The Practice Of Integrated E-cd^{TM} & MPD In HTHP Wells

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High pressure, narrow mud window and well control risks are common challenges encountered in High Temperature High Pressure (HTHP) wells. Reducing the complexity of incidents and ensuring the safety while drilling in high pressure and narrow mud window wells are technical challenges which need to be urgently solved. Managed Pressure Drilling (MPD) effectively solves the challenges of safety drilling under narrow safe pressure margin by establishing a trapped pressure environment to control the annular pressure profile. However, the risk of down hole pressure fluctuation still exists due to the switch of circulation from downhole circulation to surface circulation during connection in MPD mode. Continuous Circulation System (CCS) is usually used to maintain the full cycle circulation during connection, but the system is also not able to precisely predict the formation pressure and immediately adjust the bottom hole pressure. In this research, the MPD technology combined with the Eni circulating device (e-cd^{TM}) system is presented to overcome the shortages of MPD and CCS technologies when they are individually applied in high temperature high pressure wells. The application of this combined practice in the Obiafu-X well located in Block OML-61, Delta, Nigeria enabled to avoid the occurrence of various non-production time accidents and improved the drilling efficiency. The combination of MPD technology with e-cd^{TM} system in HTHP wells can therefore provide an advantageous reference in the domestic HTHP drilling industry.

Keywords: Wellbore instabilities; High temperature high pressure; Managed pressure drilling; Continuous Circulation System

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1. Introduction

According to the International Association of Drilling Contractor (IADC), the HTHP wells are characterized with bottom hole temperature greater than 150 °C/300 F and formation pore pressure greater than 10,000 psi/70 MPa, or formation pore pressure equivalent drilling fluid densities greater than 1.80 g/cm^3. Many challenges in HTHP wells lead to frequent incidents such as loss, kick and sticking during drilling operations. HTHP wells often lead to an increase of 30% of non-productive time in comparison with conventional wells and the drilling cost can be tripled [1]. With the increasing number of exploration HTHP wells, MPD technology have been developed and applied by several companies to mitigate wellbore instabilities. For example Halliburton developed Flex Mobile integrated MPD system which applied hydraulic real-time modeling to prevent losses and spills. Weatherford invented Victus MPD system which used intelligent control, equipment automation technologies that enabled the accurate simulation of the bottom hole pressure. Schlumberger invented @balance Deepwater MPD System that enabled to control the wellbore pressure during drilling operations in narrow margin wells [2].

Other theoretical researches related to the application of MPD during drilling operations were equally achieved by researchers: Vieira et al. [3] investigated the downhole pressure uncertainties related to the deep wells using automated MPD technology and demonstrated that MPD can address Non Productive Time and is therefore of greatest potential benefit to deep wells. Al Mutawa et al. [4] equally applied the MPD and underbalanced drilling compounded role in solving the exploration and appraisal challenges of biogenic gas resources and also demonstrated that the combination of these two technologies can eliminate most of the non-productive time in offset wells. Then, Lovorn et al. [5] presented an optimization method of the drilling process using MPD techniques in deep water applications and demonstrated that MPD technologies can effectively be used to mitigate the problems caused by the narrow pressure window environments. Verma et al. [6] presented the first implementation of MPD to drill exploratory and near wildcat well and showed that the formation in lower Bhuban which was previously non-drillable was made drillable by using the MPD technology. Kazakbayeva et al. [7] have successfully implemented the MPD and Managed Pressure Cementing Techniques in Fractured carbonate formation prone to total lost circulation in far north region. The application of MPD technique enabled drilling 6-1/8" hole section with statically underbalanced mud holding constant bottom hole pressure both in static and dynamic conditions.

Apart from the MPD technology, Continuous Circulation System (CCS) has equally been implemented to solve wellbore stability problems in HTHP wells. For example, Colaianni [8] demonstrated that continuous circulation drilling provide a simple solution to mitigate wellbore instabilities in drilling environments with very narrow margins and more extreme deep-water, high-pressure/high-temperature situations. Then, Petrie and Doll [9] have presented the benefits of using CCS in Extended Reach Drilling wells to manage equivalent circulating density (ECD) and bottom hole pressure. They demonstrated that CCS can enhance the management of ECD and control the bottom hole pressure on the well by never switching off the pumps. Moreover, Ashena et al. [10] demonstrated that the application of innovative drilling technologies including casing while drilling to eliminate the casing running time with potential reduction in drilling time, and CCS to prevent cuttings settling and kick flows during connections can be an effective way to handle wellbore instabilities while drilling. Arellano et al. [11] presented a case study of combination of MPD and CCS to drill in the challenging Perla gas field in Offshore Venezuela and demonstrated that combining MPD and CCS system is highly applicable in offshore Latin America, including but not limited to Venezuela.

Although MPD and CCS technologies have successfully been implemented to handle wellbore instabilities in HTHP wells, however, both MPD and CCS have their own limitations when applied individually. In MPD process, the risk of down hole pressure fluctuation still exists due to the switch of circulation from downhole circulation to surface circulation during connection. Additionally, the relatively long connection time increases the risk of sand bridge sticking and full circulation loss prevents proper release of downhole temperatures from the wellbore. On the other hand, wellbore profile could not be controlled due to trapped pressure is not established in CCS process. The limitations of both systems still pose risks in the operations of HPHT wells that require resolution. On account of the aforementioned reasons, it is extremely urgent to find an alternative strategy to handle wellbore instabilities problems in HTHP wells. Eni combines MPD system with e-cd^{TM}, a developed CCS system, in HTHP wells which demonstrates the complementarity of the two systems. The combination of the MPD technology and the e-cd^{TM} system is presented in this research as a solution to solve wellbore stability problems in HTHP wells. The combined practice of these two technologies has already been carried out in operation field and positive results have been obtained proving that it can be an effective way to mitigate wellbore instabilities problems during the exploration of HTHP wells.

2. Characteristics and challenges of HTHP wells

Abnormal pore pressure and narrow safe pressure window are common characteristics in HTHP wells. Due to under compaction deposition, tectonic extrusion, fracture charging, pore fluid expansion and other factors, the formation pressure of narrow window strata is abnormal and the formation fracture pressure is low [12]. The safe drilling pressure window refers to the equivalent circulating density (ECD) range that can maintain the stability of the borehole wall during the drilling process, without the occurrence of well leakage, blowout, well collapse and stuck drilling accidents. Which means $\min\left(\rho_b, \rho_p\right) < \rho_{ECD} < \max\left(\rho_f, \rho_L\right)$. The above equation is expressed in pressure form and can be expressed in Eq. (1)

$$\min\left(P_b, P_p\right) < P_{\mathrm{ECD}} < \max\left(P_f, P_{\mathrm{L}}\right) \quad (1)$$

In Eq. (1): P_p is the pore pressure, psi. P_b is the collapse pressure, psi. P_f is the fracture pressure, psi. P_L is the leakage pressure, psi. Loss would occur if $P_{ECD} > P_f$ or P_L Kick would occur if $P_{ECD} < P_p$. Collapse would occur if $P_{ECD} < P_p$ [13]. It is difficult for the traditional drilling mode to maintain constant bottomhole pressure under high temperature and high pressure conditions. In fact , the main down hole ECD consists of hydrostatic fluid pressure and circulating pressure while drilling, however, the circulation should be off when making connections in conventional drilling which means that the circulating pressure would be lost in connection section. This drawback of conventional drilling could not able to be addressed in HTHP wells. The graph of hydrostatic column pressure and bottomhole ECD in conventional drilling mode is shown in Fig. 1.

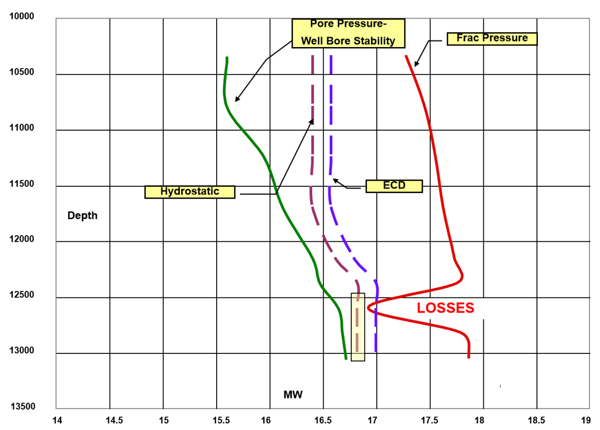

Fig. 1. Hydrostatic column pressure and bottomhole ECD in conventional drilling modes

3. Managed pressure drilling

3.1. Characteristics of managed pressure drilling

To solve the challenge of narrow safe pressure window, the concept of MPD was proposed. MPD is an adaptive drilling program that precisely controls the entire annular pressure profile. MPD is able to monitor the annular pressure profile while drilling and feed it back to the automatic control system, by adjusting the surface back pressure.

MPD system solves the narrow safe pressure window problem by establishing a surface back pressure in the trap environment to compensate for the missing of circulating pressure in traditional drilling connection. The rotating control device (RCD) of MPD system that surrounds the top of the string can seal the annular between the drilling string and the well. Meanwhile, the None Return Valve (NRV) in the bottom of the drilling string only allows forward flow. Thus, the pressure is trapped between the RCD and the NRV. Under this trapped environment, the surface back pressure can establish and compensate the missing of circulating pressure which is the main advantage of MPD. During pipe connection, the bottom hole pressure is equivalent to the hydrostatic pressure plus the surface back pressure. The The graph of hydrostatic column pressure and bottomhole ECD in MPD mode is shown in Fig. 2.

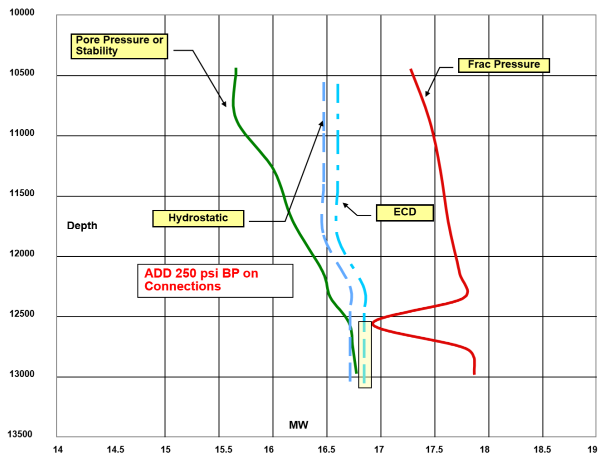

Fig. 2. Hydrostatic column pressure and bottom hole ECD in MPD mode

The ECD is composed of static mud density and added value in the traditional drilling mode, which can be expressed in Eq. (2) [14].

$$ECD = ESD + AECD = \frac{P_b + \int_0^H \rho g dH}{gH} + \frac{P_a}{gH} \quad (2)$$

In Eq. (2): P_b is surface back pressure, psi. P_a is annular friction, psi. G is the gravity acceleration, m/s^2. ρ is the mud density, kg/m^3. H is vertical depth, m. In addition, MPD system can maintain the ECD as close as possible of the safe margin, which has a significant effect on improving the Rate Of Penetration (ROP), protect the reservoir and avoid differential pressure sticking [15–18].

3.2. The imperfection of MPD system

The MPD system compensates the lack of circulating friction while making connection by applying surface back pressure in the trapped pressure environment that can solve the narrow safe window problem, however, the risk of getting stack raises due to cuttings settling which is caused by prolonged lost circulation under complex MPD connection process since the full circulation is interrupted. Besides, the pressure fluctuation problem is also raised when the full circulation is switched to surface circulation.

1) Error in annular pressure loss fitting

Various measured and calculated data cannot be accurately determined during drilling operations therefore are still some pressure fluctuations and errors in the actual operation.

The bit pressure loss can be expressed in Eq. (3) [19].

$$\Delta p_b = \frac{0.081\rho Q^2}{C^2 d_{ne}^4} \tag{3}$$

In Eq. (3): C is the flow coefficient of bit nozzle, d_{ne} is the equivalent diameter, ρ is the density of the fluid.

The pressure loss in the string can be expressed in Eq. (4) [20].

$$\Delta P_p = \frac{0.2 f \rho_m L V^2}{d} \tag{4}$$

In Eq. (4): $f = 0.0265\left(\frac{\eta}{\rho m d V}\right)^{0.2}$ in IF drill pipes, $f = 0.0295\left(\frac{\eta}{\rho m d V}\right)^{0.2}$ in FH drill pipes. ΔP_p is pressure loss, MPa. L is the length of the string, m. V is the average flow rate of drilling fluid in the drill pipe, m/s. d is the ID of the drill pipe, cm. f is the hydraulic friction coefficient in the string, zero dimension. η is the plastic viscosity of drilling fluid, Pa·s.

The annular pressure loss can be expressed in Eq. (5) [21].

$$P_{fr} = \frac{61.1\gamma v L_p Q_m}{(D_h - D_p)^3 (D_h + D_p)} + \frac{0.004 Y_p L_p}{(D_h - D_p)} \tag{5}$$

In Eq. (5): P_{fr} is annular pressure loss, kPa. γv is the plastic viscosity of drilling fluid, mPa·s. Q_m is the flow rate, L/s. D_p is the ID of the drill pipe, mm. D_h is the OF of the well or casing, mm. L_p is the length of the string, m. Y_p is the yield value, Pa.

2) The risks of hole cleaning

Compared with the conventional drilling, MPD technology is relatively complex, and the connection time is relatively long. After the interruption of full circulation, cuttings will quickly sink and accumulate in the hole which can result in the reduction of the hole cleaning efficiency. Cutting bed can easily form in highly deviated wells and horizontal wells, and there is the risk of sand bridge sticking if the situation is serious.

3) The effect on temperature

During connection of the MPD in HTHP Wells, the down hole temperature can not be released from the wellbore due to the high temperature in the wellbore. As a result, the rheology and density of the drilling fluid also change while the temperature of the drilling fluid increases, and the final change of the bottom hole ECD affects the stability of the bottom hole pressure. After the circulation stops, The slurry column in the wellbore has the following energy balance equation [22].

The inner temperature of the string can be expressed in Eq. (6).

$$\rho_t c_{pt} \frac{\partial T}{\partial t} \pi r_{ti}^2 = \frac{2\pi r_{ti} k_t (T_a - T_t)}{r_{to} - r_{ti}} \tag{6}$$

The annular temperature can be expressed in Eq. (7).

$$\begin{aligned} \rho_a c_{pa} \frac{\partial T_a}{\partial t} \pi \left(r_{ci}^2 - r_{to}^2\right) = \\ (T_{ei} - T_a)\, 2\pi r_{ci} \left[\frac{r_{wb} - r_{co}}{k_{cem}} + \frac{r_{co} - r_{ci}}{k_{cas}}\right] \\ -1 - \frac{2\pi r_{to} k_t (T_a - T_t)}{r_{to} - r_{ti}} \end{aligned} \tag{7}$$

In Eq. (7): ρ_t, ρ_a are the mud density in the string and annular, kg/m^3. k_t, k_{cas} are the thermal conductivity of string and casing respectively, W/(m·°C). r_{ci} is the radius of the casing, m.

4. Continuous circulation system

4.1. The characteristics of CCS

In conventional drilling, cuttings stop returning back after full circulation stops during connection, and cuttings gradually increases in the bottom hole with the time. In the severe case, the bottom hole assembly (BHA) may be buried or the string may become stuck if the cutting bridge is formed and the pump is switched aggressively, besides, it is possible to lead the formation leaked when switching on the mud pump. Therefore, the concept of CCS was proposed. CCS switches the circulation path from the top drive system (TDS) to bypass without turning off the mud pump before connection and continue full circulation during connection. The circulation path is switched from bypass to TDS without turning off the mud pump after connection which means the full circulation is sustained among the connection operation. CCS does not only avoid pressure fluctuations caused by pumping on and off during connection, but also improves hole cleaning by continuously carrying out the cuttings from the bottom hole and annular which are its primary advantages [23].

4.2. The development status of CCS

The CCS was first invented by Maris. The system consists of connectors, well head tools and a three-stage BOP which include upper pipe ram, lower pipe ram and middle bland ram, shown in Fig. 3. The tool joint in the middle of the three-stage BOP is set before connection, the mud is then introduced through the connector into the ram to equalize the pressure inside and outside the string. After the drill string is disconnected, the mud enters the lower string and continues going downstream to continue full circulation. Soon afterwards, the string is picked up to proper position and the middle bland ram is closed which forms two trapped rooms. The new pipe is connected after the pressure is released from the upper room and the drilling fluid is leaded to the upper room to balance the pressure, and subsequently the middle bland ram is opened to connect the previous tool joint. The reciprocation is achieved continuously through the above way [24, 25].

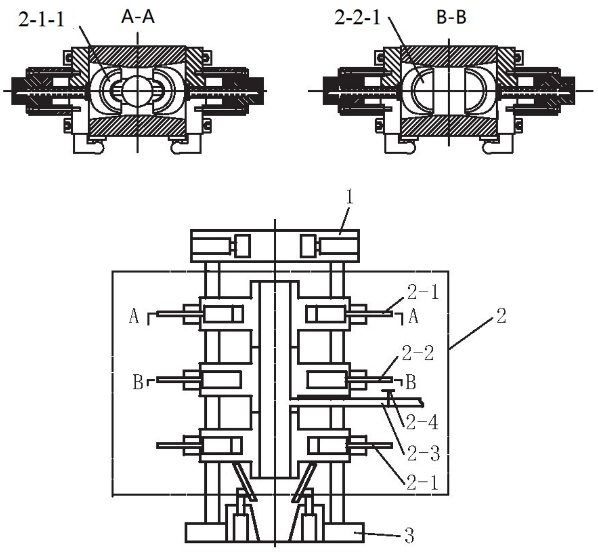

Fig. 3. The wellhead of CCS, 1 Back-up tong, 2 Drilling fluid switching system, 2-1 Pipe ram, 2-1-1 Elements of pipe ram, 2-2 Bland ram, 2-2-1 Elements of bland ram, 2-3 Bypass, 2-4 Valve of bypass, 3 Power slip

Due to the, complexity and high cost of CCS system, Eni proposed the Eni circulating device (e-cd^{TM}), shown in Fig. 4. e-cd^{TM} sub is the key device of the system which includes a switching guide part and a continuous cycle valve. The e-cd^{TM} sub consists of two valves in the upper and middle. The valve can be opened in one direction at low pressure and closed at reverse pressure. The e-cd^{TM} sub includes two types: 4 1/2" IF and 5 1/2" FH [26, 27]. The e-cd^{TM} system has the characteristics of simple operation, reliable and light structure, which makes it safer and more efficient in the operation.

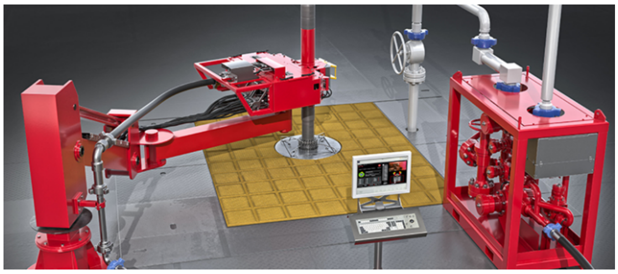

Fig. 4. e-cd^{TM} system

4.3. The disadvantages of The e-cd^{TM}

Although e-cd^{TM} system achieves continuous full circulation during connection which solves the problems of bottom hole pressure fluctuation and hole cleaning, however it can not predict the safe pressure margin and control the wellbore profile. It can not equally detect the kick and loss at the first time in complex formation due to not equipped with Early Kick Detection System (EKDS). e-cd^{TM} system can not equally control the downhole pressure by adjusting surface back pressure due to the trapped pressure environment not established, especially during the drilling mode. Besides, e-cd^{TM} system is not able to carry out choke circulation at the first time but it can only establish choke circulation after closing the well.

To address the aforementioned shortcomings of e-cd^{TM}, a trapped pressure environment need to be established by using MPD system.

5. The integration of e-cd^{TM} and MPD in HTHP wells

5.1. The complementarity of e-cd^{TM} and MPD

Eni integrated e-cd^{TM} and MPD systems to address the limitations of each systems that can be finally applied in HTHP operation, the combination not only integrated the advantages of both system but also alleviated their individual defects. The combination of e-cd^{TM} and MPD enables to control the formation pressure profile and maintain the full circulation during connection to mitigate wellbore instabilities. It avoided the fluctuation of bottom hole pressure during circulation switch from the full circulation to surface circulation in traditional MPD circulation, but also prevented the stuck by continuously circulating out of the cuttings from the annular. The integrated use of e-cd^{TM} and MPD method is proved be applicable to most types of HTHP well, especially in extreme narrow safe pressure window wells.

5.2. The process of connection

MPD drilling mode is applied before connection. The drilling fluid goes through the top drive, passes through the bit to the annular, goes up in the annular and enters the trapped choke line against the RCD (rotating control device) and finally returns back to the active tank after choke system. The circulation is maintained with full circle and the pressure profile is controlled as shown in Fig. 5.

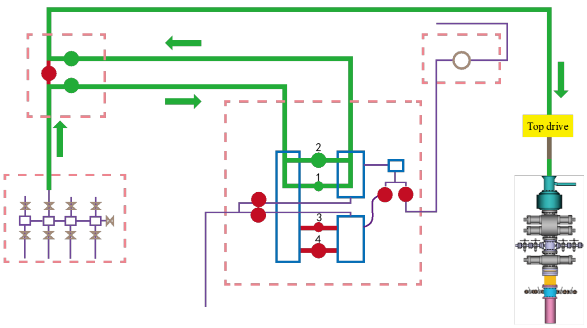

Fig. 5. The circulation path during drilling mode

1) Line up the unit to bypass e-cd^{TM} sub, then open 3# auxiliary valve and balance the pressure through the compensation control system, meanwhile MPD system maintains the downhole pressure by adjusting the auto choke and the full circle circulation is continued, the process diagram is shown in Fig. 6.

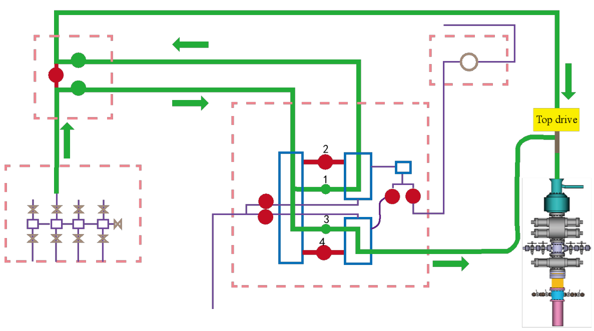

Fig. 6. Line up the path of e-cd^{TM} bypass

2) Open 4# valve and increase the flow rate through bypass to normal flow rate, then gradually close 1# and 2# valves step by step. The circulation path is switched to bypass. MPD system maintains the downhole pressure by adjusting the auto choke and the full circle circulation is maintained during the process, the process diagram is shown in Fig. 7.

3) Conduct the connection operation, meanwhile the bottomhole pressure is managed and the full circle circulation

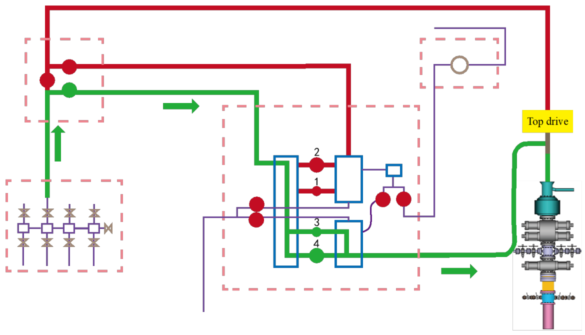

Fig. 7. Circulation path is switched to bypass

is maintained , the process diagram is shown in Fig. 8.

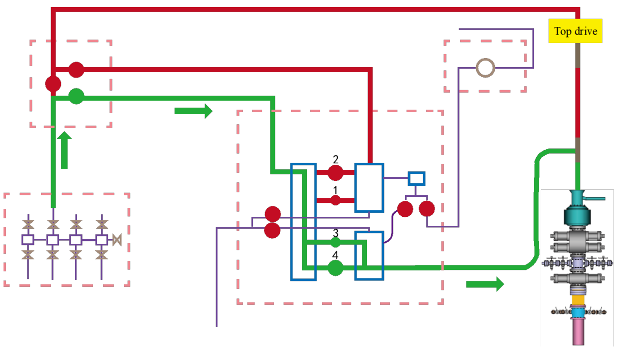

Fig. 8. Make new connection

4) Open 1# valve after making new connection, balance the pressure and break circulation through TDS, meanwhile MPD maintains the downhole pressure by adjusting the auto choke and the full circle circulation is continued during the process, the process diagram is shown in Fig. 9.

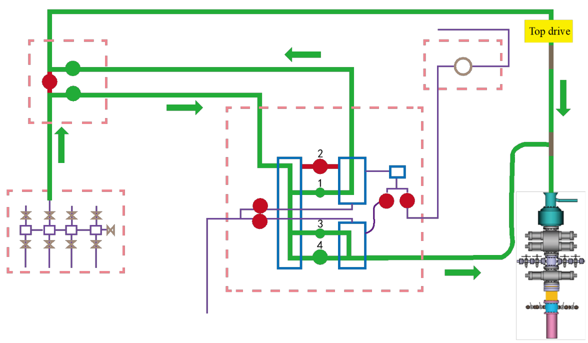

Fig. 9. Break the circulation path through TDS

5) Open 2# valve, increase flow rate through TDS to normal flow rate gradually meanwhile close 3# and 4# valves step by step. The circulation is switched back to TDS. Drilling mode is resumed after the line up is disconnected

Table 1. Related operation data

Well name	Depth (ft)	Max pressure (psi)	Max temperature (°C)	Technology applied	Drilling time (day)
Baran-X	17,274	14,875.0	145	MPD	248.85
KOLO CREEK-X	15,457	14,639.5	126.1	MDP	147.80
EPU-X	15,900	11,602.0	132.2	MPD	148.14
Obiafu-X	15,125	14,572.2	153	MPD and e-cd^{TM}	110.49

from the bypass. MPD maintains the downhole pressure by adjusting the auto choke and the full circle circulation continues during the process which is shown in Fig. 10.

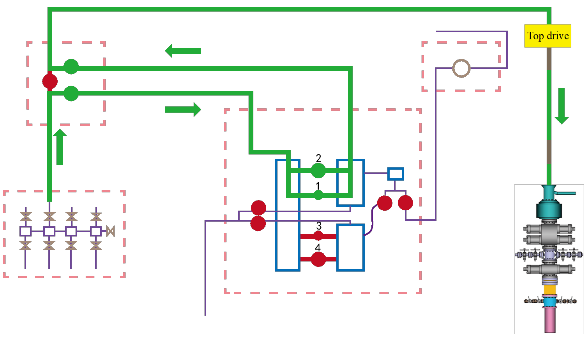

Fig. 10. The circulation is switched to TDS

5.3. The application effect of combined MPD and e-cd^{TM}

Due to the challenges of HTHP Wells, a significant amount of non-productive time is caused due to loss, kick, trip resistance, and stuck pipe that use singulary MPD or CCS/e-cd^{TM} alone.

For example, Gbaran-X well is a narrow mud window HTHP well. Kick was detected while drilling from to 16,578 ft in Φ215.9 mm hole section, the max shut in pressure was raised to 10,700 psi gradually in the end. Three months were spent to deal with the incident which caused a great economic loss. According to the investigation of the incident, the root cause is directly related to the multiple full circulation lost and the inaccurate ground back pressure fitting during the pump stops, which can not balance the actual formation pressure.

Another example is Kolo Creek-X well which is also a narrow mud window HTHP well. Kick was observed while pumping out to 11,573 ft. The max shut in pressure raised to 4,500 psi after shutting in the well. The well was then collapsed and the string got stuck. Downhole pressure fluctuated which caused by lost full circulation is believed the root cause according the investigation.

In both incidents, the failure was caused by full circulation loss during connection. The probability of failure would be greatly reduced if e-cd^{TM} and MPD were combined and applied in the operation.

Obiafu-X well is located in Block OML-61, Delta, Nigeria. The well has a maximum formation pressure of 14,572.2 psi, a maximum bottomhole temperature of 153 °C, a maximum bottomhole ECD of 2.24 g/cm^3, a safe pressure window of 0.04 g/cm^3 in Φ270 mm hole section and a safe pressure window of 0.09 g/cm^3 in Φ215.9 mm hole section, it is an extremely HTHP well with a very narrow safe pressure window. Eni integrated MPD and e-cd^{TM} into this well. During the operation, the bottomhole pressure was very stable, and there were no complex problems such as loss and kick. Moreover, there were no obstacles during tripping, which avoided the occurrence of various non-production time accidents. In the end, it took 110.49 days to complete the drilling operation safely and smoothly, which greatly improved the operating efficiency and produced good economic benefits. The integrated use of E-CD and MPD method in Obiafu-X well is the typical successful case of implementing this drilling technique, the practice of this well is a valuable reference for learning. The related operation data is shown in Table 1.

Yet, since MPD system and e-cd^{TM} are provided and operated by different independent companies, the equipments need to be designed simpler to form an integrated system, the teams is also to be optimized.

6. Conclusion

1. MPD and e-cd^{TM} technologies can hardly alleviate their respective defects when applied separately. The combined application of MPD and e-cd^{TM} in Obiafu SW deep E has successfully verified the complementarity, safety and economy of MPD and e-cd^{TM} system.
2. Many deep exploration operations have encountered problems such as abnormal high pressure and narrow safe pressure window. The successful combination of MPD and e-cd^{TM} provides experience and reference for solving similar problems.
3. The optimization and integration of MPD and e-cd^{TM} system to form an independent and integrated technology is of great significance to effectively solve the

narrow density window drilling technology problem, which needs to be further explored and practiced.

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