile fractures will be generated if the mud weight is larger than the upper bound of the window, which would result in lost circulation or at least formation damage. The managed pressure drilling technique could retain the wellbore pressure constantly within the mud weight window all the time. The root principles applied by the MPD technique in maintaining the wellbore stability are introduced as follows.

2.2 Constant Bottom Hole Pressure
Generally, the bottom hole pressure during drilling operation can be formulated as

\[ BHP = P_{\text{Hydrostatic}} + P_{\text{Friction}} + P_{\text{Surge}} - P_{\text{Swab}} \]  (1)

Where \( BHP \) is the bottomhole pressure, MPa; \( P_{\text{Hydrostatic}} \) is the hydro-static pressure of the drilling fluid, MPa; \( P_{\text{Friction}} \) is the annulus frictional pressure during circulating, MPa; \( P_{\text{Surge}} \) is the surge pressure caused by running in hole operation; \( P_{\text{Swab}} \) is the swab pressure created during the pull out of the hole operation.

An additional surface back pressure is generated by the manged pressure drilling technique to manage the annular pressure profile within a designed range. The bottom hole pressure can be reformulated by

\[ BHP = P_{\text{Hydrostatic}} + P_{\text{Friction}} + P_{\text{Surge}} - P_{\text{Swab}} + P_{\text{Back}} \]  (2)

Where \( P_{\text{Back}} \) is surface back pressure generated by MPD technique. According to the data provided by the pressure while drilling (PWD) instrument and the equivalent circulation density (ECD) calculated by the hydraulic calculation software, the MPD equipment apply surface back pressure in real time to maintain the annular pressure profile constant within the mud weight window as well as minimizing the pressure fluctuations. This is illustrated by Figure 1.

![Figure 1. Pressure Profiles of Constant Bottom Hole Pressure](image)

2.3 Micro-flux Control
As discussed before, wellbore pressure beyond the upper boundary of mud window could inevitably lead to the loss of circulation. Therefore, precise monitor of mud losses is an efficient way to detect the wellbore tensile failure. Another way of MPD technique to keep the wellbore stability is to precisely monitor any micro changes of fluid flow rate in the wellbore based on mass flowmeter. The process flow chart of Micro-flux Control is shown in Figure 2.

The drill mud outflow rate on the surface is equal to the pumped flow rate in the case of no kick and loss, which is illustrated by equation (3).

\[ Q_{\text{Inflow}} = Q_{\text{Outflow}} \]  (3)

Where \( Q_{\text{Inflow}} \) is the inflow rate of drilling fluid, \( L; \) \( Q_{\text{Outflow}} \) is the outflow rate of drilling fluid, \( L. \)
The difference of inflow and outflow rate is a strong indication of kick and loss. Kick could make the outflow rate of drilling fluid to be larger than the inflow rate. In contrast, smaller outflow rate implies the occurrence of lost circulation, which could be expressed by equation (4).

\[ Q_{outflow} = Q_{inflow} - Q_{Loss} \]  

(4)

Where \( Q_{Loss} \) is the loss rate of drill mud, L.

3. Equipment Description

The pressure control drilling system represents the typical equipment combination of managed pressure drilling equipment. The major elements of the equipment are illustrated as follows.

3.1 Auto-choke Manifold

The auto-choke manifold is the component of the MPD equipment to apply surface backpressure, which includes high precision chokes and accessory channels with different diameters suitable for different flow rates. The surface back pressure could be generated by adjusting the choke position. Mass flowmeter is set in the low-pressure side of the manifold to measure the outflow rate, assisting the wellbore tensile failure. The general configuration of auto-choke manifold is shown in Figure 3.

3.2 Back Pressure Compensation Pump

Back pressure compensation pump (shown in Figure 4) provides additional flow rate for the functioning of high precision auto-choke, therefore maintaining the surface back pressure application, when the circulation is reduced or stopped. The drilling fluid pumped by the compensation pump and then flows through the auto-choke manifold, creating a surface loop of circulation.
3.3 Automatic Centre
The automatic centre is responsible for the data collection, real-time calculation and decision making. The parameters provided by specific sensors, such as bottom hole pressure, stand pipe pressure, inflow and outflow rates are gathered and analyzed, orders are sent to the other components of the MPD equipment to exert proper back pressure. The hydraulic simulations are conducted based on specific hydraulic calculation software, providing reference for decision making.

3.4 Accessory Instrument
Rotating control device is located on the top of the blowout preventor and acts as the auxiliary instrument to create a closed loop of drill mud circulation, generating a closed environment for the back pressure application. The pressure while drilling instrument is another important cooperative instrument of the MPD equipment, which assists to describing the down hole condition and supplying real-time data for decision making.

4. Preparation of Field Applications

4.1 MPD Design
Designing is a necessary stage of MPD application, which pre-determines the annular pressure profile to be within the narrow drilling window. The equivalent circulating density are determined according to the geological design, especially the profiles of formation pressure, collapse pressure and fracture pressure. The application and termination conditions of MPD operation are declared, and procedures during MPD operation are illustrated in detail.

4.2 Hydraulic Simulation
Hydraulic simulation is performed through the two stages of MPD design and operation. In the design stage, the parameters such as frictional pressure, equivalent circulating density, based on the existing data, providing reference for the determination of the range of surface back pressure in the design stage of MPD. In addition, real-time hydraulic calculation is conducted according to the actual data collected during the field application of MPD, giving more accurate hydraulic parameters to decision making.

4.3 Equipment Installation and Pretesting
One choke channel of the auto-choke manifold is connected to the rotating control device, which generates surface back pressure by throttling the back flow of drilling fluid. The back pressure compensation pump is connected to the dedicated channel of the auto-choke manifold for the purpose of fluid compensation during the operations such as making connection, run in hole and pull out of the hole. The automatic centre collects data and send orders through electronic cables and also obtain logging data for comprehensive analysis. The general equipment connection is illustrated by Figure 5. Equipment pretesting and debugging should be performed as the requirement in case of any unexpected equipment failure.
5. Field Application of MPD in Coping with Wellbore Instability

5.1 MPD Successfully Assisting Drilling through Narrow Drill Mud Window
Well A is a horizontal well located in the Qianshan structure, which had experienced several kick, lost circulation issues as well as the coexistence of kick and loss. The formation pressure coefficient of the target zone was predicted to be 0.99-1.03 and quite sensitive to pressure fluctuations. The reservoir possesses the typical characteristic of narrow mud window: lost circulation occurred when the equivalent circulating density is larger than 1.02 g/cm³, while kick would occur during the ECD is smaller than 0.99 g/cm³. The high well control risk and high content of H₂S (99.66 mg/m³ of nearby well) increased the difficulty of MPD operation.

In the application process of the pressure control drilling system, the oil-in-water drill mud with the density of 0.93 g/cm³ was utilized and cooperated by proper surface back pressure to create the equivalent circulating density of 0.99-1.03 g/cm³. The pressure fluctuations were minimized during different operation procedures by the precise application of back pressure and smooth cooperation of MPD elements. Any early sign of kick and loss were detected in advance and surface back pressure was promptly applied to response the down hole changes.

As the result of MPD utilization, the target layer was successfully drilled through without any rock failure and kick issue reported. Indeed, the rate of penetration was dramatically enhanced and the loss volume was reduced by more than 3000 m³ compared to the adjacent well.

5.2 Tensile Failure Prevention and Lost Circulation Detection
Well B is a horizontal well with the length of horizontal section of 335 m, whose target zone faced frequent fracture loss issue. Due to the quite high temperature, the PWD could not be applied, increasing the difficulty of operation.

The pressure control drilling system was applied in the Well B for minimizing lost circulation and formation damage, and indeed enhancing the extension of horizontal section. The pumping rate and returning rate of drilling fluid was precisely monitored, and surface back pressure was adjusted in real time to avoid the formation tensile failure. The cumulative pumping and returning volumes of drilling fluid as well as their difference in a given period were calculated and compared with the volume of drill string, offering an innovative way to loss detection during tripping operation.

On the basis of the PCDS, several lost circulations are detected ahead of time, providing enough response time to deal with the rock tensile failure and implemented real-time feedback of back pressure reduction, preventing the further deterioration of the losses. Besides the wellbore stability benefits, the PCDS is also valuable in the remedial operations including density reduction of drilling fluid as well as wellbore strengthening operation.

5.3 Shear Failure Prevention and Wellbore Collapse Elimination
Well C is an appraisal well located in the Bohai Bay Basin with a design depth of 6000 m. The formation pressure coefficient in the same layer of the nearby well is 1.54 and multiple collapse
incidents were occurred using the drill mud with the density of 1.6 g/cm³. Serious wellbore stability issue and kick and loss incidents declared the application of MPD technique. Based on hydraulic simulation, the density of drill mud is designed to be 1.4 g/cm³ and the ranges of surface back pressure are designed to be 0-2.74 MPa during circulation and 2.14-4.88 MPa during rig pump is stopped. During the MPD operation, any minor indication of wellbore collapse were monitored, such as torque increase, density of outflow drill mud increase, increase of drilling cutting size, and proper surface back pressure would immediately added within the designed range. If the collapse still dominates, the density of drilling fluid was planned to be increased by 0.01-0.02 g/cm³ cooperated by adequate back pressure. The back pressure compensation pump was activated in advance and cooperate auto-choke manifold to ensure the adequate surface back pressure, maintaining the bottom hole pressure to be always larger than the formation collapse pressure. Application of pressure control drilling system plays a significant role in preventing the collapse issue of the Well C, no collapse, kick and loss issues were reported during the MPD operation. Due to the application of MPD technique, the bottom hole pressure is just slight greater than the formation collapse pressure, therefore reducing the cutting-hold effect and enhancing the rate of penetration. As a result, the ROP of the Well C is 1.5 times higher than that of adjacent well.

5.4 Successful Dealing with Formation Creep
Well D is first-level risk development well, located in the Keshen structure, Kuqa depression, Tarim Basin. There is a large salt-paste layer in the open hole section of this well with a maximum inclination angle of 63°, which is highly prone to creep, raising the difficulty of drilling and casing. Lost circulation occurred when the bottom hole ECD exceeds 2.28 g/cm³, while salt water invasion occurred when the ECD was lower than 2.26 g/cm³, demonstrating a typical tight drilling window. The pressure control drilling system was used to perform the managed pressure reaming and managed pressure circulating operation in the 5169–6511.8 m of this well, successfully solving the issue of salt paste layer creep. During the reaming operation, hydraulic calculations were carried out to simulate the dynamic changes of major hydraulic parameters in real-time, the bottom hole pressure was accurately monitored and controlled according to the hydraulic calculation results. The inflow and outflow rate of drill mud were precisely monitored, preventing the salt water invasion and loss of drill mud. After several reaming operations, the casing operation was successfully performed without any stuck pipe incidents reported. The issue of salt paste layer creep was dealt with in a safe and efficient manner with the assistance of the pressure control drilling system. Besides, participation of MPD technique reduced the mud density to 2.18 g/cm³, decreasing the potential of lost circulation and preventing the salt water invasion at the same time.

6. Conclusion
A pioneering work of utilizing an innovative managed pressure drilling equipment, which is named as pressure control drilling system, to solve wellbore instability issues is introduced in this paper. The basic principles used to maintain wellbore stability and MPD equipment configuration are illustrated. The procedures in the filed application are detailed. Application of the PCDS enables the smooth drilling through the formation with limited drilling window, prevents rock tensile and shear failure and successfully deal with the formation creep, demonstrating its technical ability in solving the wellbore instability issue as well as efficiency and economy enhancement.

7. Reference
[1] J B Cheatham, Wellbore Stability J 1984 J. Pet. Technol 36 889-896
[2] BORIVOJE PAŠIĆ, NEDILJKA GAURINA-MEDIMUREC, DAVORIN MATANOVIĆ, Wellbore Instability: Causes and Consequences J 2007 Then Mining Geological Petroleum Bulletin 19 87-98
[3] R Kiran, S Salehi, M Mokhtari, A Kumar 2019 Effect of Irregular shape and Wellbore Breakout on Fluid Dynamics and Wellbore Stability, 53rd US Rock Mechanics/ Geomechanics Symposium held in New York, NY, USA, 23–26 June
[4] M Dessouki, M T Myers, L A Hathon 2020 An Investigation into the Effects of Wall Thickness in Thick-Walled Cylinder Tests on Near Cavity Deformations for Wellbore Stability Applications, 54th US Rock Mechanics/Geomechanics Symposium held in Golden, Colorado, USA, 28 June

[5] J Wang and R Weijermars 2019 Expansion of horizontal wellbore stability model for elastically anisotropic shale formations with anisotropic failure criteria: Permian Basin case study, 53rd US Rock Mechanics/Geomechanics Symposium held in New York, NY, USA, 23–26 June

[6] A S Dahab, Abdulaziz M Abdulaziz, Asmaa Manhalawi, et al 2020 Managing Wellbore Instability through Geomechanical Modeling and Wellbore Stability Analysis, 54th US Rock Mechanics/Geomechanics Symposium held in Golden, Colorado, USA, 28 June

[7] K C Gao, S G Shang, X Wu, et al 2020 Numerical Modeling of Wellbore Stability during Open-hole Well Test in Sandy Conglomerate Reservoir, 54th US Rock Mechanics/Geomechanics Symposium held in Golden, Colorado, USA, 28 June

[8] Jose F Consuegra Murgasa and Lida Vanessa Tovarb 2019 Wellbore Stability Improvement Using Caving Analysis, Eighth International Symposium Geomechanics, 6 – 10 May

[9] Mishari Al Hajeri, Waleed Al Safar, Pravind K Gu, et al 2017 Wellbore Stability Management to Avoid Serious Drilling Hazards in High Deviated Well-Application of Real Time Geomechanics, Abu Dhabi International Petroleum Exhibition & Conference held in Abu Dhabi, UAE, 13–16 November

[10] Nancy Zhou, Yongkang Wu, Meng Lu 2020 An Experimental Study to Demonstrate that Nanoparticles can Filter into Shale Formations and Improve Wellbore Stability, Abu Dhabi International Petroleum Exhibition & Conference held in Abu Dhabi, UAE, 9 – 12 November

[11] Scott William Petrie and Rick Doll 2021 Using Continuous Circulation in Geothermal Wells to Improve Drilling Performance and Reduce NPT Related to Wellbore Stability, SPE/IADC International Drilling Conference and Exhibition to be held virtually on 8 - 12 March

[12] Andreas Sadlier, Chris Wolfe, Mike Reese, et al 2011 Automated Alarms for Managing Drilling Pressure and Maintaining Wellbore Stability—New Concepts in While-Drilling Decision Making, SPE Annual Technical Conference and Exhibition held in Denver, Colorado, USA, 30 October–2 November

[13] I Henry, J Hernandez, A Ngan, et al 2015 Drilling Through Layers of Unstable Shale Formations and Depleted Sand Sequences, the Managed Pressure Drilling / Wellbore Strengthening Approach to Successfully Drill Offshore Development Wells. A Case History, SPE Annual Technical Conference and Exhibition held in Houston, Texas, USA, 28–30 September

[14] Joyde Zein, Fikri Irawan, Andri M Hidayat, et al 2016 Case Study - Constant Bottom Hole Pressure of Managed-Pressure Drilling Utilization to Maintain Wellbore Instability in East Java Drilling Operation, Indonesia, SPE Asia Pacific Oil & Gas Conference and Exhibition held in Perth, Australia, 25-27 October