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Digitalization in Drilling: Automated back pressure drilling (MPD) for controlling and keeping BHP constant

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Contents

Nomenclature

MPD	**Managed Pressure Drilling**
CBHP	**Constant Bottom Hole Pressure**
NPT	**Non-productive Time**
PMCD	**Pressurized Mud Cap Drilling**
FMCD	**Floating Mud Cap Drilling**
DGD	**Dual Gradient Drilling**
RFC	**Return Flow Control**
AFP	**Annular Friction Pressure**
ECD	**Equivalent Circulating Density**
BP	**Back Pressure**
AFL	**Annulus Friction Loss**
BHP	**Bottom Hole Pressure**
NRV	**Non-Return Valve**
ROP	**Rate of Penetration**
RCD	**Rotating Control Device**
BOP	**Blow out Preventer**
SBP	**Surface Back Pressure**
TVD	**True Vertical Depth**
MW	**Mud Weight**
CMCD	**Controlled Mud Cap Drilling**

1 Introduction

The digitalization of drilling processes has revolutionized the oil and gas industry, leading to significant advancements in drilling techniques and technologies. One of the key areas of focus in this digitalization is the development of automated back pressure drilling, also known as Managed Pressure Drilling (MPD), for controlling and maintaining the Bottom Hole Pressure (BHP) constant. This approach has been facilitated by the integration of digital twin frameworks, artificial intelligence methods, and advanced hydraulic models, which have collectively enhanced the accuracy and drilling operations efficiency.

The digitalization of hydraulic rotary drilling processes has enabled the continuous mechanical profiling of siliciclastic sedimentary rocks, leading to the identification of variations in drilling speed that are consistent with the properties of different geomaterials and ground conditions (1). This digitalization has provided factual drilling data that are crucial for understanding the behavior of different formations and optimizing drilling parameters.

Furthermore, the development of a digital twin framework for robotic drilling processes has facilitated real-time monitoring and control of drilling operations, allowing for the virtual assessment of dynamic drilling behaviors such as speed and feed irregularities (2, 3). This has significantly enhanced the ability to maintain BHP constant during drilling operations.

Artificial intelligence methods have also played a pivotal role in the digitalization of drilling processes, particularly in the context of MPD. These methods have been successfully applied in various aspects of the oil and gas industry, including reservoir characterization, prediction of PVT properties, and optimization of well production (4).

Moreover, the integration of a hybrid neural network model has provided valuable insights for predicting BHP in MPD, offering guidance for fine pressure control in complex formations (5). This demonstrates the potential of artificial intelligence in optimizing drilling processes and ensuring the stability of BHP.

In addition to digital twin frameworks and artificial intelligence, advanced hydraulic models have been instrumental in the development of automated MPD control systems. These models have been used to intelligently estimate downhole pressure, thereby enhancing the accuracy of pressure control systems in MPD operations (6, 7).

Furthermore, the comparison of latero-medial versus dorso-palmar/plantar drilling approaches has highlighted the usefulness of digital fluoroscopy in assessing the percentages of articular cartilage removed during drilling, emphasizing the role of digital technologies in enhancing precision and control during drilling procedures (8).

The digitalization of drilling processes has not only improved the accuracy and efficiency of drilling operations but has also facilitated the digital archiving and characterization of drill core samples, contributing to the repeatability of experiments and the comprehensive understanding of rock formations (9).

Moreover, the application of digital technologies has enabled the real-time monitoring and control of drilling processes, leading to the development of automated drilling algorithms and tools for strengthening the understanding of drilling operations and automating routine tasks (10).

The digitalization of drilling processes, facilitated by digital twin frameworks, artificial intelligence methods, and advanced hydraulic models, has significantly advanced the capabilities of automated back pressure drilling for controlling and maintaining BHP constant. These technological advancements have not only enhanced the accuracy and efficiency of drilling operations but have also paved the way for the development of automated drilling algorithms and tools, ultimately revolutionizing the oil and gas industry.

In this thesis, the focus is on Automated back pressure drilling (MPD) for controlling and keeping BHP constant using Python.

2 Managed Pressure Drilling

Managed Pressure Drilling (MPD) is an advanced drilling technique that aims to precisely control the wellbore pressure profile while enhancing downhole pressure-control performance and improving drilling safety (11). It involves maintaining near-constant bottom hole pressure by adjusting the drilling fluid density, equivalent circulating density, and casing back pressure in a closed system (12). This method is particularly useful in formations with a narrow tight mud window between fracture pressure and formation pore pressure (13).

Automated MPD systems have been developed to enhance pressure-control performance and safety during drilling operations (7). These systems can contribute to improving wellbore stability and drilling safety by precisely controlling the annular pressure profile throughout the wellbore (14). Additionally, the use of MPD has been associated with reducing various drilling problems such as kicks, formation damage, wellbore instability, and drilling fluid circulation loss (15).

Furthermore, the application of digitalization and automation in MPD systems has the potential to revolutionize drilling operations. Automation of various aspects of the drilling process, including precise borehole-pressure control, pipe handling, and different drilling operations, is becoming increasingly available and can significantly improve safety on drilling rigs by reducing or removing personnel from the drilling floor (16).

Additionally, the use of deep learning approaches in drilling operations, such as well control space out, has been proposed to optimize drilling safety operations, indicating the potential for integrating advanced technologies into MPD systems (17).

The integration of automation and digitalization in MPD systems grants great assurance for the future of drilling operations, offering enhanced safety, improved pressure control, minimizing non-productive time (NPT), and greater efficiency.

2.1 MPD Vs. Under-balanced Drilling and Conventional Drilling

This section will compare managed pressure drilling (MPD) with underbalanced drilling and conventional drilling. The ranges in which these techniques can be operated are illustrated in Figure 1.(18) below.

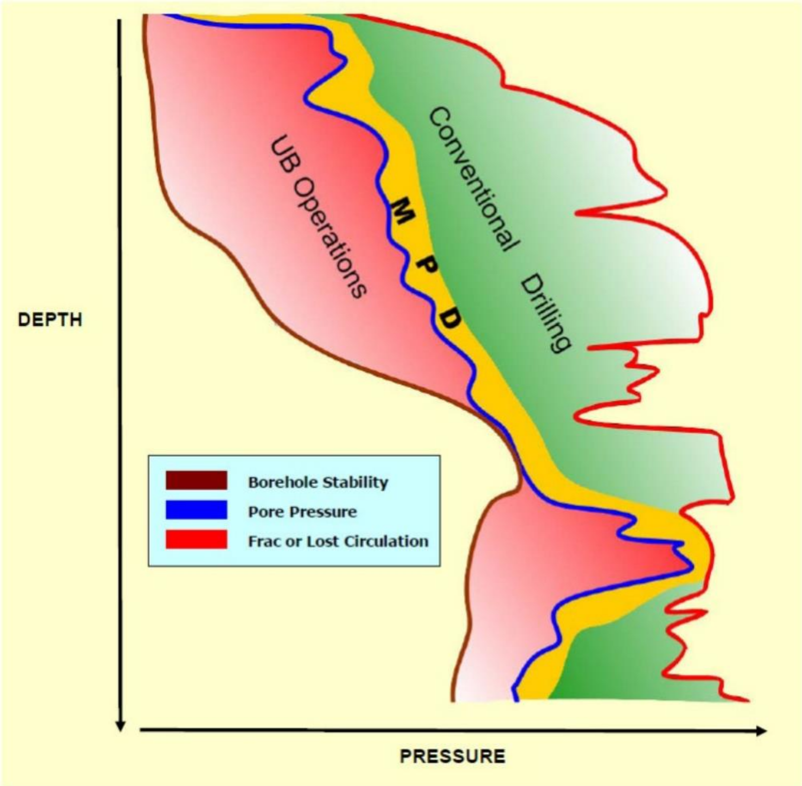

Figure 1 Mud Window for Different Drilling Methods (18)

As depicted in Figure 1, underbalanced drilling is conducted at pressures lower than the pore pressure, in contrast to conventional drilling, where the bottom hole pressure consistently exceeds the pore pressure. Managed Pressure Drilling (MPD), on the other hand, keeps the pressure slightly above the pore pressure to enhance the rate of penetration, all while staying within a safe pressure range. More comprehensive explanations of these methods are provided in the subsequent sections.

Conventional Drilling

In conventional drilling, the well is always maintained at an overbalanced pressure, meaning the pressure in the wellbore remains higher than the pore pressure across the entire exposed formation. Key factors such as mud density and mud flow rates are used to regulate the annular pressure in this technique (18).

During static conditions, the bottom hole pressure is determined by the hydrostatic pressure of the drilling fluid column. In dynamic conditions, annular friction pressure is also considered. The static condition in conventional drilling can be described by the following equation, where $\boldsymbol{P_{Hyd}}$ represents the hydrostatic pressure and $\boldsymbol{P_{BH}}$ denotes the bottom hole pressure(19).

$$\boldsymbol{P_{Hyd} \geq P_{BH}}$$ **Equation 1**

When the mud pump is actively circulating, the bottom hole pressure under dynamic conditions can be described by the following equation, where $\boldsymbol{P_{AF}}$ denotes the annular friction pressure.

$$\boldsymbol{P_{BH} = P_{Hyd} + P_{AF}}$$ **Equation 2**

Figure 2.(18) elaborates on the dynamic and static pressure conditions described in equations 1 and 2. It illustrates that with increasing true vertical depth (TVD), the effect of annular friction pressure $\boldsymbol{P_{AF}}$ intensifies, leading to greater divergence between the dynamic and static pressure profiles.

Conventional drilling operations are associated with a higher risk of hazardous situations, including kicks, lost circulation, and stuck pipes, which can endanger human life and harm the environment.

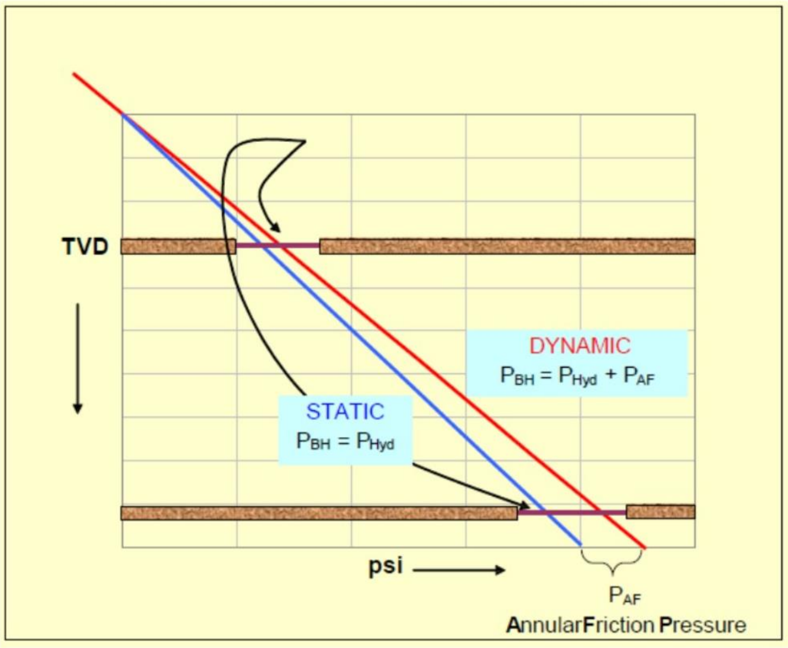

Figure 2 Dynamic and Static Pressure Profiles (18)

Underbalanced Drilling

Underbalanced drilling is a technique where the pressure exerted by the drilling fluid in the wellbore is intentionally maintained below the pore pressure of the exposed formations. This approach aims to enable formation fluids to flow to the surface, as described by the relationship in Equation 3 (18).

$$P_{BH} > P_{Hyd}$$ Equation 3

This technique is frequently used to improve reservoir productivity, reduce the risk of formation damage, prevent lost circulation, and increase the rate of penetration (ROP). Nonetheless, keeping the bottom hole pressure below the pore pressure can raise the borehole instability risk, as it may lead to the failure or yielding of the rock surrounding the borehole (20).

Managed Pressure Drilling

Managed Pressure Drilling (MPD) is employed in unconventional drilling situations when the narrow gap between fracture pressure and pore pressure makes wellbore integrity susceptible to bottom hole pressure (BHP) fluctuations resulting from mud pump operations.

The leading objectives of MPD are to address various drilling challenges, improve drillability, and lower costs by reducing non-productive time (NPT). Unlike conventional drilling methods, MPD has several unique features, as summarized by (21):

- The main goal of MPD is to maintain bottom-hole pressure within a specified range. Figure 3 (21) compares conventional drilling and MPD methods under different conditions such as increasing flow rate, tripping, making connections, and decreasing flow rate. It demonstrates that the active response of MPD has more stability and less erratic than that of conventional drilling. This improved stability is due to precise control of wellhead pressure and keeping the drilling fluid density below the equivalent pore pressure of the formation.

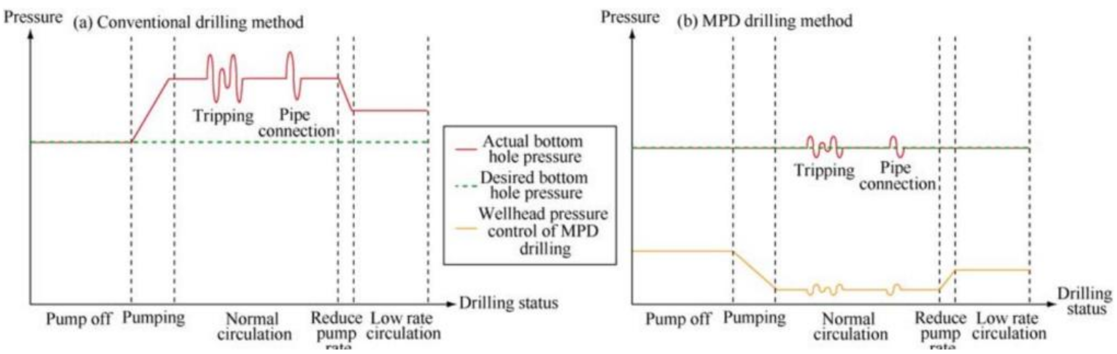

Figure 3 Conventional and MPD Drilling BHP Comparison (21)

- Managed Pressure Drilling (MPD) technology can be divided into several categories based on its application, including Dual Gradient MPD, Constant Bottom Hole Pressure MPD, Return Flow Control (RFC), and Mud-Cap MPD. Of these, Constant Bottom Hole Pressure MPD is the most straightforward to be implemented and is the most widely used. MPD also might be classified by its approach into Proactive and Reactive MPD. Reactive MPD is planned and follows a predetermined procedure, while Proactive MPD adapts in real time using installed equipment as needed.

- MPD offers more control variables than conventional drilling methods, as shown in Table 1. (21), enabling it to manage bottom hole pressure (BHP) more effectively within narrow technical limits. For example, in conventional drilling, the friction of the annulus cannot be utilized when the pump stops and adjustments to drilling fluid density are impossible to be made instantaneously. In contrast, MPD can control pressure more precisely by using methods like dual gradient drilling fluid density or controlling the back pressure.
- MPD employs specialized equipment that distinguishes it from conventional drilling, including a control system of surface pressure, a constant circulation system, a rotating control device, a multiphase separator, and other tools specific to different MPD applications.

Table 1 MPD and Conventional Methods (21)

Drilling Methods	Control Variables	Control methods
Conventional Drilling	Flow rate of drilling fluid Density of drilling fluid	Adjust annulus friction Adjust density of drilling fluid
MPD Drilling	Flow rate of drilling fluid Density of drilling fluid Wellhead back pressure Downhole pressure at certain depth	Adjust annulus friction Adjust density of drilling fluid Sealed wellhead or choke valve Special down hole tool

In summary, MPD optimizes bottom-hole pressure by adjusting one of its control parameters. One such method involves tweaking the wellhead back pressure, which can be understood through the following equation illustrates the BHP calculation when MPD is utilized:

$$\boldsymbol{P_{BH} = P_{Hyd} + P_{AF} + P_{B}} \quad \text{Equation 4}$$

The additional term $\boldsymbol{P_B}$ represents the surface back pressure. Adjusting $\boldsymbol{P_B}$ allows for an immediate change in $\boldsymbol{P_{BH}}$, making it an ideal control variable. In MPD systems with automation, the term corresponding to surface pressure ($\boldsymbol{P_{BH}}$) is typically adjusted automatically by a choke valve controlled via a system (22).

2.2 Managed Pressure Drilling Techniques

Managed Pressure Drilling (MPD) encompasses various techniques which are employed to keep the pressure near-constant bottom-hole pressure and enhance drilling operations. These techniques include (23):

- Constant Bottom-Hole Pressure (CBHP)
- Mud Cap Drilling (MCD)
  - Pressurized Mud Cap Drilling (PMCD)
  - Floating Mud Cap Drilling (FMCD)
- Dual Gradient Drilling (DGD)
- Return Flow Control (RFC)

Constant Bottom Hole Pressure (CBHP) is a primary MPD technique that involves adjusting the drilling fluid density, equivalent circulating density, and casing back pressure to maintain a constant bottom hole pressure. This technique is particularly useful in formations with a narrow window between fracture pressure and formation pore pressure, as it allows for precise control of the wellbore pressure profile.

Pressurized Mud Cap Drilling (PMCD) is another MPD technique that involves the use of a light fluid (such as seawater or foam) to maintain a pressurized mud cap in the annulus. This technique is often employed in challenging drilling environments, such as deepwater drilling or drilling in narrow pressure windows, to control wellbore pressure and prevent influxes of formation fluids.

Dual Gradient Drilling (DGD) is a technique that involves the utilization of two different drilling fluid gradients in the wellbore to control bottom hole pressure. This technique allows for the manipulation of the hydrostatic pressure in the wellbore to maintain a constant bottom hole pressure, particularly in challenging drilling scenarios.

Return Flow Control (RFC) is a critical component of MPD techniques, as it involves the use of advanced monitoring and detection systems to identify and respond to kicks or influxes of formation fluids at an early stage. This technique is essential for maintaining well control and preventing wellbore instability during drilling operations.

These MPD techniques play a vital role in enhancing drilling safety, improving wellbore stability, and mitigating drilling challenges in various geological formations and drilling environments. The integration of these techniques with digitalization and automation further enhances their effectiveness in modern drilling operations.

2.2.1 Constant Bottom-Hole Pressure (CBHP)

Managed Pressure Drilling (MPD) is a technique used in drilling operations to manage wellbore pressure precisely, particularly where drilling within a narrow window between fracture pressure and pore pressure (24). One specific MPD technique is the Constant Bottom-Hole Pressure (CBHP) method, which aims to maintain a relatively constant bottom-hole pressure, allowing for the circulation of small influxes out of the well without shutting in (25). This technique involves a closed system that utilizes a mixture of drilling fluid density, casing back pressure (BP), and equivalent circulating density (ECD) to achieve near-constant bottom-hole pressure (12).

The CBHP method is crucial in maintaining wellbore pressure above the pore pressure or in other words wellbore stability and below the fracture pressure, thus preventing well-control issues such as kicks and blowouts (24). Research has been conducted to address challenges in implementing the CBHP method. For instance, an algorithm was developed to automatically opt for the best well-control response to any kick or influx during CBHP MPD operations (26, 27). Additionally, a study evaluated substitutable initial responses to kicks happen during CBHP MPD operations, aiming to enhance the well-control procedures in such scenarios (28). Furthermore, a proposed scenario for planning the most effective initial response to kicks during MPD operations using the CBHP method was investigated, highlighting the industry's interest in optimizing well control methods for CBHP (29).

Moreover, the CBHP method presents challenges related to uncertainties in the drilling process, including unknown system parameters and unmeasured bottom-hole states, which require robust adaptive control and estimation techniques (11). To address this, research has focused on developing adaptive controllers and estimators to monitor and control bottom-hole pressure in real time, considering uncertainties and unmeasured parameters (11, 14). In practical applications, the CBHP method has been successfully applied in controlling bottom-hole pressure within an exact range, demonstrating the feasibility and effectiveness of managed pressure technology in drilling operations (30).

Additionally, the CBHP method has been identified as a key component in the full pressure profile control method, which is an extension of the well-known CBHP method, further emphasizing its significance in MPD operations (31).

Research efforts have focused on addressing challenges and optimizing the implementation of the CBHP method, highlighting its importance in enhancing drilling operations.

As the pumps are activated and mud is circulating, the term Annular Friction loss (AFL) or Annular Friction Pressure (AFP) will be contributed to BHP and when the pumps are deactivated, this term will vanish. So we use a parameter as Back Pressure (BP) to keep BHP in the mud window. (it will be more explained in the next chapter). Figure 4 (32) shows the ECD compensation during active and deactivated pumps and BPs.

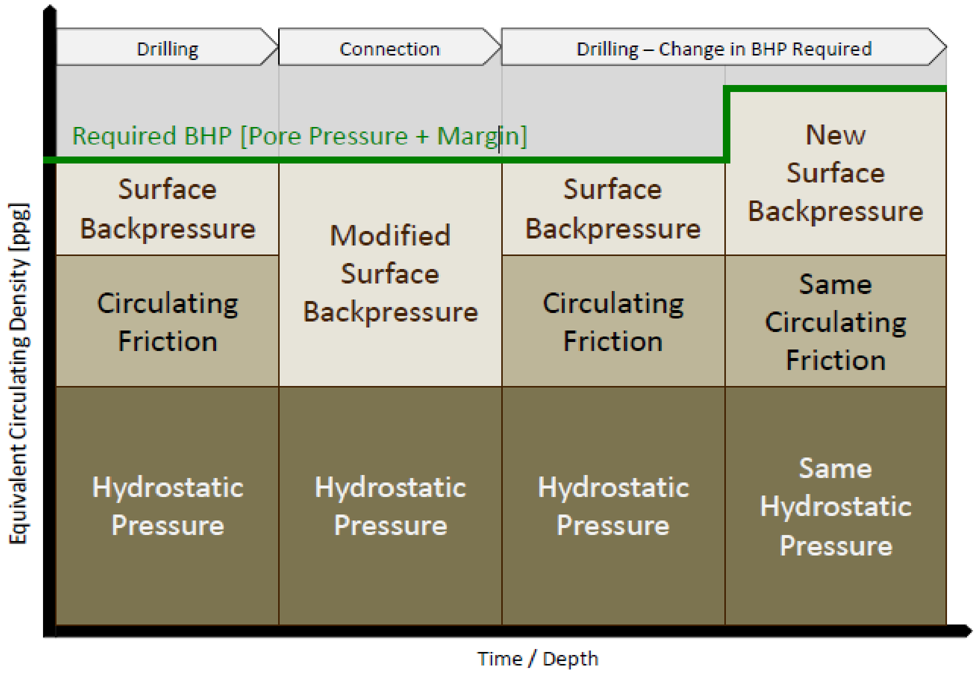

Figure 4 ECD compensation during connection with MPD (32)

2.2.2 Mud Cap Drilling (MCD)

Mud Cap Drilling (MCD) is a technique used in Managed Pressure Drilling (MPD) to control wellbore pressure and mitigate the risks of fluid loss and gas kick disturbances, particularly in challenging environments where conventional operations are costly (33).

MCD is designed to allow better control of the well in demanding environments, especially in situations where fracture pressures and pore pressure gradients are close to each other, making it difficult to drill adequate depths without a casing setup procedure (34). This technique involves the use of pressurized mud to create a mud cap, which helps in the annular pressure profile control throughout the well (14).

The principle behind Mud Cap Drilling (MCD) is to lower the water activity in the mud filtrate, thereby encouraging water movement from the formation to the wellbore or balancing the differential hydraulic pressure gradient from the mud column toward the formation through osmotic processes (27). Additionally, MCD is particularly useful in highly fractured formations, as it provides an alternate means of controlling the well and safely drilling ahead in such challenging geological conditions (35).

In the context of MPD, MCD plays a vital role in providing surplus control over the well pressure, besides the frictional pressure drop and mud weight, by using a choke at the annulus upper side outflow to control the pressure of mud to a setpoint with desired characterizations (36).

Furthermore, MCD is essential for addressing various drilling problems such as wellbore instability, formation damage, and well collapse, especially in depleted reservoirs and deep offshore reservoirs (12). The technique is also valuable in formations with a narrow window between fracture pressure and formation pore pressure, where MPD, including MCD, is often employed to manage annulus pressure within safe bounds (13, 22).

Overall, MCD is a critical component of MPD, offering precise control over annular pressure profiles, and enabling safe and efficient drilling operations in challenging geological and operational conditions.

2.2.2.1 Pressurized Mud Cap Drilling

Pressurized Mud Cap Drilling (PMDC) is a subcategory of Mud Cap Drilling (MCD) that focuses on the utilization of pressurized mud to create a mud cap for controlling wellbore pressure. PMDC involves the pressurization of the drilling fluid to maintain a specific pressure profile within the wellbore, thereby enabling precise control over the annular pressure. This technique is particularly beneficial in environments where maintaining wellbore stability and managing pressure differentials are vital for drilling operations in safety and more efficient ways.

In the PMCD process, drilling occurs without the returning of fluids to the surface, while ensuring there is a continuous column of fluid encircling the formation where injected fluid and drilled cuttings are received. The maintenance of this fluid column requires applying noticeable surface pressure to equalize the pressure within the wellbore (23).

PMCD tackles lost circulation challenges by employing a dual-drilling fluid approach. A dense mud with higher viscosity is pumped to the annulus to create a mud cap, serving as a protective barrier. Meanwhile, a lighter, less harmful, and more economical fluid is used by the driller to penetrate softer geological formations (19).

The driller injects the less dense mud which is known as sacrificial fluid down the drill pipe, which then circulates and cleans the drill bit area, carrying cuttings, and is directed into a segment positioned above the last casing shoe, often a fragile stratum. Meanwhile, the dense mud with higher viscosity remains in the annular space, creating a protective mud cap above the vulnerable segment. If needed, the driller can use back pressure to regulate the pressure in the annulus. This utilization of a less dense drilling fluid improves the Rate of Penetration (ROP) by boosting power of hydraulics and minimizing chip retention(23). Figure 5 (37) illustrates the PMDC schematic.

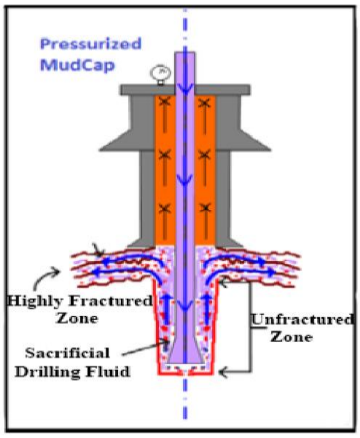

Figure 5 PMDC Schematic (37)

2.2.2.2 Floating Mud Cap Drilling

Floating Mud Cap Drilling (FMCD) is a professional technique, designed to address specific challenges encountered during drilling operations, particularly in situations where conventional methods struggle to maintain control over formation pressures and prevent influxes. It becomes relevant when designing the annular fluid to establish surface pressure proves difficult in comparison with PMCD.

FMCD involves creating a mud cap above the formation being drilled. Initially, drilling progresses conventionally until encountering problematic zones such as shallow water flows or gas pockets. At this point, specialized equipment is employed to establish a weighted mud cap, effectively "floating" on top of the formation. This cap exerts hydrostatic pressure, preventing influxes from the formation while drilling continues below it.

The primary goal of FMCD is to enhance well control and safety in drilling operations. By maintaining a mud cap, FMCD reduces the risk of encountering formation influxes, blowouts, and other hazardous situations. This is particularly crucial in offshore drilling where shallow water flows and gas pockets are prevalent.

Implementing FMCD requires specialized equipment and expertise. While it enhances safety and well control, it also introduces complexities and potential costs associated with procuring and operating this equipment. Additionally, maintaining a mud cap can pose challenges for real-time formation evaluation as it may hinder the visibility of formation samples and logging operations. In Figure 6. FMCD schematic is available.

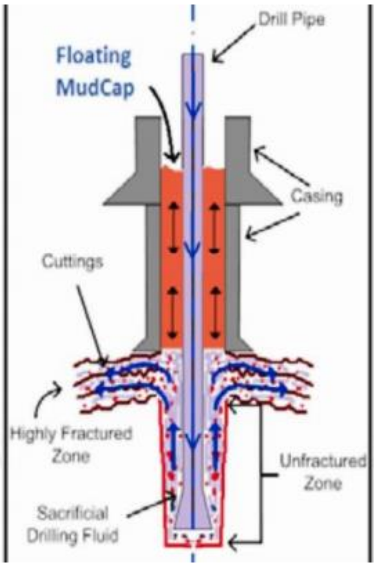

Figure 6 FMCD Schematic (37)

2.2.3 Dual Gradient Drilling

Dual Gradient Drilling (DGD) is a technique within Managed Pressure Drilling (MPD) that involves the application of two pressure gradients in the wellbore and (or) pipeline. This method is particularly useful in scenarios where the fracture pressure and pore pressure are close, such as in deep water or reservoirs with narrow drilling windows (38). DGD, along with other MPD technologies like casing while drilling (CWD) and managed pressure casing drilling (MPCD), utilizes engineered drilling fluids and a skilled workforce to enhance drilling operations (39).

The primary objective of employing DGD is to manage equivalent circulating density (ECD) effectively, especially in high-pressure, high-temperature (HPHT) wells where the operational window between pore pressure and fracture gradient is narrow (40). By controlling the fluctuation range of formation pressure, DGD helps optimize drilling parameters to ensure safe and efficient operations (41). Additionally, DGD allows for the drilling of significant intervals by maintaining near-constant bottom hole pressure through a closed system that considers casing back pressure, drilling fluid density, and ECD (12).

Furthermore, the integration of DGD with gas lift positive circulation drilling technology has been proposed to further enhance pressure control during drilling operations (41). This integration aims to address the challenges posed by complex structures in deepwater shallow layers by optimizing the safe mud weight window and proposing innovative drilling methods like Multi-gradient Drilling (MGD) (42).

Dual Gradient Drilling (DGD) refers to a range of techniques employed to manage up-hole annular pressure during deepwater marine drilling operations. This approach has proven particularly effective in deep water scenarios, where a huge portion of the overlying strata consists of water. The presence of this less dense overburden in the liquid phase creates a narrow drilling window due to the bounded borders between fracture pressure and pore pressure. In conventional deepwater drilling, the fragility of formations often requires at shallow depths the utilization of several casing strings to avoid significant circulation loss when using one-density drilling mud (23).

To counteract the challenges posed by the offshore overburden, the balance of the drilling system can be done by reducing the mud density in the upper sections of the marine riser or by implementing seawater into the riser. Alternatively, the two-parts system can be introduced into the seabed. Figure 7. illustrates the DGD system.

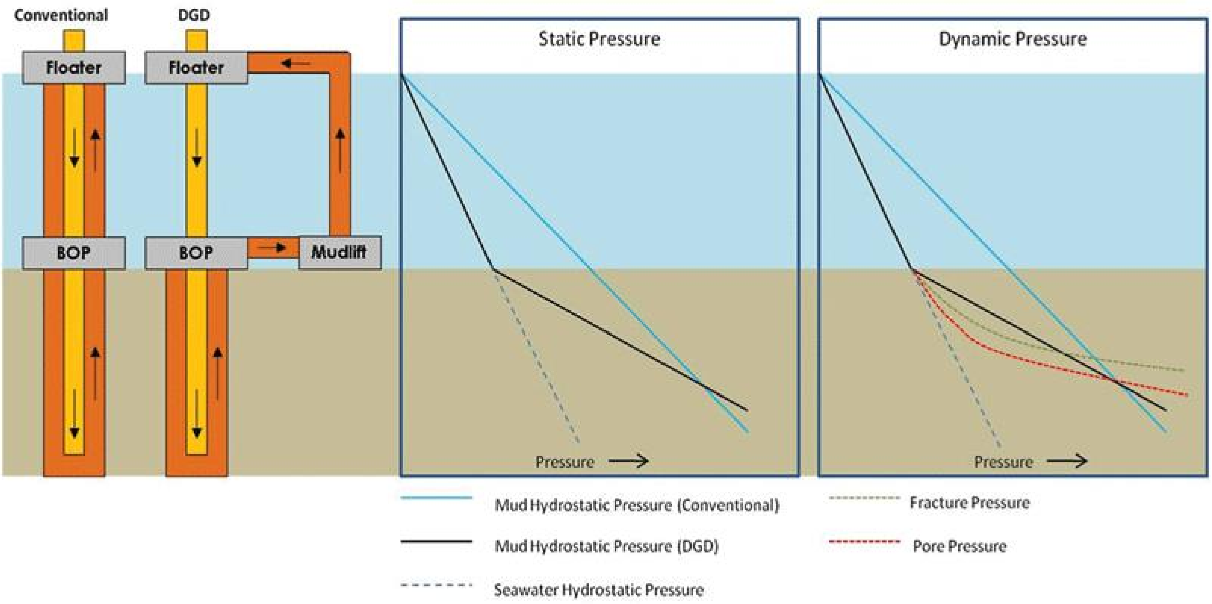

Figure 7 DGD System

2.2.4 Return Flow Control

Return Flow Control (RFC) is a fundamental technique within Managed Pressure Drilling (MPD) systems that aims to enhance pressure-control performance and ensure drilling safety. RFC involves the management and regulation of the annulus pressure profile throughout the wellbore, which is crucial for controlling downhole pressure effectively (33).

By utilizing RFC, MPD systems can precisely control the pressure dynamics in the well, providing surplus control over the pressure in addition to frictional pressure drop and mud weight (36). This control is essential for mitigating various drilling challenges including kicks, circulation loss, formation damage, and wellbore instability (15).

The implementation of RFC in MPD systems allows for adaptive drilling processes that can dynamically control pressure profiles, leading to a more efficient and safer drilling operation (7). Through RFC, MPD technology aims to improve wellbore stability, drilling safety, and overall operational efficiency by ensuring accurate pressure control throughout the drilling process (11).

Additionally, RFC enables the active control of wellbore pressure during drilling operations, representing a significant advancement from conventional well control procedures (43). Furthermore, RFC in MPD systems involves the use of chokes to regulate mud pressure to desired setpoints, contributing to better pressure control while drilling (36).

This method of pressure regulation is particularly beneficial in challenging environments where precise pressure management is critical for successful drilling operations (34). By incorporating RFC techniques, MPD systems can achieve accurate pressure control in long wells, surpassing the capabilities of conventional drilling methods (22).

The primary objective of this method is conducting drilling using an annulus return system which is closed, mainly for HSE or Health, Safety, and Environmental reasons. For example, in conventional drilling operations employing a system that is open to the atmosphere, there's a risk of explosion when gases escape from drilled cuttings. This phenomena could results in atmospheric monitors triggering and potentially result in automatic shutdowns of production in other parts of the platform. Another utilization of this variation of the Rotary Flow Control (RFC) method includes addressing concerns related to the toxicity of drilling muds emitting hazardous vapors onto the rig floor, taking precautions in regions with shallow gas dangers, and drilling in densely populated areas. Typically, only a Rotating Control Device (RCD) is incorporated into the drilling operation to implement this variation (20).

2.3 MPD Operation

Managed pressure drilling (MPD) is a sophisticated drilling technique that has gained significant traction in the oil and gas industry due to its ability to address challenging drilling scenarios effectively.

MPD involves controlling the annulus pressure profile throughout the wellbore to optimize drilling operations (14). The core of an automated MPD system lies in its hydraulics model, which plays a crucial role in determining the accuracy and efficiency of the system (6). By utilizing a closed system that adjusts casing back pressure, equivalent circulating density (ECD), and drilling fluid density, MPD enables drilling like an overbalanced system while maintaining a near-constant bottom hole pressure, allowing for the drilling of longer intervals (12). One of the key advantages of MPD is its capability to mitigate various drilling challenges such as kicks, fluid circulation losses, wellbore instability, and formation damage (15).

The technology has been instrumental in enhancing safety and reducing non-productive time in drilling operations, particularly in deepwater environments (44). Additionally, MPD techniques have been applied to optimize drilling parameters, minimize risks corresponding to well control, and enhance drilling efficiency, especially in unconventional shale development (45).

To achieve precise control throughout the drilling process, MPD systems rely on automated features such as topside choking for downhole pressure control (46). These systems leverage advanced control strategies and models to manage pressure oscillations and disturbances, ensuring stable and efficient drilling operations (47-49).

Furthermore, the utilization of surface back pressure with water-based mud in MPD techniques has been shown to effectively address lost circulation problems in drilling operations (50).

Drilling in Managed Pressure Drilling (MPD) mode is closely similar to conventional drilling in most aspects, with the main divergence found in the management of pressure at the surface, in other words, Surface Back Pressure or SBP, where other operational procedures typically remain consistent. Despite the procedural similarities between conventional drilling and MPD, the stringent pressure control necessitates a comprehensive monitoring approach for all parameters influencing Bottom Hole Pressure (BHP). During MPD drilling, specific focus is directed towards several key parameters, among which the following are pivotal (23):

- The Standpipe Pressure trend provides crucial insights into downhole events.
- Variations in cuttings observed at the shakers, whether an increase or decrease, may signal changes in the effectiveness of cleaning of the hole. The accretion of cuttings within the annulus space can markedly affect BHP.
- Parameters corresponding to influx or loss including the Pit Volume, alterations in inflow and outflow, and the Rate of Penetration.
- It is imperative to recognize that pressure of hydrostatic significantly contributes to the bottom hole pressure exerted by mud weight.
- Modifications in Flow Rate or Mud Rheology can impact AFL or annular friction losses, consequently affecting BHP.

Managed pressure drilling represents a cutting-edge approach in the oil and gas industry, offering a comprehensive solution to complex drilling challenges. By integrating advanced automation, control systems, and hydraulic models, MPD enables precise pressure management, enhances safety, and optimizes drilling performance in a wide range of drilling environments.

In drilling procedures, the beginning of circulation of fluid is typically by obtaining fluid from the tanks containing mud, which then rig pumps will give the energy to this mud for its return to the surface. From the mud tanks, the mud moves through standpipe and Kelly hose and other equipment into the drill string. At the Bottom Hole Assembly (BHA), the fluid exits through the bit nozzles and ascends within the annular space, eventually returning to the surface through the Blow Out Preventor stack and flowing through the bell nipple to an atmospheric open system. Then the fluid moves through an atmospheric flow line which does not hold any pressure and the next step is the solids control equipment, followed by returning fluid to the mud pits and the circulation cycle will be completed (51).

In Managed Pressure Drilling (MPD), the fluid circulation system has a resemble route with slight key differences. Instead of a bell nipple, an RCD (Rotating Control Device) creates a system which is sealed around the drill pipe, establishing a closed system. The fluid then is redirected from the RCD to the MPD choke manifold through a main line with the ability to tolerate pressure. While in rigs with conventional drilling systems, a choke manifold is available for well control, systems with MPD technology need a surplus choke manifold, known as an MPD choke manifold, for constant regulation of surface pressure which is the main method of pressure control. Downstream from the MPD choke manifold, there is a pipeline directing the fluid back to the shale-shakers.

Figure 8. (23) illustrates the backpressure MPD system necessitates several key pieces of equipment, including:

- Mud gas separator
- Backpressure pump
- Choke manifold
- The Rotating Control Device

The RCD or Rotating Control Device functions as a vital pressure seal system situated between the drill floor and the BOP, guiding the flow from the annulus and maintaining a closed system. Depending on the circumstances, the Choke manifold manages the pressure of the well, from manual control to fully automated or semi-automated, depending on the operation variation. It might be used without any dependency or coupled with the backpressure pump. Moreover, the system can incorporate an integrated pressure management and hydraulic flow model, which continuously updates flow parameters and adjusts the choke opening in response to pressure fluctuations. This hydraulic model also aids in the early detection of kicks. If a kick occurs, a mud gas separator can separate fluids while the well remains open and circulation continues. (51).

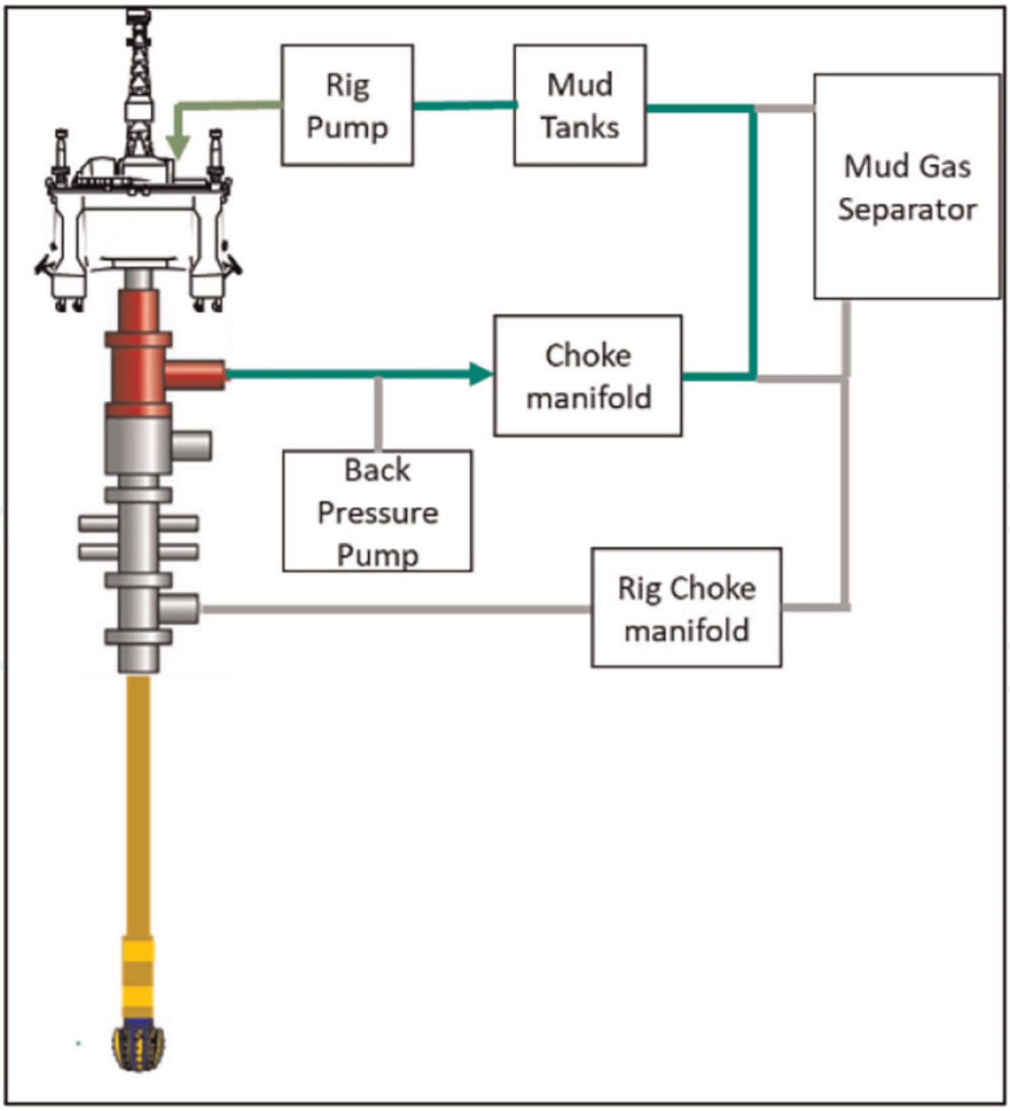

Figure 8 MPD Setup (23)

3 Mud Hydraulics

Mud hydraulics stands out as a paramount factor influencing the performance of mud drilling operations. Leveraging cutting-edge techniques in hydraulic optimization can yield substantial enhancements in the rate of penetration (ROP), ultimately leading to significant cost reductions in drilling operations. The primary objective of this optimization process is to maximize the utilization of a pump's power to facilitate optimal drilling efficiency. This objective is realized through the minimization of energy losses attributed to friction within the system of circulating, thereby redirecting the conserved energy to enhance bit hydraulics.

3.1 Drilling Mud Characterization

Various drilling mud types are employed in drilling endeavors, chosen for their distinct rheological characteristics. This section delves into the categorization, rheological attributes, and methods for measuring the drilling mud properties utilized within the petroleum sectors.

3.1.1 Classifications of Drilling Mud

The industry employs a wide array of drilling mud types, each exhibiting distinct behaviors within circulation systems of drilling. Pressure losses within flow lines, such as the drill string and annular section, stem from resistance to flow. This resistance manifests as frictional forces acting upon fluid particles flowing along the conduit walls, opposing the flow direction and impeding particle velocity. Likewise, adjacent fluid particles exert frictional forces on one another. The magnitude of these flow resistances or frictional forces between conduit walls and fluid particles, as well as fluid particles among each other, varies based on fluid properties and disparities in particle velocities. This study of flow resistance is known as rheology, which fundamentally examines the deformation or flow of substances.

Rheology typically characterizes flow or deformation using shear stress and shear rate parameters. The shear rate represents the gradient of velocity perpendicular to the direction of flow; higher shear rates correspond to increased friction among flowing particles. Shear stress, on the other hand, quantifies the friction between particles per unit area of the shearing layer. Fluids undergo classification in rheological studies based on their distinct flow behaviors (52).

Figure 9.(52) illustrates five distinct fluid types frequently encountered in the industry. Curve a represents fluids commonly found in nature. In these fluids, shear stress exhibits a linear relationship with shear rate, indicating the increase of flow resistance proportionally with deformation of flow. Oil and water exemplify fluids falling into this group, classified as Newtonian fluids.

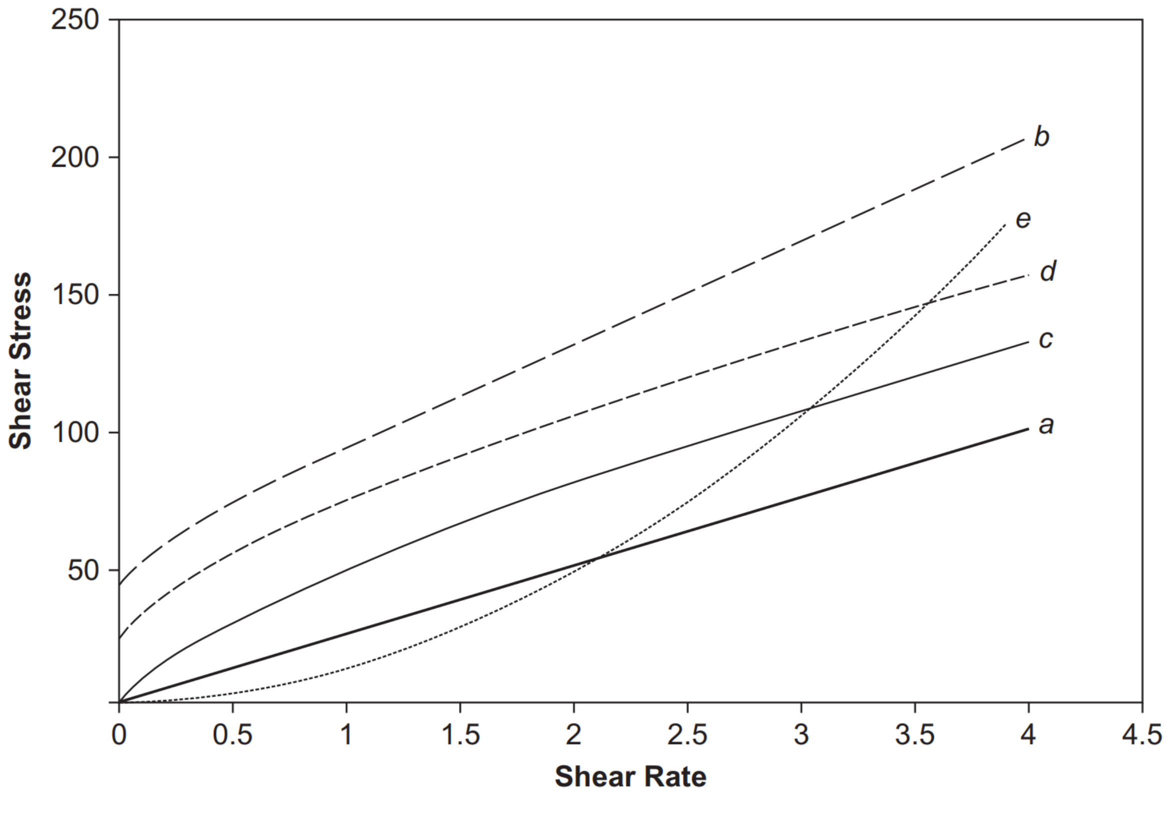

Figure 9 Fluid Types Used in Drilling (52)

Curve b exhibits a relationship in linear type between shear stress and shear rate, except within the low range of shear rate, where shear stress retains a value more than zero. This intersection with the shear stress axis is termed gel strength, signifying the initial force needed to make the fluid deformed and mobilized. Due to this plastic behavior, such fluids are termed plastic fluids or Bingham plastic fluids. Plastic fluids are typically derived by incorporating clay-like solid particles into Newtonian fluids.

Curve c illustrates a relationship in nonlinear type between shear stress and shear rate, where flow resistance increases less than linearly with deformation. Fluids of this nature are referred to as pseudoplastic fluids or Power Law fluids, with polymer solutions often falling within this classification.

Curve d showcases a relationship in nonlinear type between shear stress and shear rate, featuring a nonzero shear stress magnitude where the shear rate is zero. Similar to plastic fluids, an initial force is needed for fluid to become deformed and mobilized, where flow resistance increases less than linearly with deformation. This fluid behavior was initially described by Herschel and Bulkley in 1926 and is termed Herschel-Bulkley fluid.

Curve e also demonstrates a relationship in nonlinear type between shear stress and shear rate, where flow resistance increases more than linearly with deformation. Dilatant fluid is the name that this type of fluid is known as, achievable by incorporating starch-like materials into Newtonian fluids.

3.1.2 Rheological Models

Various rheological models are employed to characterize the flow characteristics of fluids. The Newtonian model, utilized to describe Newtonian fluids, is represented by the expression:

$$\tau = \mu\gamma \qquad \text{Equation 5}$$

Where:

τ = shear stress [Pa or lb/100 ft^2]

μ = viscosity [Pa.s or cP]

γ = Shear rate [S^{-1}]

While the Bingham plastic model serves to elucidate the flow characteristics of Bingham plastic fluids. It is mathematically represented as:

$$\tau = \tau_y + \mu_p\gamma \qquad \text{Equation 6}$$

Where:

τ_y = yield point (YP) [Pa or lb/100 ft^2]

μ_p = plastic viscosity (PV) [Pa.s or cP]

Evidently, the model of Bingham plastic, being linear, fails to accurately depict the flow dynamics of Bingham plastic fluids within the low range of shear rate. This discrepancy is illustrated in Figure 10.(52) Notably, the model parameter is known as the yield point (τ_y) tends to overestimate the gel strength (τ_s) of the fluid.

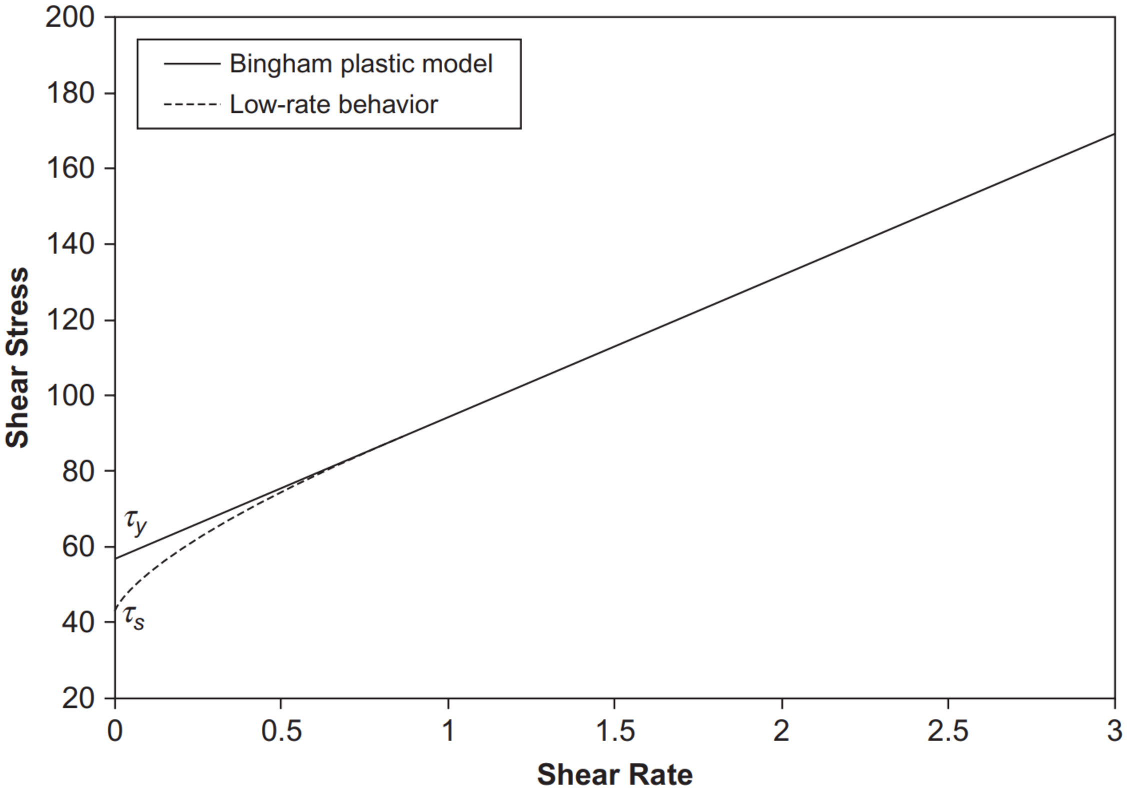

Figure 10 Bingham Model in low shear rate region (52)

The flow characteristics of both pseudoplastic and dilatant fluids, on the other hand, can be effectively captured by the Power Law model, expressed as:

$$\tau = K\gamma^n \quad \text{Equation 7}$$

Where:

K = consistency index [Pa.s or cP]

n = flow behavior index [-]

For n < 1, the model of Power Law characterizes the behavior of pseudoplastic fluids or Power Law fluids. When n = 1, the Power Law model represents the behavior of Newtonian fluids. Conversely, for n > 1, the Power Law model delineates the behavior of dilatant fluids.

The flow behavior of HB fluids, described by their model, is expressed as:

$$\tau = \tau_y + K\gamma^n \qquad \text{Equation 8}$$

Clearly, the three-parameter model serves as a comprehensive framework capable of describing the behavior exhibited by all fluids depicted in Figure 5. The majority of drilling fluids are too intricate to be accurately known by the simplistic Newtonian model.

Fluids lacking a direct proportionality between shear rate and shear stress fall under the classification of non-Newtonian fluids. Among the non-Newtonian fluids extensively utilized in the drilling industry are the plastic and pseudoplastic fluids, expounded upon by the Bingham plastic and Power Law models, respectively. The Herschel-Bulkley model finds widespread use among engineers in offices for fluid hydraulics designing.

These non-Newtonian fluids demonstrate thixotropic behavior, wherein the apparent viscosity (the division of shear stress by shear rate) diminishes over time subsequent to an increase in shear rate. This property known as shear-thinning proves highly advantageous in drilling procedures, as it facilitates a decrease in viscosity to mitigate circulating pressure during routine drilling while ensuring elevated viscosity during circulation fails in the suspension drill cuttings within the annular section. Presently, the thixotropic nature of drilling fluids lacks a comprehensive mathematical model. Nonetheless, drilling fluids are typically agitated before apparent viscosities measurements at varying shear rates to attain conditions in a steady state. Although disregarding thixotropy suffices for the majority of scenarios, substantial errors may arise in flow systems characterized by numerous directional and dimensional changes.

In contrast to pseudoplastic and plastic fluids, dilatant fluids exhibit an increase in apparent viscosity with an escalating shear rate. As this property known as the shear-thickening proves unfavorable in drilling procedures, dilatant fluids are not intentionally employed as drilling fluids. Hence, there are instances where pseudoplastic fluids can transition into dilatant fluids, particularly when a substantial quantity of additives similar to starch such as CMC are introduced into the system (52).

3.1.3 Rheological Properties Measurements

Various types of devices are available for assessing the rheological characteristics of fluids. The Viscometer, as depicted in Figure 11, finds extensive application in the drilling sector. It facilitates rapid measurement of rheological properties across six different speeds, encompassing all fluid types. However, when dealing with a new fluid, it is imperative to initially conduct tests at different speeds to obtain a comprehensive dataset comprising shear stress and shear rate values. Plotting this data aids in discerning the fluid type, enabling the determination of the associated rheological properties in accordance with the fluid model.

Figure 11 Viscometer

Newtonian model:

The viscosity of Newtonian fluids can be determined using the following formula:

$$\mu = \frac{300\,\theta_N}{N} \quad \text{Equation 9}$$

Where:

N = rotary speed of Viscometer [RPM]

θ_N = Dial reading of Viscometer at rotary speed N

Bingham model:

The plastic viscosity (PV) for Bingham plastic fluids, can be computed employing the subsequent formula:

$$\mu_p = \frac{300}{N_2 - N_1}\left(\theta_{N_2} - \theta_{N_1}\right) \quad \text{Equation 10 (52)}$$

Where:

θ_{N_1} = Dial reading of Viscometer at rotary speed N_1

θ_{N_2} = Dial reading of Viscometer at rotary speed N_2

Power Law model:

For Power Law fluids, the flow behavior index (n) can be determined using the following equation:

$$n = \frac{\log\left(\frac{\theta_{N_2}}{\theta_{N_1}}\right)}{\log\left(\frac{N_2}{N_1}\right)} \quad \text{Equation 11 (52)}$$

The consistency index (K) of Power Law fluids can be calculated using the following formula:

$$\boldsymbol{K} = \frac{\mathbf{510}\ \boldsymbol{\theta}_{\boldsymbol{N}}}{(\mathbf{1.703}\boldsymbol{N})^{\boldsymbol{n}}}$$ Equation 12 (52)

Herschel-Bulkley model:

For HB fluids, the fluid yield stress (τ_y) is typically determined from the 3 rpm reading. The flow behavior index (n) and the consistency index (K) can then be obtained graphically or calculated from the 300 or 600 rpm magnitudes. The approximate yield stress (τ_y), commonly referred to as the point with a low shear rate, can be obtained by:

$$\boldsymbol{\tau_y} = \mathbf{2}\boldsymbol{\theta}_{\mathbf{3}} - \boldsymbol{\theta}_{\mathbf{6}}$$ Equation 13 (52)

The fluid flow index (n) is given by:

$$\boldsymbol{n} = \frac{log\left(\frac{\theta_{N_2} - \tau_y}{\theta_{N_1} - \tau_y}\right)}{log\left(\frac{N_2}{N_1}\right)}$$ Equation 14 (52)

The fluid consistency index (K) is calculated by:

$$\boldsymbol{K} = \frac{\mathbf{500}\ (\boldsymbol{\theta}_{\boldsymbol{N}} - \boldsymbol{\tau}_{\boldsymbol{y}})}{(\mathbf{1.703}\boldsymbol{N})^{\boldsymbol{n}}}$$ Equation 15 (52)

At high shear rates, Herschel-Bulkley fluids can be treated like Power Law fluids, under the assumption that the log-log slope of the HB flow equation is numerically close to that of the Power Law flow equation.

3.2 Hydraulics Models

How drilling mud flows can be elucidated through mathematical constructs termed hydraulic models. As it is known, these models delineate the correlation between pressure drop and flow rate concerning the specific geometry of the flow passage and fluid characteristics. Additionally, this correlation is contingent upon the flow regime.

3.2.1 Flow Regimes

Drilling commonly encounters three flow regimes: laminar, turbulent, and transitional. Laminar flow involves fluid moving in parallel layers at consistent speeds, with minimal inter-layer particle movement. The central layers typically move faster than those near the conduit's walls. Turbulent flow, in contrast, involves erratic velocity fluctuations among fluid particles, disrupting layer boundaries and creating a flow pattern in chaos. Transitional flow shares both turbulent and laminar regime characteristics, occupying a nebulous region where neither state dominates. Additionally, there's a less common regime known as plug flow, which describes in low velocities, sublaminar fluid movement as a homogeneous mass. However, this regime isn't typically observed in standard drilling operations. In Figure 12. (53), different flow regimes can be observed.

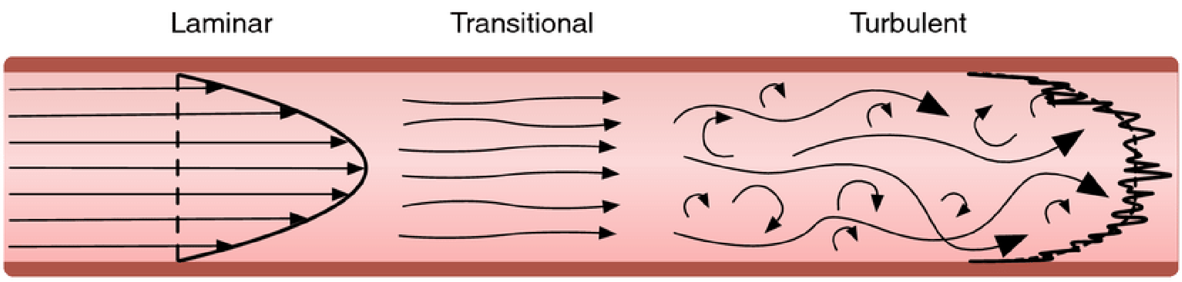

Figure 12 Flow Regimes

Preferably, laminar flow is desired in the annulus to facilitate cuttings transport and erosion prevention, while turbulent flow is more beneficial at the wellbore's bottom, aiding in cleaning and cuttings removal. Identifying flow regimes can be challenging due to fluid behavior variations within the system, with multiple regimes potentially coexisting at a given point. For instance, while the primary annular flow may be laminar, the fluid near the pipe's boundary may exhibit turbulent behavior (52).

As in this study, only two methods of Power Law and Herschel-Bulkley are used, other methods will not be discussed.

Power law model:

Utilizing some correlations (54), the pipe flow and annular flow Reynolds number is given by:

$$N_{Re} = 89100 \frac{\rho v^{2-n}}{K} \left[\frac{0.0416\, d}{3+{}^{1}\!/_{n}}\right]^{n}$$ Equation 16 (52)

And

$$N_{Re} = 109000 \frac{\rho v^{2-n}}{K} \left[\frac{0.0208(d_2-d_1)}{2+{}^{1}\!/_{n}}\right]^{n}$$ Equation 17 (52)

Where:

ρ = Mud weight [ppg]

v = Velocity [ft/sec]

K = fluid consistency index [cp]

d_1 = Inner Diameter [inch]

d_2 = Outer Diameter [inch]

n = fluid flow index [-]

The criterion of turbulency for Power Law fluids hinges on a Reynolds number known as critical (N_{Rec}), which is contingent on the flow behavior index. A straightforward correlation for approximating the critical Reynolds number at the upper threshold of laminar flow is:

$$N_{Rec} = 3470 - 1370\, n$$ Equation 18 (52)

For the transitional-to-turbulent flow region, the critical Reynolds number is:

$$N_{Rec} = 4270 - 1370\,n$$ Equation 19 (52)

Herschel-Bulkley model:

For HB fluids, the Reynolds number can be determined using the following equations. Inside the drill pipe:

$$N_{Re} = \frac{2(3n+1)}{n}\left[\frac{\rho v^{2-n}\left(\frac{d_1}{2}\right)^n}{\tau_y\left(\frac{d_1}{2v}\right)^n + K\left(\frac{3n+1}{nC_c}\right)^n}\right]$$ Equation 20 (52)

Where in the annulus is:

$$N_{Re} = \frac{4(2n+1)}{n}\left[\frac{\rho v^{2-n}\left(\frac{d_2-d_1}{2}\right)^n}{\tau_y\left(\frac{d_2-d_1}{2v}\right)^n + K\left(\frac{2(2n+1)}{nC_a^*}\right)^n}\right]$$ Equation 21 (52)

The constants C_c and C_a^* are expressed respectively as follows:

$$C_c = 1 - \left(\frac{1}{2n+1}\right)\frac{\tau_y}{\tau_y + K\left[\frac{q(3n+1)}{n\pi\left(\frac{d_1^3}{8}\right)}\right]^n}$$ Equation 22 (52)

$$C_a^* = 1 - \left(\frac{1}{n+1}\right)\frac{\tau_y}{\tau_y + K\left[\frac{2q(2n+1)}{n\pi\left(\frac{d_2}{2}-\frac{d_1}{2}\right)\left(\frac{d_2^2}{4}-\frac{d_1^2}{4}\right)}\right]^n}$$ Equation 23 (52)

Where:

ρ = Mud weight [lb/ft³]

v = Velocity [ft/sec]

K = fluid consistency index [lbf/100ft²]

d_1 = Inner Diameter [ft]

d_2 = Outer Diameter [ft]

τ_y = yield stress [lbf/100ft²]

q = Flow Rate [ft³/sec]

Inside the drill pipe and in the annulus, the critical Reynolds number N_{Rec} can be determined respectively as:

$$N_{Rec} = \left[\frac{4(3n+1)}{ny}\right]^{\frac{1}{1-z}}$$ Equation 24 (52)

$$N_{Rec} = \left[\frac{8(2n+1)}{ny}\right]^{\frac{1}{1-z}}$$ Equation 25 (52)

Where:

$$y = \frac{log(n)+3.93}{50}$$ Equation 26 (52)

$$z = \frac{1.75-log(n)}{7}$$ Equation 27 (52)

3.2.2 Annular Friction Loss

Annular friction loss (AFL) in managed pressure drilling is a critical aspect of drilling operations that requires careful consideration to ensure efficiency and safety in operations. Managed Pressure Drilling (MPD) is a technology that allows for control of the annular pressure profile in the wellbore precisely (33).

The annular frictional pressure loss (AFP) is a key parameter that needs to be managed effectively during drilling operations. Studies have shown that annular frictional pressure losses increase with added shear rate, even when the drilling fluid becomes thinner (55). In deep offshore drilling, accurate annular pressure loss estimation is crucial to maintain the Equivalent Circulating Density (ECD) within safe limits (56).

Proper frictional pressure loss estimation is essential for hydraulic horsepower requirements determinations and selecting the appropriate system of mud pump to prevent hydraulic issues during drilling operations (57). Excessive annular frictional pressures can lead to various issues including wellbore instability, stuck pipe, and lost circulation, which can limit the depth of drilling operations (58). Therefore, understanding and accurately calculating annular pressure losses are paramount for effective drilling design and construction (59).

Various studies have focused on modeling and estimating annular frictional pressure losses in different drilling scenarios. For instance, computational modeling has been used to study drilling fluid dynamics in casing drilling, where the smaller annular space significantly increases annular pressure loss compared to conventional drilling (60).

Additionally, artificial neural networks have been employed in flow patterns and frictional pressure loss estimation of two-phase fluids in horizontal annular geometries, offering an alternative to conventional mechanistic models (61).

The management of annular friction loss in managed pressure drilling plays a vital role in ensuring the safety and success of drilling operations. Accurate estimation and control of annular pressure losses are essential for maintaining wellbore stability, preventing issues like lost circulation, and optimizing drilling performance.

The primary procedure for system pressure loss calculations follows these steps:

- At the specific point determine the fluid velocity and Reynolds number.
- Determine the flow regime using critical velocity and Critical Reynolds number.
- Choose the appropriate pressure loss equation according to the rheological model and flow regime relevant to the specific point.

In the practical field, calculate both the actual Reynolds number ($\boldsymbol{N_{Re}}$) and the critical Reynolds number ($\boldsymbol{N_{Rec}}$). If $\boldsymbol{N_{Re}}$>$\boldsymbol{N_{Rec}}$, the flow is turbulent; if $\boldsymbol{N_{Re}}$<$\boldsymbol{N_{Rec}}$, it's laminar. When the actual and critical Reynolds numbers are nearly equal, perform pressure loss calculations for both flow regimes and use the results that show the higher pressure loss.

Power Law model

The power law model is a fundamental concept in drilling fluid rheology, particularly in understanding the behavior of drilling fluids at different shear rates.

Various studies have highlighted the significance of the power law model in predicting the rheological parameters of drilling fluids (62, 63). McMordie et al. demonstrated the use of the power law model to describe drilling fluid properties under high-pressure, high-temperature conditions, providing a mathematical model to relate power law parameters to HTHP conditions (63). This indicates the versatility and applicability of the power law model in characterizing drilling fluid behavior in challenging operational environments.

Moreover, the power law model has been utilized to model drilling fluid flow through fractures, with studies characterizing drilling fluids as yield power law fluids to enhance predictions of fluid behavior within fractures (64). The yield power law model, also known as the Herschel-Bulkley viscosity model, has been shown to correlate well with drilling fluid viscosity curves, emphasizing its relevance in accurately representing drilling fluid rheology (65).

Additionally, developed a theoretical model based on the yield-power-law (YPL) fluid behavior to analyze drilling fluid losses in naturally fractured formations, further underlining the importance of the power law model in understanding fluid behavior in complex geological settings (66, 67).

In drilling hydraulics calculations, the power law model is commonly used alongside the Bingham Plastic model due to their simplicity and ease of parameter estimation (68, 69). These models are standard in the field and are essential for describing the rheological properties of drilling fluids in various drilling operations (70, 71).

The power law model's ability to provide a versatile description of fluid rheology, encompassing different types of drilling mud rheology, further solidifies its importance in the drilling industry (72).

The power law model plays a vital role in characterizing drilling fluid behavior, especially in complex drilling scenarios and high-pressure, high-temperature conditions. Its application extends to predicting fluid flow through fractures, analyzing fluid losses, and optimizing drilling processes, highlighting its significance in enhancing operational efficiency and understanding fluid dynamics in drilling operations.

For Power Law fluids, the pressure loss under laminar flow can be calculated using specific equations for the drill string and the annulus, respectively:

$$\boldsymbol{\Delta P_f} = \left[\left(\frac{96v}{d_1}\right)\left(\frac{3n+1}{4n}\right)\right]^{n} \frac{KL}{300\, d_1}$$ Equation 28 (52)

And

$$\boldsymbol{\Delta P_f} = \left[\left(\frac{144v}{d_2-d_1}\right)\left(\frac{2n+1}{3n}\right)\right]^{n} \frac{KL}{300(d_2-d_1)}$$ Equation 29 (52)

No straightforward correlation exists to determine the friction factor for pressure loss under turbulent flow conditions for Power Law fluids, the original friction loss equation must be used. The equations provided below are applied for pipe flow and annular flow, respectively:

$$\Delta P_f = \frac{f \rho v^2 L}{25.8\, d_1}$$ Equation 30 (52)

$$\Delta P_f = \frac{f \rho v^2 L}{21.1(\; d_2 - d_1)}$$ Equation 31 (52)

Where for smooth pipe, Colebrook's (1938) friction factor function which was first presented by Blasius (1913), can be simplified to:

$$f = \frac{0.0791}{{N_{Re}}^{0.25}}$$ Equation 32 (52)

Herschel-Bulkley model:

The Herschel-Bulkley model is a commonly used rheological model in the drilling industry for describing the flow behavior of drilling fluids. This model has been extensively applied to characterize the rheological properties of various drilling mud formulations (73). It is considered a recommended standard in drilling due to its ability to adequately describe the rheology of drilling fluids (36).

The Herschel-Buckley equation has been specifically utilized to model the rheological characteristics of drilling fluids (74). Researchers have found that the Herschel-Buckley model provides a good fit for describing the viscosity measurements of drilling fluids across a wide range of shear rates (75).

Moreover, the Herschel-Buckley model has been integrated into generalized models to optimize the rheological parameters of non-Newtonian drilling fluids (76). Studies have shown that the Herschel-Buckley model approximates the yield stress of drilling fluids quite well among various non-Newtonian rheology models (77).

Furthermore, the Herschel-Buckley model has been applied to predict the settling velocity of irregular shale cuttings in drilling fluids with high accuracy (78). It has also been found that the flow behavior of water-based drilling fluid systems aligns well with the Herschel-Buckley flow model (79). Additionally, the Herschel-Buckley model has been used to represent the viscosity values of ice-cream mixes and has shown satisfactory results (80).

The Herschel-Buckley model plays a crucial role in the drilling industry by accurately modeling the drilling fluids rheological properties, aiding in the optimization of drilling processes, and predicting the behavior of drilling fluid systems under various conditions.

To determine the pressure loss under laminar flow for Herschel-Bulkley fluids, the following equations can be utilized both inside the drill pipe and in the annulus respectively:

$$\Delta P_f = \frac{4kL}{14400\, d_1}\left[\left(\frac{\tau_y}{k}\right) + \left[\left(\frac{3n+1}{nC_c}\right)\left(\frac{8q}{\pi d_1^3}\right)\right]^n\right]$$ Equation 33 (52)

$$\Delta P_f = \frac{4kL}{14400(d_2-d_1)}\left[\left(\frac{\tau_y}{k}\right) + \left[\left(\frac{16(2n+1)}{nC_a^*(d_2-d_1)}\right)\left(\frac{q}{\pi(d_2^2-d_1^2)}\right)\right]^n\right]$$ Equation 34 (52)

During turbulent flow, the pressure loss inside the drill pipe and in the annulus can be determined respectively as:

$$\Delta p_f = \frac{f_c q^2 \rho L}{1421.22 d_1^5}$$ Equation 35 (52)

$$\Delta p_f = \frac{f_a q^2 \rho L}{1421.22(d_2-d_1)\left(d_2^2-d_1^2\right)^2}$$ Equation 36 (52)

Where the friction factors f_c inside the drill pipe and f_a in the annulus are calculated respectively as:

$$f_c = y(C_c N_{Re})^{-z}$$ Equation 37 (52)

$$f_a = y(C_a^* N_{Re})^{-z}$$ Equation 38 (52)

4 Methodology

In this chapter, the methodology for digitalization in MPD for CBHP using Python will be discussed.

4.1 Data Collection and Import

A key aspect of developing the mathematical and simulation model is ensuring the availability of accurate data or inputs for the system. The whole necessary input data is available in Excel. The necessary data required for designing the code and simulation includes:

4.1.1 Mud Rheological Data

Mud rheological data refers to the study of the flow properties of drilling fluids (mud). This data is vital in drilling operations as it helps in understanding how the drilling fluid behaves under different pressure and temperature conditions. Proper rheological properties ensure efficient drilling, effective cuttings transport, and wellbore stability.

Key Rheological Properties

- Plastic Viscosity (PV): Indicates the flow resistance due to the internal friction of the fluid. It is calculated by subtracting the yield point from the apparent viscosity.
- Yield Point (YP): The stress needed to initiate flow. It is crucial to determine the capability of the mud to lift and suspend cuttings.
- Gel Strength: The ability of the mud to develop and retain a gel-like structure when static. This helps in suspending cuttings and weighting materials when circulation is stopped. Measured at 10 seconds and 10 minutes intervals to assess the mud's ability to suspend solids over time.
- Thixotropy: The property of the fluid to become less viscous vs. time where implemented by shear and to regain viscosity when at rest. This is important for preventing the sagging of cuttings and barite when circulation stops.

These data will be provided by Mud Engineer and will be saved in the Mud Rheological Data sheet in Excel file data.

4.1.2 Pump Data

In this Excel sheet, mud flow rate (Q) in units of gallon per minute (gpm) and mud weight in pound per gallon (ppg) should be input.

4.1.3 Drilling Parameters

In this section, all the data about drilling equipment and criteria will be as below:

- Hole Diameter (inch)
- Outer Diameter of Drill Collar (inch)
- Outer Diameter of Drill Pipe (inch)
- Inner Diameter of Casing (inch)
- Drill Pipe Length (ft)
- Drill Collar Length (ft)
- Casing shoe Depth (ft)
- Drilled depth (where bit touches formation) (ft)
- Start depth (ft)
- End depth (ft)
- Deviation Start depth or Kick off Point (ft)
- Deviation End depth
- Horizontal Start depth
- Horizontal Length
- Rate of Penetration or ROP (ft/hr)
- Inclination

4.1.4 Mud Window

To achieve optimal results for back pressure, it is essential to have the fracture pressure and pore pressure data for each depth. Therefore, the mud window of the well should be recorded in one of the Excel sheets. In Figure 13. the mud window from data is ostensible.

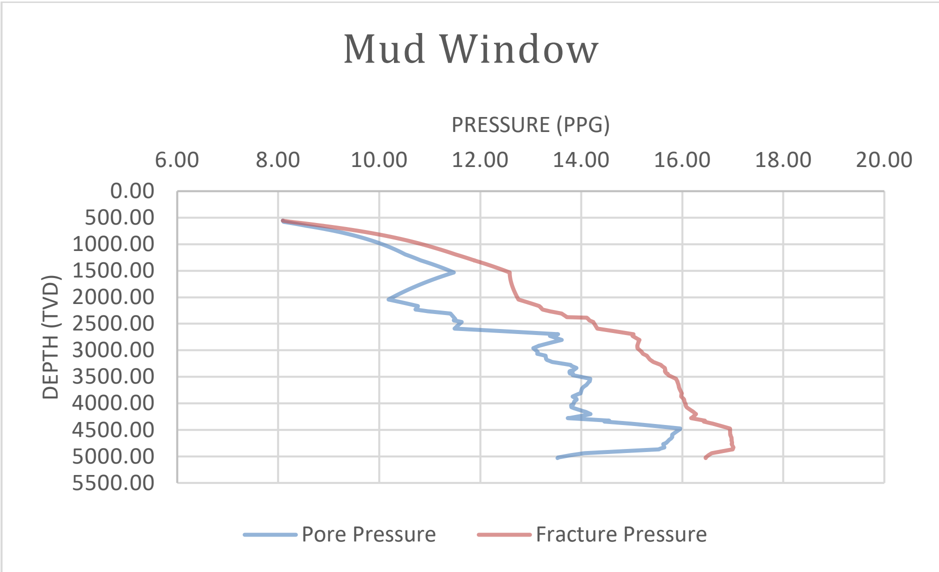

Figure 13 Mud Window Profiles

4.1.5 Dynamic Sensor Data

The final sheet of the Excel file corresponds to the Dynamic Sensor Data, which is vital for the real-time simulation part. In this sheet, sensor data which is always one step behind the current depth will be imported to be compared with the previous data from the mud window. This issue will be discussed more in the real-time section. These data are:

- Depth in MD(ft)
- PP(ppg)
- FP(ppg)

4.1.6 Data Import

To import data to Python code. A library named Pandas should be used and installed. Pandas is a versatile and robust open-source library for data analysis and manipulation in Python. It offers essential data structures, such as Data Frames and Series, for managing structured data. Pandas simplifies the process of importing, manipulating, and analyzing data from a variety of sources, including Excel spreadsheets.

If you haven't installed Pandas yet, you can do so using pip:

```
pip install pandas
```

To use Pandas in your Python script, you need to import it. It is common practice to import Pandas with the alias pd:

```
import pandas as pd
```

Pandas provides the read_excel function to read data from an Excel file. Here's how you can use it:

```python
import pandas as pd
# Read rheological data
PV = pd.read_excel("Data.xlsx", sheet_name='Mud Rheological Data', usecols="B", nrows=1).iloc[0, 0]
YV = pd.read_excel("Data.xlsx", sheet_name='Mud Rheological Data', usecols="B", nrows=2, skiprows=1).iloc[0, 0]
Theta_600 = pd.read_excel("Data.xlsx", sheet_name='Mud Rheological Data', usecols="B", nrows=3, skiprows=2).iloc[0, 0]
Theta_300 = pd.read_excel("Data.xlsx", sheet_name='Mud Rheological Data', usecols="B", nrows=4, skiprows=3).iloc[0, 0]
Theta_6 = pd.read_excel("Data.xlsx", sheet_name='Mud Rheological Data', usecols="B", nrows=5, skiprows=4).iloc[0, 0]
Theta_3 = pd.read_excel("Data.xlsx", sheet_name='Mud Rheological Data', usecols="B", nrows=6, skiprows=5).iloc[0, 0]
```

Figure 14 Import Data

In the Figure 14. Mud Rheological Data is imported from the Excel file to the code as inputs.

4.2 Pressure Loss Calculation

After importing data from the Excel file to the code, calculating the pressure loss in the annular section is the next step. First of all, based on Equations 11 and 12 and Equations 14 and 15 the fluid behavior index ($\boldsymbol{n}$) and consistency index ($\boldsymbol{K}$) will be determined respectively for both power law and HB models**.**

After determining the $\boldsymbol{n}$ and $\boldsymbol{K}$ values, the well should be segmented into four distinct sections. The first section represents the length where the drill collar and borehole are facing each other. The second section covers the length where the drill pipe interacts with the borehole. The third section pertains to the length where the drill collar encounters the casing, while the fourth section corresponds to the length where the drill pipe encounters the casing.

This version clarifies the segmentation process and makes the description more concise and precise. The figure below is the coding part to determine these segments.

```
    for depth, dp_length in zip(Drilled_depth, Dp_Length):
        if depth > Casing_shoe_Depth:
            L1 = min(DC_Length, depth - Casing_shoe_Depth)
            L2 = max(0, depth - Casing_shoe_Depth - L1)
            L3 = max(0, DC_Length - L1)
            L4 = max(0, dp_length - L2)
        else:
            L1, L2, L3, L4 = 0, 0, DC_Length, dp_length

```

Figure 15 Length Segments

The length of each segment is now known. The next step involves the calculation of annulus velocity and Reynolds numbers. Based on the previously discussed Reynolds number and critical Reynolds number formulas, these two parameter can be obtained. Since the annular diameter and length differ for each of the four segments, four different velocities and Reynolds numbers need to be calculated. Figure 16 illustrates the determination of velocities and Reynolds numbers (using the Power Law model) for each segment.

```
    # Calculate V_Annulus1
    V_Annulus1 = (1.28342246 * Q) / (math.pi * ((Hole_Diameter) ** 2 - (OD_Dc) ** 2))

    # Calculate Re_PL1
    Re_PL1 = 109000 * ((MW * V_Annulus1 ** (2 - n)) / (K)) * ((0.0208 * (Hole_Diameter - OD_Dc)) / (2 + (1 / n))) ** n

    # Calculate V_Annulus2
    V_Annulus2 = (1.28342246 * Q) / (math.pi * ((Hole_Diameter) ** 2 - (OD_Dp) ** 2))

    # Calculate Re_PL2
    Re_PL2 = 109000 * ((MW * V_Annulus2 ** (2 - n)) / (K)) * ((0.0208 * (Hole_Diameter - OD_Dp)) / (2 + (1 / n))) ** n

    # Calculate V_Annulus3
    V_Annulus3 = (1.28342246 * Q) / (math.pi * ((ID_Casing) ** 2 - (OD_Dc) ** 2))

    # Calculate Re_PL3
    Re_PL3 = 109000 * ((MW * V_Annulus3 ** (2 - n)) / (K)) * ((0.0208 * (ID_Casing - OD_Dc)) / (2 + (1 / n))) ** n

    # Calculate V_Annulus4
    V_Annulus4 = (1.28342246 * Q) / (math.pi * ((ID_Casing) ** 2 - (OD_Dp) ** 2))

    # Calculate Re_PL4
    Re_PL4 = 109000 * ((MW * V_Annulus4 ** (2 - n)) / (K)) * ((0.0208 * (ID_Casing - OD_Dp)) / (2 + (1 / n))) ** n

```

Figure 16 Velocity and Reynolds Number

After acquiring the Reynolds numbers and velocities, the subsequent task is to identify the flow regime. Based on these regimes, pressure losses can be determined. Figure 17 demonstrates the calculation of annular pressure loss for the first segment using the power law model. The pressure losses for the remaining segments can be calculated in a similar manner.

```
    for i in range(len(L1_list)):

    # Calculate Annular Friction loss (Power Law Model)
       if Re_PL1 <= 3470 - 1370 * n:
          Laminar_Delta_P1 = (((144 * V_Annulus1 * ((2 * n) + 1)) / (((Hole_Diameter - OD_Dc) * 3 * n))) ** n) * (
                    K * L1_list[i] / (300 * (Hole_Diameter - OD_Dc)))
          Turbolant_Delta_P1 = 0

       elif Re_PL1 >= 4270 - 1370 * n:
            f1 = (0.0791 / (Re_PL1 ** 0.25))
            Turbolant_Delta_P1 = (f1 * MW * (V_Annulus1 ** 2) * L1_list[i]) / (21.1 * (Hole_Diameter - OD_Dc))
            Laminar_Delta_P1 = 0

       # Append P1 to the list
       P1 = Laminar_Delta_P1 + Turbolant_Delta_P1
       P1_list.append(P1)

```

Figure 17 Annular Pressure Loss Calculation

As the drilling progresses, calculations must be performed and stored for each depth. To facilitate this, lists of pressures need to be generated for use as input in subsequent calculations. Therefore, after the pressure loss calculation, a list named AF (Annular Friction) is created which is the summation of the annular pressure losses of segments 1 to 4. This list remains consistent for the HB model and is detailed in the Appendix.

4.3 ECD and BHP Calculation

Equivalent Circulating Density (ECD) refers to the effective density of the drilling fluid when it is circulating through the wellbore, accounting for the pressure exerted by the fluid in motion. ECD is crucial for managing wellbore stability and preventing issues such as wellbore collapse or fracturing due to excessive pressure. It holds significant importance in drilling operations as it directly impacts the hydraulic efficiency of the drilling fluid, subsequently influencing the rate of penetration and overall well performance.

Notably, ECD is a parameter exclusive to dynamic mode drilling. It can manifest in two different states:

- When circulation ceases, ECD equals the mud weight (MW).
- During circulation, ECD surpasses MW.

As mud circulation takes place during drilling operations, the Equivalent Circulating Density (ECD) consistently exceeds the Bottom Hole Pressure (BHP). The Python code for calculating ECD and Dynamic BHP can be prominently displayed in Figure 18. For both power law and HB models.

```
    ECD_PL = []
    for depth, af_pl in zip(TVD, AF_PL_list):
        ecd_pl = ((af_pl / (0.052 * depth)) + MW)
        ECD_PL.append(ecd_pl)

    # ECD Calculation Based on HB Model
    #TVD = Drilled_depth
    ECD_HB = []
    for depth, af_hb in zip(TVD, AF_HB_list):
        ecd_hb = ((af_hb / (0.052 * depth)) + MW)
        ECD_HB.append(ecd_hb)

    # BHP Calculation Based on Power Law Model
    BHP_PL = []
    for depth, ecd_pl in zip(TVD, ECD_PL):
        bhp_pl = ((0.052 * depth) * ecd_pl)
        BHP_PL.append(bhp_pl)

    # BHP Calculation Based on HB Model
    BHP_HB = []
    for depth, ecd_hb in zip(TVD, ECD_HB):
        bhp_hb = ((0.052 * depth) * ecd_hb)
        BHP_HB.append(bhp_hb)
```

Figure 18 ECD and BHP Calculation

4.4 Mud Window Calculation

As the mud window is a critical data input for this coding program, it is incorporated using the Pandas library. When investigating a depth range between two points of mud window data, such as when the true vertical depth (TVD) in the mud window increases in 10-foot increments but the program's coding step is 5 feet, some points will lack fracture pressure and pore pressure data. To address this, interpolation of the mud window is highly beneficial. Figure 19 illustrates the coding solution for this issue. After interpolation, the new fracture pressure (FP) and pore pressure (PP) values, measured in pounds per gallon (ppg), will be listed by TVD. For enhanced comparison, FP and PP will also be converted and listed in pounds per square inch (psi).

```
# Linear interpolation for FP
    FP_interpolated = interp1d(TVD_MW, FP_ppg, kind='linear', fill_value="extrapolate")
    FP_calculated = FP_interpolated(TVD)

# Linear interpolation for PP
    PP_interpolated = interp1d(TVD_MW, PP_ppg, kind='linear', fill_value="extrapolate")
    PP_calculated = PP_interpolated(TVD)

    FP_ppg =  FP_calculated
    PP_ppg =  PP_calculated
    # Fracture Pressure Calculation
    FP=[]
    for depth, fp_ppg in zip(TVD, FP_ppg):
        fp = ((0.052 * depth) * fp_ppg)
        FP.append(fp)

    # Pore Pressure Calculation
    PP=[]
    for depth, pp_ppg in zip(TVD, PP_ppg):
        pp = ((0.052 * depth) * pp_ppg)
        PP.append(pp)
```

Figure 19 FP and PP Calculation

4.4.1 Update for Real-time Calculation

In real-time calculations, the process differs slightly. Suppose the drill bit is currently at depth X. The code performs calculations based on the mud window data obtained from other wells in the area. The next calculated point, determined by the step size specified in the Excel file, will be at depth X + Step. Sensors in the well can then read and obtain fracture pressure (FP) and the pore pressure (PP) at depth X. Consequently, the code is always one step ahead of the sensors.

The sensor data for PP and FP at depth X should be saved in the Excel file. The code will then compare this newly inserted data with the previously used mud window data. Figure 20 illustrates this process: if the sensor data matches the previously used data, no action is taken. However, if there is a discrepancy, the list is updated with the new data to prevent any potential kicks or washouts.

```

        Depth_MD = pd.read_excel("Data.xlsx", sheet_name='Dynamic Sensor Data',
                                 usecols="B", nrows=1).iloc[0, 0]
        PP_ppg_sensor = pd.read_excel("Data.xlsx", sheet_name='Dynamic Sensor Data',
                                      usecols="B", nrows=2, skiprows=1).iloc[0, 0]
        FP_ppg_sensor = pd.read_excel("Data.xlsx", sheet_name='Dynamic Sensor Data',
                                      usecols="B", nrows=3, skiprows=2).iloc[0, 0]
        index = Drilled_depth.index(Depth_MD)

        if PP_ppg[index] != PP_ppg_sensor :
            PP_ppg[index] = PP_ppg_sensor
        if FP_ppg[index] != FP_ppg_sensor :
            FP_ppg[index] = FP_ppg_sensor

```

Figure 20 Dynamic Sensor Data

4.5 Back Pressure Calculation

All the preceding calculations lead to this critical point. Now, it is time to calculate the back pressure (BP) necessary to stay within the mud window and prevent any kicks or fractures, especially in zones with very narrow mud windows. Maintaining the Bottom Hole Pressure (BHP) within the mud window is essential, but keeping the BHP close to the pore pressure (PP) can further enhance the rate of penetration (ROP) and mitigate non-productive time (NPT).

Figure 21 demonstrates how the code is designed to calculate BP and Adjusted BHP. The Adjusted BHP is always maintained near the PP, as indicated by the equation provided below:

$$\boldsymbol{Adjustd\ BHP = PP + 0.15\ (FP - PP)} \quad \text{Equation 39}$$

```python
for pp, fp, bhp_pl, bhp_hb in zip(PP, FP, BHP_PL, BHP_HB):

   # Power Law Model
    if pp < bhp_pl < fp:
       bp_pl = pp + 0.15 * (fp-pp) - bhp_pl
       bhp_pl = pp + 0.15 * (fp-pp)
       Adjusted_BHP_PL.append(bhp_pl)
       BP_PL.append(bp_pl)

    elif bhp_pl <= pp:
        bp_pl = pp - bhp_pl + 0.15 * (fp-pp)
        adjusted_bhp_pl = bhp_pl + bp_pl
        Adjusted_BHP_PL.append(adjusted_bhp_pl)
        BP_PL.append(bp_pl)

    elif bhp_pl >= fp:
        bp_pl = fp - bhp_pl - 0.85 * (fp-pp)
        adjusted_bhp_pl = bhp_pl + bp_pl
        Adjusted_BHP_PL.append(adjusted_bhp_pl)
        BP_PL.append(bp_pl)
```

Figure 21 BP Calculation

4.6 Alternative Flow Rate and Back Pressure

To determine the flow rate at which the adjusted BHP, calculated in the previous section, can be achieved, the code needs to perform iterations to find the optimal flow rate and minimum back pressure. The potential flow rate range can be broad, such as from 20 gpm to 600 gpm. Various factors influence this range, including the minimum flow rate required for effective cuttings transport and the pump capacity.

To mitigate potential issues, a margin of Q-50 to Q+50 will be introduced, where Q represents the current flow rate used to drill the well. Within this margin, the code will identify the best flow rate (Q) that achieves the adjusted BHP. Once the optimal Q is determined, the alternative BHP and back pressure (BP) will be reported. The purpose of this part of the code is to ensure that by drilling with the alternative flow rate (Q'), the adjusted BHP is achieved again, but with a new BHP and a reduced BP compared to the previous values. This code is available in the Appendix.

4.7 Real-time

As mentioned in section 4.4.1, the mud window needs to be continuously updated, requiring the code to run at specific time intervals. This interval, or time step, is defined as follows:

$$\boldsymbol{Time\ Step} = \frac{\boldsymbol{Step}}{\boldsymbol{ROP}} \quad \text{Equation 40}$$

where $\boldsymbol{Step}$ represents the incremental depth in feet (ft) and $\boldsymbol{ROP}$ denotes the Rate of Penetration in feet per hour (ft/hr). According to Equation 40, the time step corresponds precisely to the duration required to drill from depth X to X+Step.

In the code, this time step is utilized to schedule the code execution, pausing for the calculated time step before running again. This approach ensures efficient synchronization between data collection from sensors and code execution, minimizing any delays and optimizing real-time updates.

5 Result

For testing the code, the Mud Flow Rate is set to 250 gal/min and the Mud Weight to 12 ppg. Additional data is available in the Appendix. This code can also be run for deviated and horizontal wells. The well depicted in Figure 22 has a kick-off point at 2565 ft and becomes horizontal at a depth of 5005 ft MD, continuing horizontally for 600 ft MD.

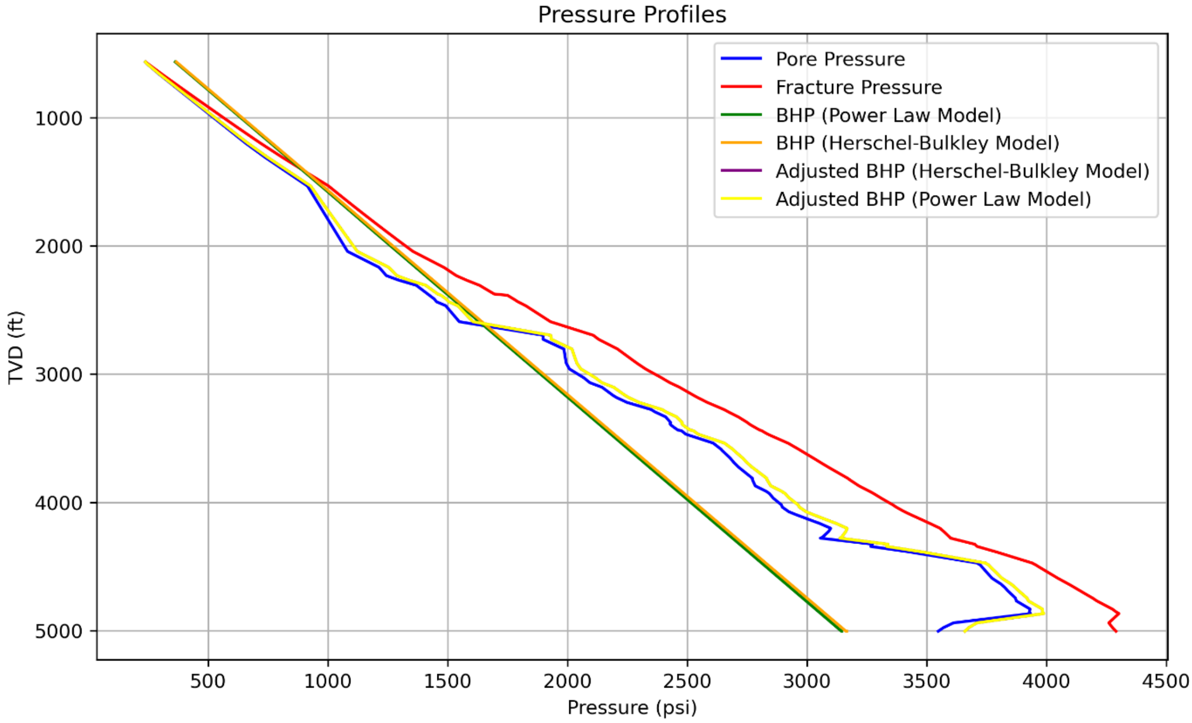

Figure 22 Pressure Profiles

As shown in Figure 22, the adjusted Bottom Hole Pressure (BHP) is consistently maintained near the pore pressure to enhance the Rate of Penetration (ROP) while remaining within the mud window. For both the power law and Herschel-Bulkley (HB) models, the magnitude of the adjusted BHP is the same. Since the BHP obtained from each model shows different values, different back pressures must be added to the BHPs to equalize them to the adjusted bottom hole pressure at each point.

As previously mentioned, one of the objectives of Managed Pressure Drilling (MPD) is to use mud with lower density. In this figure, the mud weight is uniform for the entire well length, as it represents the starting and ending points. The code is designed to operate section by section. For instance, if the depth is set from 3000 ft TVD to 5000 ft TVD, drilling can proceed with a single mud weight (e.g., 13 ppg) to reduce back pressure.

The magnitude of back pressures (BPs) is then managed by the Back Pressure Valve and Pump to take appropriate action. At the end of the code, the user is prompted to enter a depth in measured depth (MD) to view the corresponding data. These data are presented in Table 2.

Table 2 Results

Drilling Data at Depth 4589

MD (ft)	Section	TVD (ft)	PP (psi)	FP (psi)	Q (gpm)	BHP (psi)	BP (psi)	Adjusted BHP (psi)	Q' (gpm)	BP' (psi)
4589	Deviated	4317.835417259704	3235.99095909676	3681.7786699897706	250	2729.629596150842	573.2295195798694	3302.8591157307114	223	570.94177983295

In Table 2, the drilling data at a depth of 4598 ft MD is presented as an example. The table details the section of the well (Vertical, Deviated, or Horizontal), the True Vertical Depth (TVD), the Pore Pressure (PP), and the Fracture Pressure (FP) at this depth. Using a Flow Rate (Q) of 250 gpm and a Mud Weight (MW) of 12 ppg, the Bottom Hole Pressure (BHP) is calculated and reported in the table. To achieve the Adjusted BHP, which is our target, the BHP is increased by the magnitude of the Back Pressure (BP). This is why these three columns share the same color.

If the driller decides to change the Flow Rate, the code suggests an Alternative Flow Rate (Q'), which results in a new Back Pressure (BP') that is lower than the original. The columns for Q' and BP' are color-coded similarly to indicate their relationship.

The code then prompts the user with "Do you want to enter another depth (Y/N)?" allowing for multiple entries. For each depth, the code will generate a table similar to Table 2, providing the relevant data.

5.1 Real-Time Results

As mentioned earlier, in real-time drilling, pore pressure (PP) and fracture pressure (FP) should be constantly updated one step before real-time drilling. This is because the sensors can only read and report the pressures for depths that have already been drilled. The code is executed for the time step discussed in previous sections. Here, the time step is 720 seconds since the drilling step is 5 ft and the Rate of Penetration (ROP) is 25 ft/hr. This means the code will execute and plot a graph like Figure 23, then wait for 720 seconds to receive new data from the sensors and update the PP and FP. The code will then run again, following the same process for subsequent depths.

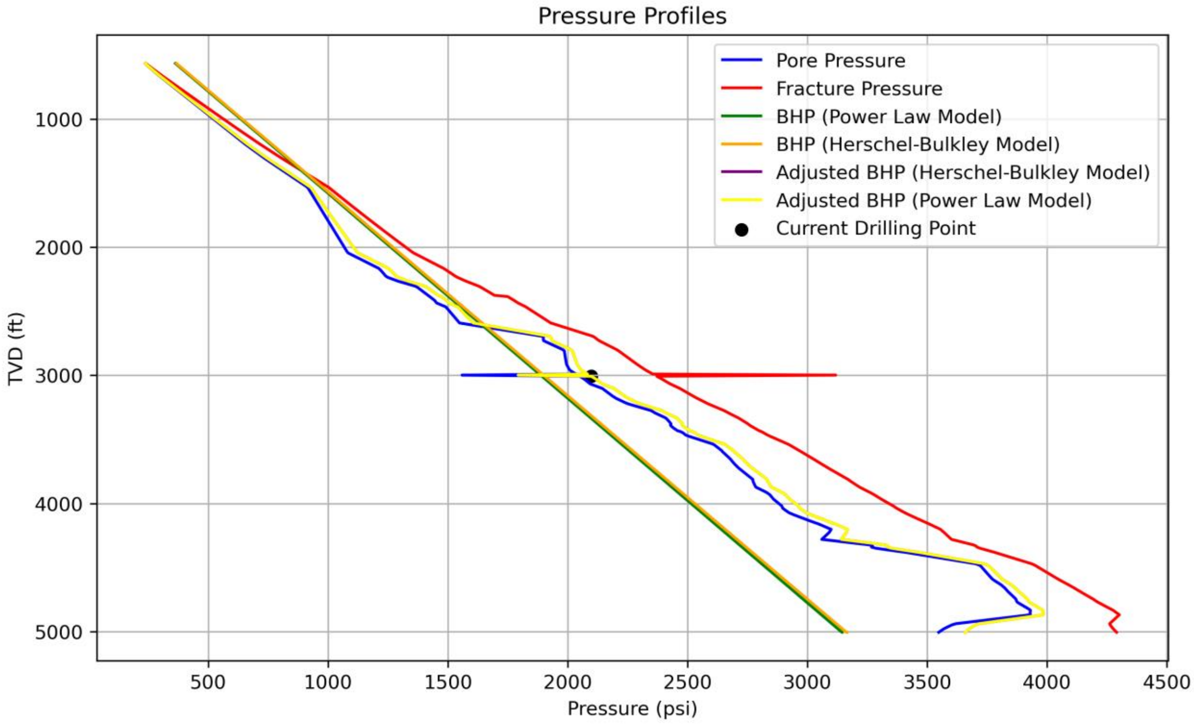

Figure 23 Real-Time Pressure Profiles

As shown in Figure 23, the current drilling point is 3070 ft MD (3006.67 ft TVD), while data from the depth of 3065 ft MD (2998.01 ft TVD) is received from the sensors and updated (one step behind). To display the updated PP and FP clearly on the graph, sensor data were inserted with exaggerated values of 10 and 20 ppg, respectively. As seen, the sensor data updates on the graph, consequently updating the BHP, Adjusted BHP, and BP to prevent the well from any kicks or fractures.

6 Conclusion

The core objective of this project was to engineer a fully automated system leveraging coding, thus eliminating human intervention. The focal point was on inputting data into the system, enabling it to function autonomously and generate the requisite outputs seamlessly.

Crafted upon specific assumptions and simplified for practicality, the code operates flawlessly without interruptions or errors. In light of these assumptions, the fully automated system is adaptable to the complexities of both deep-water and ultra-deep-water drilling scenarios.

The coding and system architecture devised in this project stands as a testament to innovation, aligning with the ongoing pursuits of esteemed petroleum entities, particularly those active in the North Sea. Prominent advantages encompass:

- Augmented Drilling Efficiency: Traditional drilling endeavors often grapple with maintaining optimal Bottom Hole Pressure (BHP), necessitating frequent manual interventions and resulting in non-productive time (NPT). By implementing a Controlled Bottom Hole Pressure (CBHP) system, BHP regulation becomes automated, diminishing manual interventions and NPT, thereby enhancing drilling efficiency and cost-effectiveness.
- Heightened Safety Measures: Automated drilling systems significantly reduce the incidence of human error, thereby bolstering safety standards by minimizing manual interventions.
- Enhanced Wellbore Integrity: The CBHP system ensures a consistent BHP, fortifying wellbore integrity and mitigating risks associated with formation damage or instability. This preemptive measure mitigates costly delays or the abandonment of wells.
- Precision and Accuracy: Automated systems offer meticulous control over drilling parameters, yielding consistent and predictable drilling outcomes, superior wellbore integrity, expedited drilling operations, and cost savings.

- Robust Data Acquisition and Analysis: Automated drilling systems excel in the acquisition and analysis of vast volumes of real-time data, empowering operators to make well-informed decisions and optimize drilling performance based on real-world conditions. This proactive approach aids in identifying and mitigating potential issues, thereby reducing NPT and enhancing overall drilling efficiency.
- Diminished Environmental Footprint: Automated drilling systems are instrumental in minimizing the environmental footprint by curbing drilling fluid consumption and mitigating the risk of leakages.

This project underscores the transformative potential of fully automated systems in reshaping drilling operations, rendering them more efficient, secure, precise, and environmentally sustainable, paving the way for a new era of drilling excellence.

6.1 Further Work and Future Research Directions

This thesis has laid the groundwork for the development and implementation of a fully automated drilling system, with significant advancements in efficiency, safety, and environmental sustainability. However, there are several areas where further research and development could enhance and extend the capabilities of the system.

- Advanced Sensor Integration: Future work could focus on integrating more advanced sensors that provide real-time data with higher accuracy and reliability. These sensors could offer enhanced detection of formation properties, fluid compositions, and other critical parameters that influence drilling operations.
- Machine Learning and AI: Incorporating machine learning algorithms and artificial intelligence (AI) can further improve the automation and decision-making processes within the system. By analyzing historical data and real-time inputs, these technologies can predict potential issues, optimize drilling parameters, and adapt to changing conditions more effectively.
- Enhanced Data Analytics: Expanding the data analytics capabilities to include more sophisticated modeling and simulation tools can provide deeper insights into drilling dynamics. This could lead to the development of predictive maintenance schedules and more accurate forecasting of drilling performance and wellbore stability.
- Real-Time Adaptability: Research could focus on enhancing the real-time adaptability of the system to respond to unexpected changes in formation pressures, fluid dynamics, and other environmental factors. This includes developing more robust algorithms that can dynamically adjust drilling parameters to maintain optimal performance.
- Environmental Impact Studies: Conducting comprehensive environmental impact studies to quantify the benefits of automated systems in reducing the environmental footprint. This includes assessing the reduction in drilling fluid consumption, minimizing the risk of spillages, and evaluating the overall sustainability of automated drilling operations.

- Cross-Disciplinary Collaboration: Encouraging cross-disciplinary research collaborations between petroleum engineering, computer science, and environmental science to foster innovative solutions that address the multifaceted challenges of modern drilling operations.
- Field Trials and Case Studies: Implementing the automated system in various field trials and case studies across different geological settings and drilling environments to validate its effectiveness and versatility. These real-world applications can provide valuable feedback and identify areas for further improvement.

6.2 Final Remarks and Suggestions

The development of a fully automated drilling system represents a significant milestone in the field of petroleum engineering, offering numerous advantages in terms of efficiency, safety, and environmental sustainability. However, it is essential to recognize that this is an evolving field, and continuous research and innovation are crucial to addressing the emerging challenges and opportunities.

Future research should prioritize the integration of cutting-edge technologies such as AI, machine learning, and advanced sensor systems to enhance the system's capabilities. Additionally, a strong emphasis on environmental sustainability and reducing the ecological impact of drilling operations will be vital in aligning with global efforts towards greener energy practices.

Collaborative efforts between industry, academia, and regulatory bodies will be essential in driving the successful implementation and adoption of these advanced automated systems. By fostering a multidisciplinary approach and encouraging innovation, the potential for transforming drilling operations into more efficient, safe, and sustainable practices can be fully realized.

In conclusion, while this project has demonstrated the feasibility and benefits of automated drilling systems, it is only the beginning. Continued research and development, driven by the insights and recommendations outlined in this thesis, will pave the way for the next generation of drilling technologies and practices, ultimately contributing to the advancement of the petroleum industry and the protection of our environment.

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Appendix

You can access the code through this GitHub link.

https://github.com/Pouyagsi/MPD