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Automated Hydraulics Program

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Abstract

The focus on digitalization and automation in the oil and gas industry has highly increased in the last decade. Automation is a technology priority in most manufacturing sectors, including petroleum (Cognizant 2019). Recent studies show that energy resource extraction industries can employ technologies to automate most of their processes.

Since the hydraulic calculations have an important role in the drilling operation, so the automation of hydraulics design in drilling and completion can reduce working hours and give better results. Each drilled well has a hydraulic calculation module for each section. The hydraulics design of any well depends on various factors that should be considered prior to drilling a hole section. It is vital to ensure full integrity while drilling a well. An insufficient design could lead to severe consequence such as poor hole cleaning. An ineffective hole cleaning means highly accumulated cuttings in the well. It might lead to being high torque and drag, high ECD and loss circulation, etc.

The integration between hydraulic design and hole cleaning is an excellent way to optimize drilling operation. It provides better solutions, better drilling parameters, and easy to use. Such forward-thinking will help the oil industry to solve challenges.

This study presents a fully automated hydraulics design program for all sections of the well by only one well schematic excel sheet for saving time and effort. It shows the effect of the parameters on hydraulics design and hole cleaning. It presents a reasonable way to save time for designing the hydraulics program of a well by using a simple Microsoft Excel program. The program enables the user to calculate and analyze the ECD and compare it with the fracture boundary, to optimize the flow rate and improve hole cleaning issue.

The fully automated hydraulics program is designed to meet the drilling engineer's needs when it comes to estimating the pump pressure or ECD quickly during the real-life drilling operation. The application contains several hidden excel sheets for process purposes and one visible well schematic excel sheet to run the simulations. The thesis provides examples of using the fully automated hydraulics program and Leading industry software . The software is tested by comparing its results with Leading industry software 's results and real data. It also analyzes and discusses the actual data and the program's results and displays good quality and accuracy. The program's results are close to the real data. The thesis contains the default values and instructions about the usage of the hydraulics program.

Acknowledgment

This work would not have been possible without the kind support of one of the world's most advanced university, Norwegian University of Science and Technology (NTNU). I am especially indebted to Dr. Bjørn Astor Brechan, who has been supportive of my career goals and who worked actively to provide me with professional guidance and protected academic time to pursue those goals. He has taught me more than I could ever give him credit for here. He has shown me, by his example, what a good scientist (and person) should be.

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Nobody has been more important to me in the pursuit of this project than the members of my family. Most importantly, I wish to thank my loving and supportive wife, Nourhan, and my wonderful child, Issam who provide unending inspiration. I would like to thank my parents whose love and guidance are with me in whatever I pursue. They are the ultimate role models.

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1 Introduction

The thesis presents a fully automated hydraulics program designed using excel. The program is designed for anyone who needs to calculate, evaluate and analyze the hydraulics of well and optimize hole cleaning. The paper provides a comprehensive comparison between results exerted by this fully automated hydraulics program and Leading industry software software.

The well-planning contains several parts to give the desired well program. Hydraulics design is one of the essential elements of well -planning. Because the hydraulics of well optimize the drilling performance, optimize hole cleaning, improve ROP, provide a better stable well and save costs. Hence, it is necessary to conduct all hydraulic calculations before the drilling operation. Later during the drilling operation, it is also imperative to perform the hydraulic calculations as fast as possible, especially when something goes wrong or a problem occurs. Hence, there is a significant need for easy to use, available, and a time-saving program which provides the possibilities to perform all hydraulic calculations for every section of well efficiently. The fully automated program provides the user at the rig or in the office the ability to perform the hydraulic calculation effectively for any or all sections of the well at the same time in only a few minutes. The user only needs Microsoft Excel for working, that gives the user high availability and simplicity of using. The program can provide a very accurate result according to user requirements. The program is tested by using real-time data and it offers excellent results compared to the real ones.

The hydraulics design for a well contains a robust evaluation of boundaries of all components of drill-string, from mud pump to drill-bit. In the open hole, the hydraulics should be analyzed to minimize the ECD. The limits start from a minimum flow rate of drilling fluid required to provide hydraulic power to MWD, power-driven tools, and maximum bit impact jet force and ECD is the upper limit and a challenge in drilling.

There are several effects of the hydraulic on the well such as control parameters of mud pump, control pressure loss system, control wellbore stability, drill bit cycle-life, improve the ROP, obtain better drill cuttings removal. (Antonino 1995)

This study has complete explanation, application, and instructions for fully automated hydraulics program which can help the user to run simulations quickly and enhances the drilling operation by:

1. Accelerating decision making
2. Boosting the productive time
3. Optimizing drilling performance

4. Optimizing hole cleaning process
5. Excellent estimation for ECD
6. Exceptional determination for mud pump pressure
7. Excellent estimation for mud pump rate
8. Excellent estimation for critical annular velocity

The fully automated hydraulics software can offer to the user.

1. Accessibility
2. Availability
3. Simplicity
4. Robust hydraulic calculations
5. Good accuracy results
6. Saving-time simulations
7. High-quality standards
8. Main visible excel sheet
9. Several hidden excel sheets
10. No need for an internet network

2 Hydraulics System

The hydraulics system is an essential part of well design. It aims to obtain maximum bit horsepower, improve cuttings transportation from the bottom hole to the shaker, improve the rate of penetration and provide the required minimum hydraulic power to the power-drive motor, MWD, and 3DRSS.

The hydraulics design includes the selection of mud pump parameters, surface-pipeline size, drill-pipe size, BHA size, MWD, 3DRSS, PDM parameters, and drill bit total flow area or number of nozzles and their size. It determines the minimum cuttings-carrying displacement and calculates the circulating system pressure loss in all sections of the well. The proper selection optimizes and improves an entire drilling well event due to reduced costs and the associated challenges with poor cuttings removal and transportation (Skalle u.d.).

The hydraulics design is to determine the frictional pressure loss system in well. It is imperative to have a proper pressure loss distribution in the system to ensure longer drill string and BHA components cycle-life, lower ECD and better hole cleaning operation.

The equivalent circulating density (ECD) is the main limitation in the hydraulics model (Ugochukwu 2015). It is established by mud flows through annulus due to friction between mud and surface of open hole and cased hole. It is challenging to estimate ECD due to complexity. It depends on mud rate, depth, friction factor, equivalent mud density (EMD) and cuttings parameters, etc.

Many studies have been conducted to improve the hydraulic parameters design methods. However, experimentation is still ongoing to achieve the optimum model. This program provides a simple manner of proper computing parameters for effective drilling operations.

The next chapter presents all elements involved in hydraulics design (Aadnoy 2010).

2.1 Hydraulic parameters

This chapter presents all elements involved to calculate the pressure loss system, ECD, annular velocity, and optimizing hole cleaning. It demonstrates the appropriate formulas used in this automated program to obtain the desired results and those used in Leading industry software software to compare between automated program and Leading industry software .

2.1.1 Mud pump

It is one of the essential elements in the drilling operation. It is a large equipment on the deck. It should be able to provide the maximum required drilling fluid displacement and pressure to the system during drilling and completion operations. The mud pump is a positive displacement pump. Displacement and pressure are commonly used to measure the pump performance. The pump rate is computed as liter per minute, related to the hole size. Large holes require higher rates. The pump discharge pressure is related to the depth of section and friction factor. For example, a deeper section requires higher pressure. The liner of the pump determines rate and pressure. Small liner size provides high pressure and flow rate and vice versa. The selection of the pump liner aims to achieve a better pump performance. In this program, a 5.5in liner size is selected to achieve the required performance. Appendix C presents more information about the mud pump.

In both the automated hydraulics program and the Leading industry software , pump pressure is calculated by summing all pressure losses over the entire system from surface to bit in addition to annulus.

The Leading industry software software and the automated program usually use this equation to calculate the mud pump pressure in the system.

$$P_{Pump} = P_{surfacepipe} + P_{dp} + P_{BHA} + P_{bit} + P_{annulus} \quad \textbf{2-1}$$

2.1.2 Drill string and surface pipe system

The surface line starts from the pump to the standpipe, rotary hose, swivel, and Kelly. Drill pipe is a significant component in the drill string, and in addition, the BHA is the rest of the drill string. Drill pipe plays a vital role in hydraulic design. It requires high-pressure loss inside the pipe due to a relatively small inner diameter. In the last decades in the drilling industry, a big part of drilling companies have been using almost the same drill string, which includes the drill pipe that is selected in this hydraulics program. The next tables below present details about the chosen pipe system.

Table 1: Drillpipe Type

Drill pipe		
Size OD in	Nominal Weight lb/ft	Grade and Upset Type
65/8	25.20	S-135

Table 2 Drill Collar

Drill Collar		
Size OD in	Weight lb.	Type
8	4640	NC- 56

Table 3 Heavy Weight Drill Pipe

Heavy Weight Drill pipe		
Size OD in	Nominal Weight lb/ft	Type
65/8	73.59	Standrad

While BHA is a relatively short part of the drillstring, however, BHA and the bit consume at least between (40% - 50%) of the total frictional pressure loss. BHA involves drill-collar, heavy-weight-drill-pipe, stabilizers, jar, joints, centralizers, MWD, 3DRSS, and PDM. Each tool in BHA has its minimum pressure drop to provide excellent performance. It will be discussed in the next chapters.

In this automated hydraulics software, the drill-pipe, drill-collar, Heavy-wall-drill-pipe, joints, and surface pipe have the same equation to calculate the frictional pressure loss through it. It is proportional to the length and decreases with inner diameter. Mudcalc has used this equation to provide pressure inside the pipe.

$$P\_pipe = 2 * 0.0006 * \upsilon\verb|^|2 * \rho\_mud * (10 * \ L)/(d * 25.4) \qquad \textbf{2-2}$$

Appendix A presents a set of equations used in hydraulics calculation.

2.1.3 Mud Motor

Mud motor is commonly known as Positive Displacement Motor (PDM). It is an essential element in the drill string to be considered in hydraulics design. It is mostly used in from mid-deep section to high-deep sections. PDM has two different purposes as steering and power generator. It generates the torque used to rotate the drill bit. It requires operating differential pressure across it for providing the necessary rotation and torque. The torque is directly proportional to pressure drop over the motor. It increases by increasing pressure drop, number of lobes in the motor. The choice of a mud motor requires sufficient hydraulic calculations and evaluations. The motor performance requires a minimum required flow rate and maximum one to provide a suitable optimum pressure drop, thereby the needed torque and RPM. In this automated hydraulics program, there is no formula to estimate the required pressure loss over mud motor due to complexity, and therefore from the best practices, it is assumed to be a (50 bar) pressure loss mud motor. While the Leading industry software has a range of choices depending on capacities and maximum pressure. Appendix C presents more information about the mud motor.

2.1.4 MWD, 3DRSS and Other tools

MWD is an electromechanical device located in the bottom hole assembly. It aims to provide essential data from the bottom hole to the surface through mud pulses. The rotation of a turbine generates the power of the tool, then transmitted to the battery. The turbine uses a mud flow rate to provide the required power; in other words, the turbine requires pressure loss to provide a high-quality performance of MWD. Because of lack of data, no formula describes the pressure loss over the MWD device, so it is selected from the experience and best practices that 15 bar is the required pressure drop over MWD.

Rotary Steerable System (3DRSS) is a tool used to direct the bit. It is mostly used in deviated and horizontal wells. It needs a little hydraulic pressure to provide effective results. However, it should be taken into account during the hydraulics design calculation. The pressure drop over 3DRSS is estimated to be 5 bar.

Other tools include stabilizers, joints, jar, and centralizers. Even though they have a short length, but they should be considered in the hydraulic design for each section by adding a particular fixed value. It is 15 bar in this case. Leading industry software however contains a broad set of choices of MWD and 3DRSS with pressure loss.

2.1.5 Bit

The drill bit has many various types, profiles, sizes, and shapes. Bit design determines bit-profile, bit-size, bit-shape and Total Flow Area (TFA) or nozzles size and number. TFA is a critical parameter in hydraulics design. It defines the drilling fluid velocity through nozzles and the required maximum jet power. The maximum jet power or horsepower is necessary to optimize the hole cleaning event. It should provide the hydraulic power to mud beneath the bit to lift and transport cuttings away. The pressure loss across the bit is considered as an essential parameter in hydraulics design. The choice of number & size of nozzles determines pressure drop over bit and larger TFA provides less pressure loss. The following equation presents pressure drops across the bit used in the automated hydraulics program.

$$P_{Bit} = \frac{8.34 * \rho_{mud} * (Q/_{3.78533})^2}{10858 * TFA^2 * 14.5} \qquad \textbf{2-3}$$

Leading industry software uses the following equation to compute the pressure loss over the drill bit.

$$P_{Bit} = \frac{\rho_{mud} * v^2}{2 * g * C_d^2} \qquad \textbf{2-4}$$

2.1.6 Annulus and ECD and Slip Velocity

The annulus is the volume existing between the drill string and open or cased hole. The flow area of the annulus is an essential part of the hydraulic system because it helps to define fluid annulus velocity, which is a crucial factor in cuttings transportation and hydraulics design. The pressure loss in the annulus is taken into account in hydraulics design. The friction factor of open hole, cased hole and outside of drill string is complicated to predict. However, it is an essential factor. It should be optimized and improved to increase drilling fluid capability to carry the rock fragments. It is limited by ECD and erosion of adjacent formation. In Mudcalc, the following equation is used to calculate pressure loss in the annulus.

$$P_{annulus} = 2 * 0.0006 * v_a^2 * \rho_{mud} * L * 10/(25.4 * OD_{hole} - 25.4 * OD_{pipe}) \qquad \textbf{2-5}$$

The equivalent circulating density (ECD) is exerted by circulating mud against the formation and cased hole. It is a crucial element because if it exceeds the formation fracture pressure then it may lead to circulation loss and and kick, especially in the small pressure window part. Hence, the ECD limits hole cleaning operation and hydraulics design. Prediction and management of ECD is highly complicated due to uncertainties and complexities. ECD can be estimated by **2-6** equation.

$$ECD = + \frac{P_{annulus}}{0{,}052 * d} \qquad \textbf{2-6}$$

Leading industry software ’s equation is almost the same.

$$ECD = \frac{P_F + P_h}{0{,}052 * d} \qquad \textbf{2-7}$$

2.2 Parameters Effect on Hole Cleaning

Hole cleaning and cuttings transportation aim to prevent cuttings to settle down and carry them to shaker. The mud’s functions are to remove and lift cuttings face drill bit away, besides cooling the bit.

Full-understanding of cutting transportation mechanism has been a critical issue for decades. Hence, determining precisely the affecting factors on it is a challenge. No universally accepted theory can account for all the observed phenomena (M.N. 1994). However, many researchers have concluded that mud capability to carry the rock fragments is related to mud type, density, and rheology, mud flow rate or annular mud velocity. And cuttings size and density, hole angle, RPM, ROP and drill pipe eccentricity have an impact as well.

The automated hydraulics program is not able to consider all previous parameters. The cuttings shape, drill pipe eccentricity, and hole cleaning pills are not considered in this program, and it could be an excellent further work in the future. While the RPM and hole angle does not directly impact on hydraulics calculations of well. However, (C. E. WILLIAMS 1951) observed that rotation of drill string effectively plays a role in the hole cleaning operation. It has been concluded that the rotation provides a centrifugal force to particles that help to push it to a high-velocity zone in the annulus to be rapidly transported. (Sifferman 1992) concluded that drill pipe rotation reduces annular cuttings buildup under certain conditions.

(Okrajni 1986)has found that the hole angle and size have a significant effect on cuttings slippage velocity, thereby cuttings transport. However, hole size is a vital factor in hydraulics calculation.

The primary common factors between hole cleaning and hydraulics are flow rate, cuttings density, size, and mud properties play a crucial role. Appendix B shows further information.

Table 4 Parametres effect on hole cleaning and hydraulics

Parameter	Hole Cleaning	Hydraulics
Hole angle	Directly effect	Indirectly effect
Hole Size	Directly effect	Directly effect
Cuttings size	Indirectly effect	Directly effect
Cuttings density	Indirectly effect	Directly effect

Parameter	Hole Cleaning	Hydraulics
Cuttings shap	Indirectly effect	Directly effect
Mud density	Directly effect	Directly effect
Mud rheology	Directly effect	Directly effect
Mud type	Directly effect	Directly effect
Flow rate	Directly effect	Directly effect
ROP	Indirectly effect	Directly effect
RPM	Directly effect	Indirectly effect
Pills	Directly effect	Indirectly effect
Drillpipe eccentricity	Indirectly effect	Indirectly effect
Drillstring size	Indirectly effect	Directly effect

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Table 4 displays all parameters impacting on cuttings transport and hydraulic module. It shows that drill pipe eccentricity effects indirectly on both cutting transport and hydraulics. While hole size, mud properties, cuttings, and the flow rate have a direct impact on hydraulics calculations and hole cleaning optimization. Hence, they are essential data for this software. Since it can control the flow rate of the drilling fluid, so the pump rate is the dominant element used in this program. Controlling the flow rate implies the control of ECD and annular velocity. The fully automated hydraulics program considers cuttings transport as a crucial issue. The program is designed based on hydraulics calculations and hole cleaning optimization. The information given in the table above is adequately taken into account in program designing.

3 Automated Hydraulics Model

3.1 Automation

In general, automation can be defined as a technology concerned with performing a process through programmed commands combined with automatic feedback control to ensure proper execution of the instructions (Groover u.d.). The main objectives of automation are saving-time, cutting-costs, higher production rate, and better efficiency. In oil companies, many applications of automated systems are used to reduce non-productive time. Automation is proven to provide high quality and effective results and solutions in all industry aspects. Automation is a turning point due to rapid development in AI (artificial intelligence) and robotic technology. Robots can conduct many functions without human intervention. Hence, oil companies tend strongly to digitalize and automate their operations and processes.

3.2 Microsoft-Excel

Excel is usually used in the oil and gas industry. Oil companies employ mostly this software due to simplicity and low cost of usage.It is one of the Microsoft programs. It features a calculation tool, graphing tool, macro, and coding via Visual Basic for Application (VBA).
In this project, Microsoft-Excel is used to create a full-detailed-automated hydraulics design. Some VBA coding and some simple excel procedures are used to develop this program. The user can effectively and quickly run this program for achieving high-quality desired results.

3.3 MudCalc

MudCalc is an Excel-based hydraulic simulation tool. It is a highly reliable program for providing the desired results. It is created at the Norwegian University of Science and Technology (NTNU). It is commonly used to calculate and estimate hydraulics for any section of a well. However, it takes a long time to run simulations for each section and operation of the entire well. That will be time-consuming to fill out all inputs and required data to run the simulation. It has several spread-sheets, and each one needs many inputs. MudCalc however is the basis of this automated program. It is used professionally as the start point of this program.

3.4 Leading industry software

Leading industry software software is one of the most used software in the drilling industry due to high quality and a lot of features. That makes Leading industry software very common.

It is a Landmark's family member, where Leading industry software is mostly used for well planning to include hydraulics calculations, surge and swab, torque and drag, etc. In this thesis, Leading industry software is solely used to compare the results with this fully automated program. The outcomes from the program are compared by both with the actual data given from the field to optimize the performance and quality for the fully automated program.

3.5 Boundaries of Model

3.5.1 Annular Velocity

This study includes several inputs, and each one has its boundaries. The annular velocity has two limits, minimum annular velocity, and maximum annular velocity. The critical annular velocity is considered as minimum annular mud velocity sufficient to overcome the cuttings slip-velocity for removing particles (Inc.) 1969). The minimum annular velocity varies based on well inclination, and this means when designing for a vertical section such as the upper two parts of most horizontal wells, there is only one minimum value. While long sections contain a vertical section, mid and high inclined sections, there are three minimum annular velocities for each portion. In this case, it should be appropriately analyzed to choose the best to obtain the desired performance. However, the maximum annular velocity is limited by ECD and resistance to the formation erosion. It exists around BHA in which it has the most significant outer diameter segments in the entire drill string. The annular velocity implies a flow rate. The high flow rate gives high annular velocity and vice versa. Hence, the maximum flow rate and minimum one are depending on annular velocity's limitations. The following equation presents the annular velocity, and each one has its boundaries.

$$v\_(a) = Q / A \quad \textbf{3-1}$$

3.5.2 Cuttings Density

The formations have various densities based on the type of formation and burial depth. It is an essential factor in hydraulics design. The higher density cuttings, the shorter time to fall out and settle down. That requires more top mud carrying capacity, thereby more hydraulic energy to lift the particles. High cutting concentration in mud may make the mud heavier than the original one. It leads to more pressure drop in the annulus and high ECD. Hence, the ECD may exceed the formation fracture pressure, and loss circulation takes place. (Egenti 2014). The fully automated hydraulics program considers the cuttings weight as a significant factor in the design. The hydraulic calculations give better results by examining the cuttings. It is worth to mention that the cuttings in the definition are the rock fragments and small broken bits of solid drilled out by drill bit.

3.5.3 Pore and Fracture pressure

All wells have a survey to demonstrate the pore pressure and fracture pressure for each formation in the column and the inclinations data. The pore pressure is defined as the hydrostatic pressure exerted by a column of seawater at a certain depth. If the bottom hole pressure is less than pore pressure, it may lead to severe consequence such as wellbore instability.

The fracture pressure of formation is a required pressure to crack formation at a certain depth. But, if bottom hole pressure exceeds fracture pressure, this may cause circulation loss and kick. Based on the importance of understanding the hydraulics design, the fracture pressure is the main limitation in total drilling design and hole cleaning optimization, especially at the narrow window.

3.6 Standardization

The oil and gas industry tends to standardize processes and equipment specifications to make significant savings. In the last decades, the well drilling industry used very similar equipment, tools, parameters, and procedures. This opens thinking-ways to create and innovate new methods, processes, and programs fit to make our life easier. The long experience and extensive database from best practice permits to standardize several inputs. Hence, it is standardized two BHAs, drilling fluid's program, and a bit design for each section in this program from the best practices and long experiences. The fully automated software offers excellent performance and satisfying results by using these standards. Standardization is an established, time-tested process to use with high quality and reliability of the product. It boosts productivity and saves time, costs, and efforts to execute any activity or simulation (Britannica 2018).

4 Automated Program/ Work Flow

As mentions above, a fully automated program is designed using excel. There is only one visible excel sheet that displays a well schematic and buttons and several hidden excel sheets. This design has fixed standardized data to facilitate the usage of it. However, the user can change a few variables to run simulations as much as desired. It enables the user to calculate all hydraulics effectively for any well consisting of five sections by only inserting some required data. This process can save a lot of time and effort for the user effectively. The program can demonstrate some informative messages to guide the user in the right way. The main page contains two buttons to switch to either BHA with mud motor mode or BHA with 3DRSS mode. It has input columns such as hole size, variable columns, i.e., flow rate and outcome columns, i.e., ECD column as well. The program has defaults and some of comments and guidelines to give the user more guidance and describing. The fully automated hydraulics program consists of:

1. Fixed standardized data columns
2. Columns for variables
3. Input parameters
4. Results
5. Informative messages
6. Comments
7. Two buttons to select the desired BHA

The next figure displays the extensive part of well schematic excel sheet in which the main page of the software. That shows above two buttons, one for BHA with 3DRSS and the other for BHA with MudMotor. And it demonstrates filling columns to the hole size, hole inclination, TVD, MD, DP, Casing, BHA, ECD, Flow rate, Mud program, Shoe, and Fracture pressure. The other missing columns and data such as Annular velocity, Mud pump pressure, ROP, Cutting's density, Status, and RPM could not appear in Figure 1.

Please note : There are two drillingsmodes, either with 3DRSS , or with Mud Motor

BHA with 3DRSS

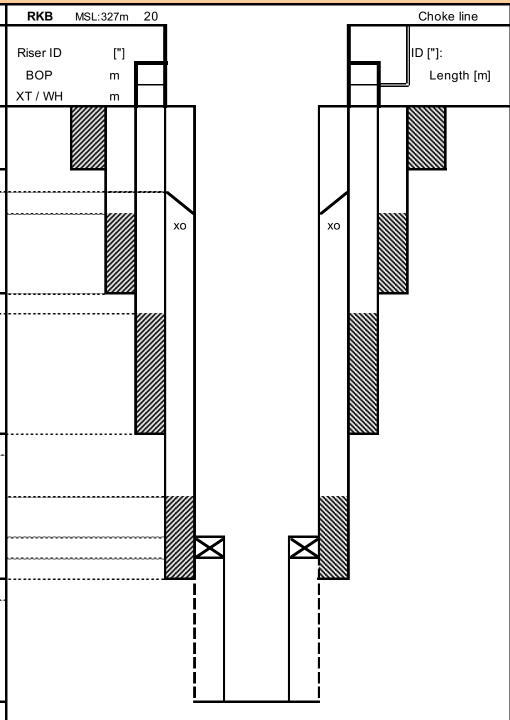
BHA with MudMotor

WELL SCHEMATIC

Well configuration

Sections 5 Liner 1

Hole: Size ["]	Hole: Inclination [degree]	Hole: TVD MD [m]	Pipe: DP	Pipe: DP	Pipe: Casing ["] OD/ID	Pipe: BHA Standard	ECD at TD [SG]	Flow Rate [Lpm]	Mud Program: Density [SG]	Mud Program: PV/YP [cP]/[Pa]	Shoe: TVD [m]	Shoe: TVD [m]	Fracture Pressure [SG]
36	0	550,0 550,0	6 5/8 25.20 S-135	Size ["] [lb/ft] Grade	30 27,3	Drill Collar 150m Heavy Wall Drill Pipe 50m	1,044	GoodValue 4000,0	1,031	SeaWater	-	-	1,41
26	0	1000,0 1000,0	6 5/8 25.20 S-135	Size ["] [lb/ft] Grade	20 18,2	Drill Collar 150m Heavy Wall Drill Pipe 50m	1,055	GoodValue 5000,0	1,031	SeaWater	550,0	550,0	1,53
17 1/2	17,79	2100,0 2081,0	6 5/8 25.20 S-135	Size ["] [lb/ft] Grade	13 3/8 12,3	Drill Collar 150m Heavy Wall Drill Pipe 50m 3DRSS MWD Jar	1,439	GoodValue 4300,0	WBM 1,40	13/10,5	1000,0	1000,0	1,74
12 1/4	73,18	4500,0 4001,0	6 5/8 25.20 S-135	Size ["] [lb/ft] Grade	9 5/8 9,5	Drill collar 150m Heavy Wall Drill Pipe 50m 3DRSS MWD Jar	1,700	GoodValue 3000,0	OBM 1,67	20/3,4	2100,0	2081,0	1,70
8 1/2	90	5891,0 4044,0	6 5/8 25.20 S-135	Size ["] [lb/ft] Grade	7,0 5 7/8	Drill Collar 150m Heavy Wall Drill Pipe 50m 3DRSS MWD Jar	1,607	GoodValue 1800,0	OBM 1,25	13/3,4	*4500,0*	4001,0	1,70



Comments: The green colums are important outputs, and the blue ones are important inputs

Figure 1 Well Schematic Sheet

4.1 The Fixed Standardized Data

Data can be standardized and fastened for saving time and effort. Beyond long study and analysis, it is concluded to design a regular mud program and TFA for each section of well based on best practices and many drilling well programs from the oil companies. It intended for two bottom hole assemblies based on rig capability and the ability to use.

4.1.1 Mud Program

As mentioned above, it is designed for each section based on depth, pore pressure, and fracture pressure. The designed mud program includes plastic viscosity, yield point, mud type, and mud density. The main principle behind the mud program design is that the mud should be able to remove and lift drilled cuttings as much as possible and at the same time should be greater than the pore pressure and less than the formation fracture pressure in that particular hole section.

The first two upper sections (i.e., conductor and surface casing sections) use water-based mud with a relatively low density which is just a bit above the normal pore pressure. Commonly sea-water without any chemical additives is used as drilling fluid for those sections for avoiding damage to the soft formation and protecting underground fresh water. Also, it is recommended to use high viscous pills for better hole cleaning issues in the intermediate casing section, and it displaces to water-based mud with higher density and viscosity to optimize cuttings transport. Designing mud of this section is related to well control issues such as shallow gas and swelling clay.

In the production casing section, it is widely prevalent that this section is relatively long and critical. It often has a small window, and some abnormal pore pressure points that make designing of drilling fluid a complicated issue. However, a viscous oil-based mud with high density to provide the best performance is desired.

The last section of well is the reservoir which has its conditions to deal with. The mud should be sufficient to carry the cuttings, but on the other side, it should not damage the interested formation. Hence, it is a low-density oil-based mud. After an extensive study and stable connection with several oil companies with real daily reports, this mud program is selected. The Table 9 mud program below displays one of the most used mud programs in the drilling industry in the last decades. Long experienced engineers and companies developed this mud program. It is designed to fit all drilling operations.

4.1.2 Bottom Hole Assembly Design and Drill Pipe

Many drilling programs have very similar bottom hole assemblies. There are small differences between them. Hence, two bottom hole assemblies have beend designed based on the most used ones in well-drilling operation. It is worth mentioning that BHA should be sufficient to provide the needed weight on bit and withstands all loads and stresses it is subjected to. The BHA is an essential segment of the drill string which transmits the drilling fluid and torque from the surface to the drill bit at the bottom. The main components in BHA are drill collar, HWDP, MWD, Mud motor, and 3DRSS. These components have a relatively large outer diameter.

The first designed bottom hole assembly consists of the drill bit, 3DRSS, stabilizers, joints, centralizer, drill collar, heavy wall drill pipe, MWD, and jar.

The other designed bottom hole assembly consists of the drill bit, mud motor, stabilizers, joints, centralizer, drill collar, heavy wall drill pipe, MWD, and jar.

In general, the designed BHAs are for the last three sections of well, while the first two sections use the same BHA but without mud motor and 3DRSS.

The most common drill pipe in drilling operations in the last decades according to industry and companies are selected in this hydraulics design — Table 6 and Table 7 present two alternatives of the drill string.

4.1.3 Bit Total Flow Area Design

The bit contains multiple nozzles. There is a broad range of various diameter of nozzles. So, the total flow area is the summation of nozzle areas in which fluid can pass through (Com -). The flow area (TFA) is one of the most critical factor in the bit design. When designing TFA, critical parameters include drilling fluid velocity through bit's nozzles, and thereby the max desired power jet to reach out high-quality bit performance and hole cleaning. This power jet or hydraulic power functions to provide the needed forces to remove and lift the cuttings beneath bit to surface. TFA can determine the pressure loss through the bit. Five TFAs are designed for five sections of the well by selecting nozzles number and size appropriately. TFA of the bit is desgned for each section depending on depth, hole size, and inclination.

Designing of TFA needs a good understanding of the importance of the jet impact force in cuttings transport and lift. The small total flow area gives large forces and power used to carry the drilled cuttings. However, very small TFA produces a substantial pressure drop that may lead to premature bit and equipment damage. The large TFA gives a tremendous flow rate, low-pressure loss, and small forces. Hence, the TFA controls the hydraulic calculations and the

designed program. The design presented in Table 8 below can provide very satisfying results comparing with real data. TTable 8 shows the RPM needed in each section.
According to the hole cleaning, the first two upper sections require a big TFA due to a large vertical hole which needs a high flow rate to effectively transport the drilled rock fragments. While due to small size and highly inclined deep hole sections, the TFA gets minor in these sections to provide maximum hydraulic jet power required to remove the drilled cuttings. Hence, during TFA design, making a sufficient balance between cuttings transport requirements and hydraulic calculations is important.

4.2 Variables

The variables are designed as intervals to give the user the possibility to change and adjust. When the user inserts any variable out of its boundaries, the program will present an informative message that warns the user. The variables involve flow rate, cuttings density, and rate of penetration (ROP). Each variable has max value and min one, which is designed based on best practices and experiences. In the excel sheet, the variables columns are blue-colored. As stated earlier, the flow rate is one of the most critical keys in the hydraulic calculations and program. So, the proper selection of flow rate requires the understanding of the balance between hole cleaning and the pressure loss system, i.e., hydraulics. It needs to be as low as possible, but at the same time, it should provide the desired force and velocity in the annulus. It should provide the pressure drop required for the bit and the equipment accompanied by BHA. The table 10 below displays the optimal flow rate used in the most oil company. AppendixB shows a table of recommended flow rates. Table 10 presents the boundaries of the flow rate as well based on the experience and best practices from the companies.
The cuttings density varies depending on the depth and formation type. So, the user can change it according to their data. The Table 12 below shows some of the various cuttings densities and the boundaries according to formation type and depth.
ROP is an essential element. High-quality drilling performance requires to drill as fast as possible, but unfortunately, it is not consistently available to do so. Each case has ROP depending on ECD, hole cleaning, rig capacity, hole size, and inclination, etc.
The Table 11 below presents some of the ideal ROPs used in the drilling industry according to the best practices.

4.3 Inputs

The inputs include well profile, fracture pressure survey, sections size, and casing program. The user needs the data about section depth, section size, section inclination, casing shoe depth, casing size, fracture pressure survey. This data is used to be from the user depending on the case. In this *chapter, the optimum hydraulics model is presented.*

Table 5 presents defaults from an actual well in the North Sea.

4.4 Outputs

The main objective beyond the fully automated hydraulics design is to calculate the hydraulics of each section of the well effectively and optimize the hole cleaning event. The fully automated program displays the computed results rapidly. The significant results are ECD, annular velocity, and pump pressure which are green-colored in the well schematic excel sheet. The ECD is a critical factor in the drilling operation. The ECD should not exceed the formation fracture pressure. Hence, it should be controlled in several ways. The software aims to control the effect of different factors on ECD.

The annular velocity is significant to overcome the cuttings slip velocity. It is directly related to the flow rate and the annular flow area.

The pump pressure is the summation of pressure losses in all components in the hydraulic system from mud pump down to the bit and annulus. It is required to select the mud pump to provide pressure overcomes total pressure drop.

In fact, according to these results, the user can manipulate the variables and frequently run new simulations to obtain the best results and design. Table 13 below displays the results achieved by using the defaults from the fully automated program.

4.5 Infomative messages

The program has several informative messages to inform the user about the status of the process. This message is short and easy to read and understand. The primary purpose is to guide the user.

The message “ Good Value” informs the user that his/her selected value is within the limitations such as in Figure 2. The message “ Exceeded ” reports that the selection is insufficient. The message is “ Success” implies that the work is successfully done and the results are satisfactory. Also, it presents the status of simulation to inform the user if it is working well or exceeding the boundaries. Table 14 shows all messages used in the software.

The one is “ ECD exceeds the fracture pressure,” which means that some of the selected values exceed the constraints. So, the user has to adjust the selections and rerun the simulation to achieve the desired results.

Figure 2 Informative message

4.6 Comments

The program has few comments. The comments present explanations about the informative messages' content. That considers as a sort of more guidance system to the user to simplify the process. The following **Error! Reference source not found.** illustrates the window of comment in the excel program.

If you get message ‘’Success’’,

Well Done.

If you get a message

‘’ ECD exceed fracture pressure’’,

Then you should adjust one of

Those parameters:

Flow rate

Cuttings Weight

ROP

Figure 3: Comments

4.7 Instruction

The program is designed for engineers who have a strong need to save time and perform precise hydraulic calculations for any part of the well during or before drilling operations. The following procedures aim to guide the user.

1. Open the excel file named “Hydraulics Design.“
2. Check out the default values
3. Enter the hole size in inches according to your well survey
4. Enter the inclination in the degree of each section depending on your data
5. Enter the total vertical depth (TVD) and measured depth (MD) in meter according to your given data
6. Keep drill pipe column (DP), modern standard drilling string as given in the program
7. Enter corresponding casing and shoe data according to your well plan
8. Enter corresponding fracture pressure data according to well profile (survey)
9. The user has two options BHAs to manipulate on
10. Click on “ BHA with 3DRSS ” bottom to employ BHA with 3DRSS mode
11. Click on “ BHA with MudMotor “ bottom to deploy BHA with MudMotor mode
12. Keep the Mud Program columns in which industry’s recently one of the most used.
13. Keep the Min Annular Velocity/ Max Av column as in the program
14. Keep the RPM as given in the program
15. Modify the Rate of Penetration (ROP) as required
16. Modify cuttings weight if you wish
17. Take controlled flow rate which has a crucial role in the program
18. Run simulation throughout only a few seconds
19. Check out the outcomes
20. Check out the ECD
21. Check out the Pump Pressure
22. Check out the Annular Velocity
23. Check out the status
24. Repeat the same procedures until you are satisfied

4.8 Optimum Hydraulics Model

In this chapter, the optimum hydraulics model is presented.

Table 5: Inputs

Section Size [in]	Depth [m]		Casing [in]		Shoe Depth [m]		Fracture [SG]	Inclination [Degree]
	TVD	MD	ID	OD	TVD	MD		
36”	550	550	27.3	30	550	550	1.41	0
26”	1000	1000	17.2	20	1000	1000	1.53	0
17.5”	2081	2100	12.3	133/8	2081	2100	1.74	17.79
12.25”	4001	4500	9.5	9 5/8	4001	4500	1.7	73.18
8.5”	5891	4044	5 7/8	7	4044	5822	1.7	90

The used standardized data:

Table 6: First alternative drill string with 3DRS

Component	OD (in)	ID (in)	Length (m)	Grad
Bit	**-**	**-**	**-**	**-**
PD, 3DRSS	**9.25**	**3**	**4**	**-**
Flex joint	**9.25**	**3.25**	**2.74**	**-**
MWD	**8.63**	**5.9**	**15**	**-**
NM Stab	**8**	**2.81**	**1.5**	**-**
NM Collar pipe	**8**	**2.88**	**27**	
Drill Collar pipe	**8**	**2.88**	**50**	
Jar	**7.63**	**3**	**10**	
Drill Collar pipe	**8**	**2.88**	**73**	
Crossover	**7.88**	**3.5**	**1**	
HWDP	**6.625**	**3.25**	**50**	
Drill pipe	**6.625**	**4.8**	**Rest of drillstring**	**S-135**

Table 7: Second alternative Drill string with MudMotor

Component	OD (in)	ID (in)	Length (m)	Grad
Bit	-	-	-	-
PD, 3DRSS	9.25	3	4	-
Flex joint	9.25	3.25	2.74	-
MWD	8.63	5.9	15	-
NM Stab	8	2.81	1.5	-
NM Collar pipe	8	2.88	47	
Drill Collar pipe	8	2.88	50	
Jar	7.63	3	10	
Drill Collar pipe	8	2.88	53	
Crossover	7.88	3.5	1	
HWDP	6.625	3.25	50	
Drill pipe	6.625	4.8	Rest of drillstring	S-135

Table 8 : Bit design (TFA) & RPM

Bit (in)	36”	26”	17.5”	12.25”	8.5”
TFA (in^2)	1.589	1.327	1.42	0.990	0.888
RPM	80	100	130	150	150

Table 9 : Mud Program

MudProgram for Section	36”	26”	17.5”	12.25”	8.5”
Mud Weight (g/cm3)	1.031	1.031	1.4	1.67	1.25
Type	SeaWater	SeaWater	WBM	OBM	OBM
Plastic Viscosity (mPa.s)	0	0	13	20	17
Yield Point (Pa)	0	0	10.6	3.4	8.6
600/300 (lbf/100ft2)	0	0	48/35	47/27	52/35
200/100 (lbf/100ft2)	0	0	30/25	19/11	27/19

MudProgram for Section	36"	26"	17.5"	12.25"	8.5"
60/30 (lbf/100ft2)	**0**	**0**	**21/17**	**7/5**	**3/1**
6/3 (lbf/100ft2)	**0**	**0**	**13/12**	**3/2**	**10/9**
Gel Strength (Pa)	**0**	**0**	**7**	**4.2**	**5**

Table 10 : Flow rate for each section

Section (in)	Min Flowrate (m3/s)	Max Flowrate (m3/s)	Best Flowrate (m3/s)
36"	**1000**	**5000**	**4000**
26"	**1500**	**5000**	**4500**
17.5"	**4300**	**5500**	**4300**
12.25"	**3000**	**4000**	**3600**
8.5"	**1800**	**2500**	**1800**

Table 11: ROP for each section

Section (in)	Min ROP (m/h)	Max ROP (m/h)	Best ROP (m/h)
36"	**2**	**8**	**4**
26"	**3**	**10**	**15**
17.5"	**35**	**55**	**40**
12.25"	**30**	**50**	**40**
8.5"	**10**	**25**	**20**

Table 12: Cuttings Weight

Section (in)	Min Cuttings weight (SG)	Max Cuttings weight (SG)	Best Cuttings weight (SG)
36"	**1.9**	**2.7**	**2.2**
26"	**2**	**2.7**	**2.23**
17.5"	**2.1**	**2.7**	**2.4**

Section (in)	Min Cuttings weight (SG)	Max Cuttings weight (SG)	Best Cuttings weight (SG)
12.25”	2.1	2.8	2.5
8.5”	2.2	2.8	2.5

Table 13: The outputs

Section (in)	ECD (SG)	Annular Velocity (m/s)	Pump Pressure (bar)
36”	1.045	0.11	87
26”	1.055	0.28	143
17.5”	1.439	0.65	170
12.25”	1.702	1.98	272
8.5”	1.62	7.18	286

Table 14: Status

Status	**Ok** **It refers that simulation is completed well.**
Status	**ECD exceeds Fracture pressure** **It refers that simulation is completed well.**
Good value	**It refers that the user has selected a proper selection.**
Exceeded	**It refers that the user has not selected a proper selection.**

5 Results

Two different tests are conducted for testing the efficiency and accuracy of the fully automated program in addition to comparing with Industry leading software's performance. The first one used BHA with a drill collar with 7.5” outer diameter, while the second one used the BHA with 7” outer diameter drill collar. Each experiment has two cases 8.5” hole and 12.25” hole. The automated program displays high-speed performing simulations and outcomes set with good accuracy comparing to real data. While the Industry leading software needs a long time to make up all data, from well profile to casing program to drill string, etc. It might take days to fill out all required inputs. Industry leading software provided less accuracy than a fully automated program as shown in Table 16 and Table 17 below. Even though the Leading industry software has a vast range of features but, the accessibility and simplicity of the fully automated program are better, especially during the drilling operation. Besides, the time factor is a decisive action all over. Actual data is obtained from the industry. The actual data presented in Table 15 is from a well located in the North Sea.

Table 15: Real data

Case	Section in	Flow rate m3/s	ROP m/h	MD m	TVD m	MD Shoe m	TVD Shoe m
1	8.5	2000	33	3168	2036	2586	1963.6
2	12.25	3300	25	2586	1962.9	1918.6	1709.4

Table 16: Results for case 1 With 7.5" OD Drill Collar

8.5” section	Actual Data	Automated Program	Leading industry software
ECD (sg)	1.38	1.497	1.52
Pump Pressure (bar)	190	180	199

Table 17: Experiment results for case 2 With 7.5" OD Drill Collar

12.25” section	Actual Data	Automated Program	Leading industry software
ECD (sg)	1.361	1.357	1.427
Pump Pressure (bar)	160	187	206

Table 18: Better Results For Case 1 With 7" OD Drill Collar

8.5” section	Actual Data	Automated Program	Industry leading software
ECD (sg)	1.385	1.446	1.49
Pump Pressure (bar)	190	171	180

Table 19: Better Results For Case 2 With 7" OD Drill Collar

12.25” section	Actual Data	Automated Program	Industry leading software
ECD (sg)	1.361	1.357	1.432
Pump Pressure (bar)	160	187	196

The Table 16,Table *17*Table *18*Table 19) present that the automated program’s outcomes are closer to the real data than the Industry leading software ’s ones. However, the 12.25” section provided higher accuracy than 8.5” section. But, there are deviations between the real data and the program's results which makes it challenging to predict the main reasons behind this. However, it can be due to:

1. Uncertainty to predict cuttings accumulation and size
2. The complexity of estimation of turbulent flow pattern built around BHA
3. The difficulty of evaluation of the hydraulic flow diameter,i.e., area
4. Poor understanding the real effect of RPM on cuttings transport event
5. The impact of hole deviation and size on cuttings accumulation
6. Lack of understanding of drillpipe eccentricity impact on cuttings removal

6 Discussion

The hydraulics design is developed to be fully automated and easy to use. The core objective is to save time, efforts, and costs through drilling well planning and operation. The results given in Table 16 and Table 17 show that outcomes for the fully automated hydraulics program are way higher than the real data due to the large outer diameter of drill collar which builds up a high-pressure loss in small annulus-space around BHA. Hence, it increases ECD value, especially in a sections with a smaller diameter. But the large size hole the value is more accurate. They display that 12.25" section gives better results than 8.5" section. However, the automated program shows closer results to real ones than Industry leading software 's ones. The lack of full understanding of cuttings accumulations and size in the bottom hole gives poor hydraulic calculations. The small flow area around BHA creates chaos and the turbulent flow condition complicates to compute and estimate it. This complexity comes up from the difficulty of understanding this flow pattern. While the sizeable annular flow area builds up a laminar flow can easily be predicted. Besides, the accurate estimation for the hydraulic outer diameter of the components of the BHA and open hole inner diameter add uncertainty. Therefore, the software's results display a substantial deviation.

In the real drilling process, the bit drills out larger than its outer diameter, which creates enlargement in some places in the open hole. And, the stabilizers in BHA have "waterways" between the blades, these waterways are channels and present an additional flow area for drilling fluid in the annulus. Hence, this enlargement and additional flow area should be involved in the annular flow area of mud around BHA. It can be estimated as 10% excess of the inner diameter of the open hole. So, this excess can be taken into account as a reduction of drill collar pipe because it is a significant component in BHA. Hence, a 7" OD drill collar pipe is used instead of 8" in the automated program. That gives better results and very close to the real data, as shown in Table 19 and Table 18 .

It is employed to calculate all hydraulics of well and optimize hole cleaning events. Many simulations are run by this fully automated hydraulics design. It is performed effectively many times to determine the limitations of this design accurately.

This hydraulic model is used for five well sections. The 36" and 26" sections are mostly not complicated to obtaining good hydraulics. They require relatively high flow rates to achieving a cleaner well. However, there is a deficient annular velocity because of the substantial hole diameter. In those sections, it is deployed a sea-water is used as drilling fluid for environmental issues. The RPM does not effectively impact hole cleaning in vertical and large-size sections. However, the ROP is relatively low in those sections due to less hard formations, and boulders cannot be drilled rapidly due to vibrations issues. The formation weight sets cuttings density 2.1 SG, which is low at very shallow depth.

The 17.5” section has most often a hole cleaning challenge that needs a suitable design. Sea-water is usually displaced to water-based mud. The optimal used flow rate is 4300 m3/s, which provides the required min annular velocity of 0.54 m/s for cuttings transport matters. Even though high flow rates are used but the annular velocity is noticed to be very low in these sections due to the sizeable annular flow area. The max annular velocity is determined according to the resistance of erosion of shallow formations which is relatively soft to hard. Hence, it cannot be too high velocity of 7 m/s. The cuttings density is generally set as 2.5 SG due to the overburden effect. The ROP is selected 40 m/h to optimize the drilling operation. RPM of 130 or higher is sufficient to obtain hole cleaning in vertical and medium-size sections.

The 12.25” section is usually long, deviated one. It is a critical part of drilling wells operations due to the complexity of wellbore stability issues and hole cleaning challenges. It requires maintaining the right balance between hydraulics and cuttings transport process to avoid missing the well entirely. It is significantly important to consider that this section involves three significant divisions, vertical, medium-inclined, high-inclined one. Each division has its conditions to determine the minimum annular velocity required to achieve the best performance. In the vertical part, the high annular velocity is not a key player; therefore, it might accept at 0.55 m/s. However, the medium-inclined part requires a fast cuttings transport to avoid cuttings fall towards low side well wall; therefore, it cannot accept less than 0.8 m/s. In the third part, there is a high potential for forming a cuttings bed which should be taken into account while designing for this section. It requires the highest minimum annular velocity to achieve the goal, which is the erosion of the formed cuttings bed and removes the cuttings up to surface. Hence, the required min annular velocity cannot be less than 0.93 m/s. The selection of 3000 m3/s min flow rate of this 12.25” section is related directly to min annular velocity which is chosen as 0.93 m/s highest one of the three to provide good hole cleaning. Because if the min annular velocity is less than 0.93, the drilling fluid can clean only the vertical and medium-inclined parts, while in the high inclined the particles start to settle down. The 3200 m/s maximum flow rate can provide the 1 m/s ideal annular velocity for the best cuttings transport process (Brechan 2015). However, the selection of the max flow rate is related directly to ECD and max annular velocity. It is unusual to choose a very high flow rate because it can lead to significant increase in ECD, thereby cracking the formation and loss of total circulation.

Therefore, the accepted max flow rate is 4000 m3/s. While exceeding 8 m/s max, annular velocity can lead to washouts and erosion of formations. It is worth to mention that max annular velocity is considered only in an open hole section. The 40 m/s ROP is best to drill as fast as possible without any suffering hole cleaning or wellbore stability issues. However, it requires at least 150 rpm to help to push rock fragments to high annular velocity zones. Indeed, it is known that most type of rock in the formation column is clay with 2.5sg weight.

The 8.5” section is known as a sensitive one due to damaging formation considerations. Throughout designing this section, it should consider that high flow rates or high ECD should not damage the interested zone. Also, in the horizontal part, the cuttings tend to fall and form the bed, which is a critical issue and must be catered for. This section has a small annular flow area which requires at least 1800 m3/s min flow rate to obtain the aim. While the 2500 m3/s max flow rate is limited as mentioned by ECD and damage interested formation. Therefore, 1900 m3/s is chosen as the pump rate to provide 7.5 m/s annular velocity and obtain a cleaner hole. The max annular velocity is set 10 m/s to avoid washouts in the formations. The 150 rpm helps to erode the formed cuttings bed and clean the bore. However, this section should be drilled carefully by 17 m/h ROP. The reservoir formation is usually sandstone, which is almost 2.6 SG.

7 Conclusion

The existing work process and software require a lot of time to simulate for each section. The fully automated hydraulics simulating tool is designed to support up to five parts. It calculates a prototype for hydraulics and optimizes hole cleaning performance effectively. Hence, it is an excellent solution to save time through a fully automated program. This program is designed by using excel software due to the simplicity of use. Some inputs are standardized based on best practices and experience. It allows the user to run many simulations quickly for all sections simultaneously. The user can estimate the required pump pressure and pump rate for each section adequately and calculate drillings parameters to optimize the cuttings transport process. The main objective beyond the program is to save time, efforts, and costs as well.

It is concluded that the annular velocity or pump rate is the most important parameter in both hydraulics and hole cleaning. Throughout designing a well, it should make a balance between hole cleaning and hydraulics. It should consider hole size, inclination, cuttings properties, mud program, bit design, and BHA. It has limitations such as ECD and min annular velocity.

It is found out that the 36" and 26" sections are not critical parts in hydraulics design while the 17.5" requires harder conditions to obtains high-quality performance. The 12.5" and 8.5" sections are smaller in size, extended and high-inclined ones which are complicated. They are considered as the most critical ones during drilling well design and operation.

The automation and standardization give excellent solutions and results to strengthen the drilling operation. The fully automated hydraulics program is more straightforward and simpler to use than the Leading industry software . The automated program requires less time to perform a simulation than Leading industry software . The results conclude that the fully automated program more accurate than Leading industry software software. But the simulation in Leading industry software includes the impact of drill pipe eccentricity, cuttings size, and RPM on hydraulics and hole cleaning while the fully automated hydraulics program does not cover their effects.

Abbreviation

ROP	Rate Of Penetration
ECD	Equivalent Circulating Density
HWDP	Heavy Wall Drill Pipe
ID	Inner Diameter
OD	Outer Diameter
Lb/ft	foot-pound
m	Meter
g/cm3	Gram per cubic centimetre
lbf/100ft2	pound-force per square foot
Pa.s	Pascal. second
in2	Inches Square
m/s	Meter Per Second
m^3/s	Qubic Meter Per Second
MD	Measure Depth
NM	Non Magnetic
RPM	Rotation Per Minute
SG	Specific Gravity
TFA	Total Flow Area
TVD	True Vertical Depth
VBA	Visual Basic for Applications
in	Inches
m/h	Meter per hour
Max	Maximum
Min	Minimum
3DRSS	3 Dimension Rotary Steerable System
PDM	Positive Displacement Motor
BHA	Bottom Hole Assembly
DP	Drill Pipe
DC	Drill Collar
MWD	Measurement While Drilling
PD	Power Drive

EMD	Equivalent Mud Density
L	Length
P_{pump}	Mud Pump Pressure
P_{dp}	Drill pipe pressure loss
P_{BHA}	Bottom hole assembly Pressure loss
P_{bit}	Pressure loss over Bit
$P_{annulus}$	Pressure loss in Annulus
$P_{Surfacepipe}$	Surface line pipe Pressure loss
P_{pipe}	Pressure loss in pipe
ρ_{mud}	Mud Density
d	Depth
v	Drilling Fluid Velocity
Q	Flow Rate
Cd	Coefficient
v_a	Drilling Fuild Annular Velocity
OD_{pipe}	Outer Diamter of Pipe
OD_{hole}	Outer Diamter of Hole
A	Flow Area
P_h	Hydrostatic Pressure change to ECD point
P_F	Frictional Pressure change to ECD point

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Appendix A

Most used equations to calculate pressure loss in pipe and annulus for various drilling fluids

Table 20 Equations

	Newtonian Model	**Bingham Model**	**Power Law Model**
Laminar pipe	$\Delta P_p = \frac{32 * \nu * \mu * L}{d^2}$	$\Delta P_p = \frac{32 * \nu * \mu_{pl} * L}{d^2} + \frac{16 * L * \tau_0}{3d}$	$\Delta P_p = 4\,K(\frac{8.\nu}{d} * \frac{3\,n+1}{4\,n})^n * \frac{L}{d}$
Laminar annulus	$\Delta P_a = \frac{48 * \nu * \mu * L}{(d_o - d_i)^2}$	$\Delta P_a = \frac{48 * \nu * \mu_{pl} * L}{(d_o - d_i)^2} + \frac{16 * L * \tau_0}{(d_o - d_i)}$	$\Delta P_a = 4\,K(\frac{12.\nu}{d_o - d_i} * \frac{2\,n+1}{3\,n})^n * \frac{L}{d_o - d_i}$
Turb. Pipe. ann.	$\Delta P = \frac{0.092 * \rho_m^{0.8} * \mu^{0.2} * \nu^{1.8} * L}{d_h^{1.2}}$	$\Delta P = \frac{0.073 * \rho_m^{0.8} * \mu^{0.2} * \nu^{1.8} * L}{d_h^{1.2}}$	$\Delta P = a\,N_{Re}^{-b} * \frac{4\,L}{d_h} * \frac{\nu^2\,\rho}{2}$
Eff. Viscosity Pipe	$\mu_{eff} = \mu$	$\mu_{eff} = \mu_{pl} + \frac{(d_o - d_i) * \tau_0}{6 * \nu}$	$\mu_{eff} = (\frac{8 * \nu}{d} . \frac{3\,n+1}{4\,n})^n * \frac{K\,d}{8\,\nu}$
Eff. Viscosity ann.	$\mu_{eff} = \mu$	$\mu_{eff} = \mu_{pl} + \frac{d * \tau_0}{8 * \nu}$	$\mu_{eff} = (\frac{12 * \nu}{d_h} . \frac{2\,n+1}{3\,n})^n * \frac{K\,d_h}{12\,\nu}$
Shear rate pipe	$\gamma = \frac{8 * \nu}{d}$	$\gamma = \frac{8 * \nu}{d} + \frac{\tau_0}{3 * \mu_{pl}}$	$\gamma = \frac{8 * \nu}{d} + \frac{3 * n + 1}{4 * n}$
Shear rate ann.	$\gamma = \frac{12 * \nu}{d_y - d_i}$	$\gamma = \frac{12 * \nu}{d_y - d_i} + \frac{\tau_0}{3 * \mu_{pl}}$	$\gamma = \frac{12 * \nu}{d_y - d_i} + \frac{2 * n + 1}{3 * n}$
General Re pipe	$N_{Re} = \frac{d^n * \nu^{2-n} * \rho}{K_p * (8^{n-1})}$	$K_p = K.(\frac{3 * n + 1}{4 * n})^n$	Fanning $f_{lam} = \frac{16}{N_{Re}}$
General Re ann.	$N_{Re} = \frac{d^n * \nu^{2-n} * \rho}{K_a * (12^{n-1})}$	$K_a = K.(\frac{2 * n + 1}{3 * n})^n$	Fanning $f_{lam} = \frac{24}{N_{Re}}$

Table 21: Criteria

Performance index	**Equation**	**Criterion**	**Fraction parasitic pressure loss**	**Flow rate**
1	$q\,P_2$	Max. HP	$\frac{1}{m+1}$	$\frac{P_1}{C(m+1)}$
2	$q\,\sqrt{P_2}$	Max. jet impact	$\frac{2}{m+2}$	$\frac{2\,P_1}{C(m+2)}$
3	$q^{3/2}\,\sqrt{P_2}$	New A	$\frac{3}{m+3}$	$\frac{3\,P_1}{C(m+3)}$
4	$q^2\,\sqrt{P_2}$	New B	$\frac{4}{m+4}$	$\frac{4\,P_1}{C(m+4)}$
5	$q^{5/2}\,\sqrt{P_2}$	New C	$\frac{5}{m+5}$	$\frac{5\,P_1}{C(m+5)}$

Table 22: Overview hydraulic system

Position	**Flow regime**	**Limitation**	**Critical parameter**
Surface piping	Turbulent	Wear	
Inside drill string	Turbulent	Wear	
Inside drill collars	Turbulent	Wear	
Through nozzles	Turbulent	Wear	
Outside drill collars	Turb/Laminar	Washout	Flow rate

Position	Flow regime	Limitation	Critical parameter
Outside drill pipe	Laminar	Cuttings Transpot	Flow rate
Inside riser	Laminar	Cuttings Transpot	Flow rate

The hydraulic system and pressure loss

Pressure losses

We will in this chapter define some simple equations to perform pressure drop calculations in the hydraulic system. First we will investigate some properties about the various flow regimes. (Bourgoyne Jr., Applied Drilling Engineering 1986)give a good overview over equations needed to calculate friction losses in tubing and annuli for non-Newtonian fluids.

In general we deal with two flow regimes. In the laminar flow regime the fluid moves along defined paths, and the flow equations are determined analytically. In the turbulent flow regime, on the other hand, fluid moves in a chaotic manner. There are no analytical models available for this case, therefore, correlations have to be established using the friction factor concept. In general, we can say that the following relations exist between pressure drop and flow rate for Newtonian fluids:

For laminar flow:

$$P \sim \mu q \qquad (2.9)$$

For turbulent flow:

$$P \sim \rho f q^2 \qquad (2.10)$$

where: P = pressure drop q = flow rate

μ = viscosity
ρ = fluid density f = friction factor

Note that the pressure drop for flow in pipes depends on the flow regime; in laminar flow the pressure drop is proportional to the viscosity and the flow rate, and in turbulent flow the pressure drop is proportional to the density and the flow rate squared. Equations (2.9) and (2.10) are valid for Newtonian fluids. For non-Newtonian fluids more complex relations exists, as described by (Bourgoyne Jr., Applied Drilling Engineering 1986). However, the trends are similar, and since we are not going to use these equations in the analysis below, they will not be further addressed here.

the hydraulic system on a floating drilling rig. Inside the drillpipe the flow velocity is high because of a small cross-sectional area. The velocity increases significantly over the bit nozzles. The inside of the drill string is usually in turbulent flow. In the annulus, the section along the bottom-hole-assembly may be in turbulent flow or in laminar flow, but the rest of the annulus, including the riser, is usually in laminar flow.

Seen in context of Equations (2.9) and (2.10), we observe that we have a mixture of flow regimes. Therefore, the total pressure loss consists of a mixture of Equations (2.9) and (2.10).

From a functionality point of view, the flow across the bit nozzles shall remove drilled cuttings away from the drill bit. The flow in the annulus have the function of transporting these cuttings up the wellbore to be disposed of on the drilling rig. The pressure drop can be split into two groups:

- the pressure drop across the nozzles, which is aiding the drilling process by providing cleaning and hydraulic power.
- the pressure drop in the rest of the system, or the system pressure drop. This is also called the parasitic pressure drop as it does not contribute to the drilling process.

If we consider the hydraulic system of a whole, we can split the total pressure drop into a useful and a parasitic group as follows:

$$P_1 = P_2 + P_3 \quad (2.11)$$

where : P_1 = pump pressure

P_2 = pressure drop across bit nozzles

P_3 = parasitic pressure loss, or system losses

For a moment we will consider the parasitic pressure loss. We observe from Equations (2.9) and (2.10), that we have a mixture of flow regimes. Instead of modelling each element of the system and add the contributions, we will use one simple equation that describe the whole system.

$$P_3 = Cq^m \quad (2.12)$$

where: C = proportionality constant

m = flow rate exponent 2

Typically the pressure losses in the annulus, or the laminar parts of the system is of the order 10-20 % of the total pressure drop. The losses inside the drill string dominates the parasitic pressure loss. Since this usually is turbulent, Equation (2.10) dominates the process. Therefore, Equation (2.12) is dominated by turbulent flow, which results in an exponent slightly less than two. We have now defined all elements required to use the total pressure drop equation.

Forces on cuttings :

The main objective is to prevent the rock fragments to settle down in well. The essential forces acting on rock fragment in annulus are shear force F_{shear} from the flowing mud and gravity force F_g.

Where:

$$F_{shear} = \tau * A_{sphere} \quad (1)$$

$$F_g = g * (\rho_{particle} - \rho_{mud}) * V_{sphere} \tag{2}$$

τ: shear stress

A_{sphere}, V_{sphere}: Area and volume of praticle

by

$$F_{shear} = F_g$$

after derivation and integration, it could obtain to what is called Slip velocity v_{slip}

$$v_{slip} = \frac{d_p^2 * g * (\rho_{particle} - \rho_{mud})}{6 * \pi * \mu} \tag{3}$$

Where:

$\rho_{particle}, \rho_{mud}$: particle density, mud density

g: gravity

d_p: diameter of particle

μ: effective viscosity

Slip velocity of cuttings (particles) is one of most critical factors in cuttings transport mechanism, therefore it is necessary to stay above mud critical annular velocity to lift and bring cuttings up to surface. There are several forces acting on cuttings particles such drag force, lift force and cohesive force and gravity force.

Appendix B

This figure provide table of most used flow rate depending on each section and annular velocity. The flow rate is calculated based on the different hole size and drill pipe. It is important to obtain the annular velocity. The annular velocity is critical parameter to optimize hole cleaning.

5.875" DP 12,25 in [LPM]	Annular velocity [m/s]	Flow rates for 6,625" DP 12,25 in [LPM]	13,50 in [LPM]	14,00 in [LPM]	15,00 in [LPM]	16,00 in [LPM]
2600	0,71	**2300**	3000	3300	3920	4590
2650	0,73	**2350**	3060	3370	4010	4690
2710	0,74	**2400**	3130	3440	4090	4790
2760	0,76	**2450**	3190	3510	4180	4890
2820	0,77	**2500**	3260	3580	4260	4990
2880	0,79	**2550**	3320	3650	4350	5090
2930	0,81	**2600**	3390	3720	4440	5190
2990	0,82	**2650**	3450	3800	4520	5290
3050	0,84	**2700**	3520	3870	4610	5390
3100	0,85	**2750**	3580	3940	4690	5490
3160	0,87	**2800**	3650	4010	4780	5590
3220	0,88	**2850**	3710	4080	4860	5690
3270	0,90	**2900**	3780	4150	4950	5790
3330	0,91	**2950**	3840	4230	5030	5890
3390	0,93	**3000**	3910	4300	5120	5990
3440	0,94	**3050**	3970	4370	5200	6090
3500	0,96	**3100**	4040	4440	5290	6190
3550	0,98	**3150**	4100	4510	5370	6290
3610	0,99	**3200**	4170	4580	5460	6390
3670	1,01	**3250**	4240	4660	5540	6490
3720	1,02	**3300**	4300	4730	5630	6590
3780	1,04	**3350**	4370	4800	5710	6690
3840	1,05	**3400**	4430	4870	5800	6790
3890	1,07	**3450**	4500	4940	5890	6890
3950	1,08	**3500**	4560	5010	5970	6990
4010	1,10	**3550**	4630	5090	6060	7090
4060	1,12	**3600**	4690	5160	6140	7190
4120	1,13	**3650**	4760	5230	6230	7290
4180	1,15	**3700**	4820	5300	6310	7390
4230	1,16	**3750**	4890	5370	6400	7490
4290	1,18	**3800**	4950	5440	6480	7590
4340	1,19	**3850**	5020	5520	6570	7690
4400	1,21	**3900**	5080	5590	6650	7790

Figure 4 Flow rate Table

Appendix C

This figure illustrates the mud motor plot used to select flow rate and pressure loss and torque.

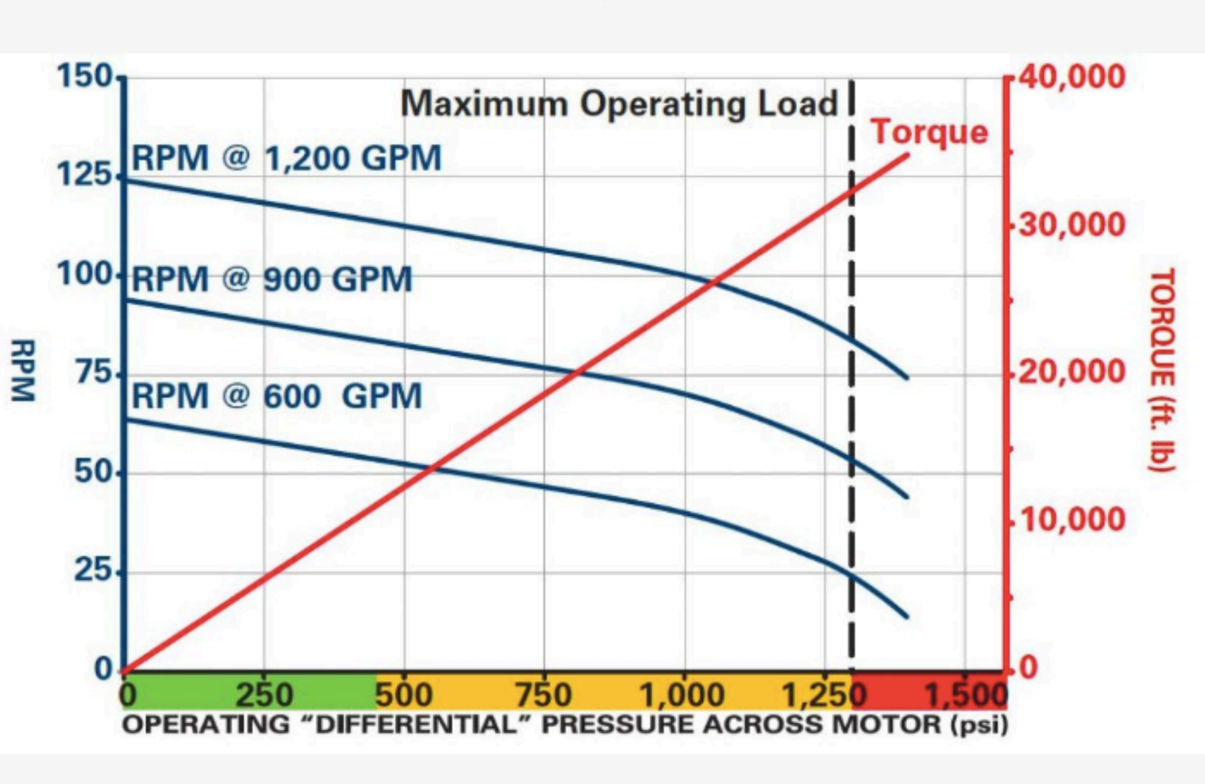

Figure 5 Mud Motor

This figure presents mud pump plot to select the liner and pump pressure depending on flow rate.

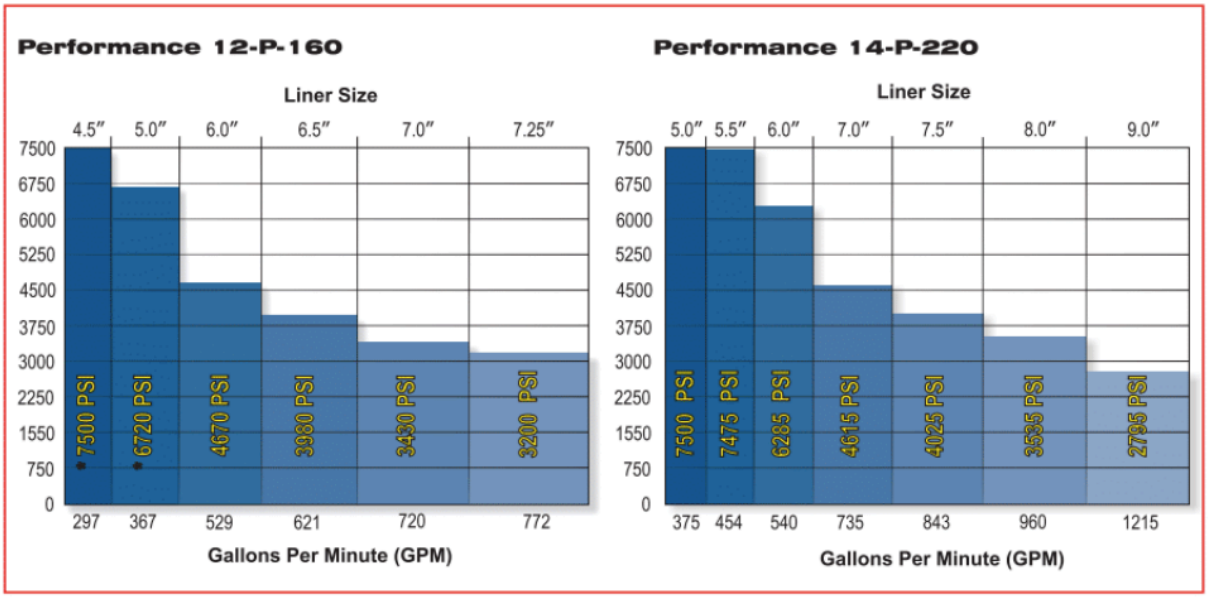

Figure 6 Mud Pump