COMPERHENSIVE STUDY ABOUT WELL CONTROL METHODS USING SIMULATION, SENSITIVITY ANALYSIS OF PARAMETERS

A Dissertation
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Department of Environment, Land and Infrastructure Engineering

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DECLARATION

I declare that this project work is my own work. It is being submitted for the degree of Master of Science in Petroleum Engineering in Politecnico di Torino, Italy. It has not being submitted for any degree or examination in any other University.

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(Signature of candidate)

..…….day of……………….year…………

DEDICATION AND ACKNOWLEDGEMENTS

I dedicate this work to my family, for their love, support, and positive energies.

Also, many thanks and appreciation to Mr. Francesco Curina, Professor Raffaele Romagnoli, Mr. Francesco Vasta, Mr. Leonardo Bori, and Mr. Vladimir Mitu, and all the other colleagues which I worked with, for persevering with me as my advisors throughout the time it took me to complete this research and write the dissertation.

ABSTRACT

This final thesis summarizes the purpose of the activities at the company of "Drillmec Spa", completing the academic career of Petroleum Engineering at the university of "Politecnico di Torino".

Drillmec is a leading company in the design, production and distribution of drilling rigs and workovers, and supplier of a wide range of drilling equipment, both on-shore and off-shore. The following thesis will outline all the phases of work supported by Mr. Francesco Curina (Training Manager and Instructor Assessor of IWCF) and the team of the Drillmec Training Center's instructors, where I carried out all my work and training activities. The purpose of this activity was to actively contribute to the projects of the department, where I was able to develop the Well Control project related to the design, and analysis of the well control model considering the important parameters for simulation of this phenomena by the simulator of the company, which was an important point of view to be considered for the training, and then performing the sensitivity analysis for the well control, and drilling parameters to check, how they can have effect on well control and drilling activities. Comprehensive study on well control methods has been conducted and the unconventional methods for well control has developed by the simulator.

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LIST OF SYMBOLS AND ABBREVIATIONS

API	American Petroleum Institute
APL	Annular Pressure Loss
μ_a	Apparent Viscosity
BOP	Blow Out Preventer
BHA	Bottom Hole Assembly
BF	Buoyancy Factor
ρ	Density
WDC	Drill Collar Weight
ECD	Equivalent Circulation Density
FCP	Final Circulation Pressure
gpm	Gallon Per Minutes
ICP	Initial Circulation Pressure
ID	Internal Diameter
MWD	Measurement While Drilling
OD	Outside Diameter
P	Pressure
ROP	Rate Of Penetration
RPM	Revolution Per Minute
N_{RE}	Reynolds Number
SF	Safety Factor
SICP	Shut-In Casing Pressure
SIDPP	Shut-In Drill Pipe Pressure

SPM	Stroke Per Minute
C_{se}	Surface Equipment Constant
TVD	True Vertical Depth
WOB	Weight On Bit
WOH	Weight On Hook
WBE	Well Bore Element
WBE	Well Bore Element
τ_y	Yield Point

CHAPTER 1. INTRODUCTION

Petroleum industry always tries to come up with innovative and fast ways to find, produce, and transport the oil and gas resources, because in today's modern world most of the activities are in direct and indirect relation with oil and gas industry. Increasing the demands for oil and gas, means more production and due to the special locations that Petroleum can form, the industry is forced to work in remote, dangerous and harsh locations like offshores, high pressure and high temperature reservoirs with narrow pressure margins and harsh weather condition, to produce the oil and gas through reservoirs and supply the demand of industries. As the wells are in more remote areas and depths are larger, the margins within well control reduces. Accordingly, controlling of the well becomes more complicated, and needs more sophisticated equipment. All of these concerns, will lead to find the best ways for being sure about the safety of people who are working in this area, environment, and company's reputation. Well control methods, are standard procedures, which are developed to be taken into account by the operator to reduce the possibilities of problems.

If formation fluid enters the well it can lead to disastrous blowouts. Accordingly, the most important reasons which makes the companies to consider the importance of kick, and take it serious, are injuries and fatalities of persons, negative effect on environment, and financial losses which finally leads to reduction of company's reputation. After recent event of the Macondo blowout in the Gulf of Mexico, which leads to death of 11 persons, focus on safety and well control has increased, and great effort has been made to investigate, what went wrong, to take lessons from this painful accident. Nowadays, most of the companies ask their employees to have the certificate of well control to be qualified for a job on the field, and they use new technologies with reliable equipment to lower the risks of blowouts.

Figure 1- Blowout, Gulf of Mexico, 2010

Recently, using of simulators are widely spreaded out, because it is possible to study and analyze the response of the system to any kind of change in easy and simple ways. Also, these results can be used in sensitivity analysis of parameters, to find out the severity and degree of importance of each parameter in the results of system. All in all, in this moment, simulations play an important role in education and preparation of people to face with the real condition, and take the best decision without taking risk.

This thesis starts with literature review of well control theory including, barriers, theoretical concepts, shut-in procedures, and then the equipment which are playing a crucial role in emergency situation. In the third chapter, it aims to find out about the different well control parameters and analytical models which are necessary to be considered for drilling operations, and dealing with kick is explained. In the fourth chapter, the data and parameters which inserted to the simulator for conduction the test are explained, and their degree of importance, by sensitivity analysis of them is measured by using a simulator software. In fifth chapter the different well control methods has simulated for the mentioned database, and they compared to each other and also it is explained that which one is suitable for the special conditions which the operators may deal. This chapter will particularly be focused on well kill operations during conventional drilling operations. well control processes simulations have decided to implement on the company's drilling simulator, and for this purpose a comprehensive research has developed to provide a package of theoretical part for this phenomena. In this method, it is tried to use the newest, realistic and suitable formulations and theories, to be taken into account by simulator's processors.

The final workflow for calculation of some parameters can be find in Appendix C.

CHAPTER 2. GENERAL DESCRIPTION

The most famous description for well control is given by NORSOK D-10, which defines it as a *"collective expression for all measures that can be applied to prevent uncontrolled release of well bore effluents to the external environment or uncontrolled underground flow".* All the efforts which should be considered for reaching to this objective, will be considered as well control processes.

Kick is the entrance of the unwanted fluid from the reservoir into the well which if it is not control by proper methods and equipment, can reach to the surface and cause a blowout. According to standards like API and NORSOK, during any operation it is better to have two barriers to avoid the blowout.

well barrier is the package of one or several well barrier elements preventing fluids flowing from the formation into the wellbore, into another formation or to the external environment in an unintentionally manner.

According to the definition of NORSOK, well barrier element is a physical element which in itself does not prevent flow but in combination with other WBE's forms a well barrier.

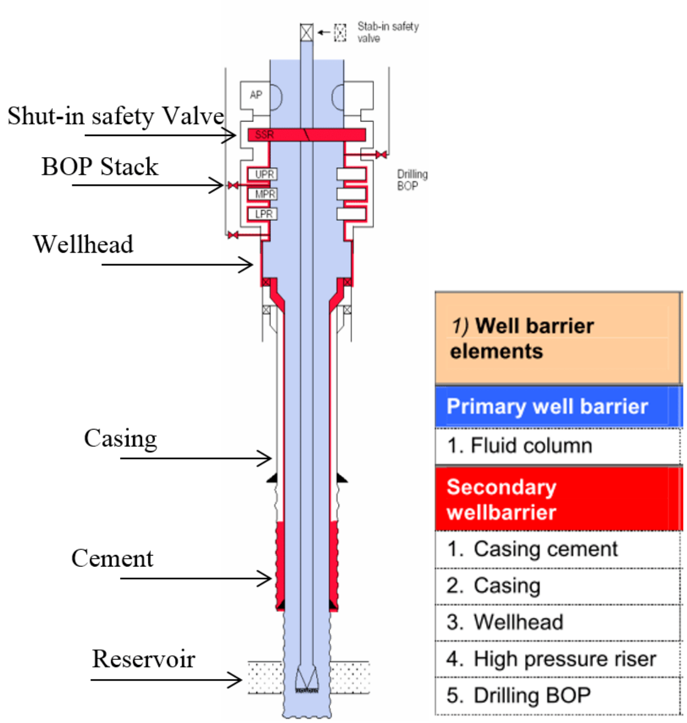


Figure 2- Well barrier, NORSOK D10, 2013

2.1 Primary and Secondary well control

2.1.1 Primary well control

Primary well control is maintaining a hydrostatic pressure in the wellbore greater than the pressure of the fluids in the formation which is drilling. This point should be taken into account that this hydrostatic pressure should not pass the formation fracture pressure and remain less than it. It uses the mud weight to provide sufficient pressure to prevent an influx of formation fluid into the wellbore. Considering this point, before drilling activity, it is necessary to use casing design plan for identifying the appropriate mud weight.

$$P_{formation} < P_{hyd} < P_{fracture}$$

For having primary well control system it is so important to have the proper mud and pumping system, because during some operations like drilling, the mud needs to be circulated, and if the pumping system cannot support the right amount of mud, the hydrostatic column of mud will have a short height and the hydrostatic pressure of that will be less than the formation pressure. Also, the mud circulation system can lead to increment of hydrostatic pressure of mud column, which can pass the limit of fracture pressure and lead to mud loss. Therefore, any deviation during operation should be detected by the operators, to perform the right action by them.

Hydrostatic pressure depends on the TVD, and mud weight.

$$P_{hyd} = 0.052 \times TVD\ (True\ Vertical\ Depth) \times \rho$$

TVD = True Vertical Depth, ft

ρ = Density, ppg

It should be taken into account that this formula is valid only when we are in static condition, and in dynamic condition the circulation pressure should be considered. For transporting the fluid in the annular section, in addition to hydrostatic pressure, the pumps should provide annular pressure loss due to the friction, accordingly the circulation pressure will be:

$$P_{Circulation} = 0.052 \times TVD\ (True\ Vertical\ Depth) \times \rho + APL$$

TVD = True Vertical Depth, ft

ρ = Density, ppg

APL= Annular pressure loss

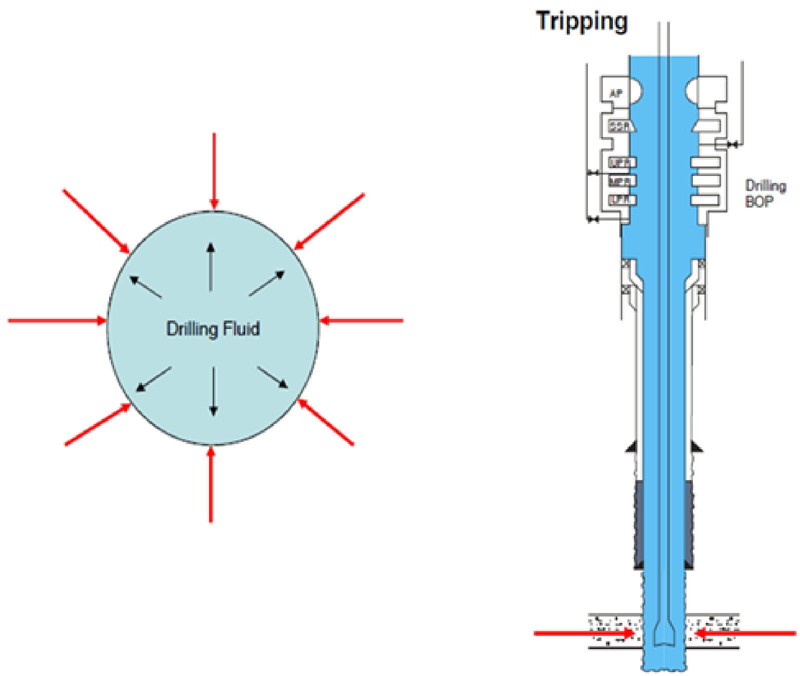


Figure 3- Primary well control barrier

Some of the references are indicating that, it is better to keep the mud density in a manner that hydrostatic pressure of that, became as close as possible to the formation pressure. It is important due to its role is increasing the rate of penetration which is discussed in nex chapters.

2.1.2 Secondary well control

Secondary well control is the equipment that will activate, after the Primary well control has failed to prevent formation fluids entering the wellbore. This process by using a blowout preventer (BOP), prevents the escape of wellbore fluids from the well. After the activation of secondary well control (BOP), all the steps which are necessary to be followed should be done by the operators to reestablish the primary barrier, and remove the existing kick.

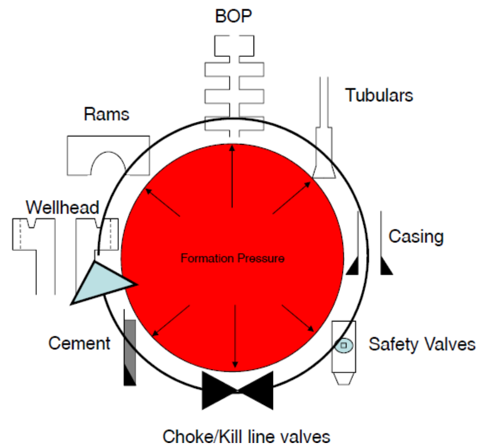


Figure 4- Blowout Preventer

2.2 Reasons for having the kick

There are several factors that can cause for having the kick during any kind of operation in the well. The parameters in order to get the kick are differential pressure between the wellbore and formation, porosity, permeability, and the length of time that the well remains underbalance. As explained in the primary well control method, hydrostatic column of fluid inside the well should be higher than formation fluid pressure, to avoid entrance of formation fluid into the well, but it is not enough if the rock is not permeable rock. If the formation has a high permeability the rock's ability to allow fluid flow into the well is high, like the sandstone formations. On the other hand, in the shale rocks usually the permeability is low and the movement of the fluid flow within the rock is hard.

The reasons for having the kick in the well are:

- **Failure to fill the hole correctly while tripping.**
- **Swabbing**
- **Insufficient mud weight**
- **Abnormal formation pressure**
- **Loss of Circulation**

2.2.1 Failure to fill the hole correctly while tripping out

As mentioned in the primary well control method the hydrostatic column of fluid inside the well is important to avoiding the kick. During trip out operation as the drill pipe and drill collars are pulling out of the hole, the volume inside the casing which needs to be filled by the fluid, starts to increase due to steel volume of drill string, and if the operators does not circulate the right amount of mud volume into the well, to fill the hole, the height of fluid will decrease, and consequently, the bottom hole pressure will be less than formation pressure, and fluid will enter to the well, if the formation is permeable.

2.2.2 Swabbing

Swabbing is a phenomenon which needs to be taken into account before trip out operation. It is the piston effect of bottom hole assembly or drill string (for the connection), due to the small clearness with the bore hole, which can reduce the bottom hole below formation pressure. Factors that can increase the risk of swabbing a kick in:

- **Pulling pipe too fast**
- **Balled up bit or stabilizers**
- **Small annular clearance**
- **Long BHA**
- **Tight hole**
- **Small trip Margin**
- **High mud viscosity**

2.2.3 Insufficient mud weight

Mud density should be higher than formation pressure. If the mud weight and pressure gradient is less than formation pressure gradient, fluid can enter the well. This is important when the circulation stops, because dynamic BHP is always higher than static BHP due to annular pressure loss. Accordingly, if the mud weight is not sufficient, during circulation, probably there will be no kick entrance into the well, but after stopping the pumps it can enter. So, it is important to be aware of the drop in downhole pressures as the pumps are shut down especially for the connection operations. Because, as soon as the pumps are shut down the well might go in underbalance and the gas enter the well. This gas which is called connection gas, reduces the mud density, and subsequently, if the proper action does not taken by the operator, can lead to large amount of kick and subsequently the blowout.

2.2.4 Abnormal formation pressure

Normal formation pressure results when the rate of sedimentation allows the water between the pore spaces to flow freely during compaction. If the sedimentation rate is high and the fluids cannot flow freely, they will trap in the pores and formation will be abnormally pressurized. The causes of abnormal pressure formations are:

- **Artesian Effect**
- **Dipping Formation**
- **Supercharged Shallow Formations**
- **Sediment Compression (under compaction)**

2.2.5 Loss of Circulation

Loss of circulation can be happening in the wells because of two scenarios. First, if the formation permeability is high, and hydrostatic column of fluid provides pressure higher than formation pressure, mud can enter to the formation due to the overbalance situation. By designing of the muds in that way which they can make a mud-cake on the wall of borehole, usually it is possible to avoid this problem. Secondly, the pressure which is provided by the mud can become higher than the fracture pressure of the formation, and can cause the fracturing of formation. If it happens, the drilling fluid will flow into the formation.

Flowing fluid into the formation in both scenarios, will cause the reduction in fluid level in the formation, and decrease in bottom hole pressure, and consequently it will lead to lose of primary well control, and entering the formation fluid into the well.

2.3 Positive Kick indicators

Positive kick indicators are the common change in the conditions due to the kick, and when positive kick indicators recognized, actions must be taken to control the well. The positive kick indicators are:

- **Increase in pit gain volume**
- **Increase in flow rate**
- **Flowing well with pumps off**

2.3.1 Increase in pit gain volume

The level of mud in the pit gain is one of the important indicators for kick entrance into the well. In close circulating system the total volume of fluid which circulating should be constant, but if the well gets the kick this volume will be higher. Detection of this change is much easier in pit gain due to the small volume and cross-sectional area of it, so the level of fluid inside the it will be more sensitive to any change in volume.

2.3.2 Increase in flow rate

The conservation of mass law says that in closed system, the amount of object which enters into a system should be equal to the amount of that which come outs. Mud circulation system is a closed system and therefore the return flow rate should be same as pumping flow rate. If the return flow rate increase it means the external fluid is entering to the system, and when an influx enters the well, the return flow rate will increase.

2.3.3 Flowing well with pumps off

During drilling operation sometimes, it is necessary to stop the circulation, for example for making the connections. If the pumps are in switch-off condition, according to the mass conservation, there should be no flow at the output part of circulation system. If there is a continuing flow up the well, it could be a kick in which is entering to the system.

2.4 Warning signs

Warning Signs that a well is approaching underbalance or is already underbalance. During entrance of kick into the well, normally one or more warning signs can be detected which it is necessary to check the well before losing the time. Warning signs are:

- **Decrease in pump pressure**

As explained in the chapter 1.1.1, the circulation pressure is the sum of hydrostatic pressure and pressure losses due to the friction. In the case of having kick in the annular part the hydrostatic pressure will decrease, and consequently the pressure which is need to be provide by the pump will decrease.

- **Increase in flow line temperature**

In abnormal pressurized formations, usually the temperature gradient is higher and it can be a warning sign to entering in the abnormal pressured formation.

- **Drilling Break**

During the drilling operation, by changing the formation, the rate of penetration will change. This change in rate of penetration is not the exclusive reason for losing the overbalance situation and having the kick, but also it can be due to the transferring from hard formation to the soft one. Accordingly, for being sure about the main reason of this change, it is necessary to stop the drilling, pull out the drilling string from the bottom hole, switch off the pumps, and check the flow through flow line. If the flow did not stop after switching off the pumps, it means that formation flow is entering to the well and it is necessary to shut the well in by the method which is indicated before by the company in charge.

- **Increase in gas levels**

When the drilling operation is conducting in a gas formation, a small portion of gas can enter to the well by the cuttings which are drilled. Sometimes, the volume of this can increase which leads to increment of its level in the well and reducing the bottom hole pressure, which finally will lead to having the large volume of kick. Usually this phenomenon can happen during the making connections which the pumps are off and the mud hydrostatic pressure is less than dynamic situation, and the gas has possibility to enter the well.

- **Sloughing or heaving shale**

It is important to consider that when the operation is conducting by oil based mud, detection of gas in the return flow is not easy, because the gas can solve in the mud and there will be no volume change in the annular fluid. When the gas is migrating to the surface by the fluid, the pressure will decrease. When the pressure reached to the flash point, the gas will start to boil out of the fluid and suddenly, there will be large volume of kick in the annular part, which is close to the surface.

2.5 Shut-in procedures

It is so important to choose the best and fastest action in the case of indicating a kick or having warning signs. If this process has been done immediately, well control can be more effective. In first chapter, it is discussed that the important parameters for having kick in the well are differential pressure, permeability and porosity, and the time. Once the kick has detected, operator should shut the well in, and then follow the instruction to kill the well and provide the situation inside the well to be able to continue the operation.

There are two conditions that shut-in the well is not the option for well control process. When there is shallow gas kick, and in the case that surface casing has not been set yet, the well should be killed directly by increasing ECD, and using a diverter to send the fluids away from the rig.

Figure 5- Shut in the well from BOP

Shut in process can be specified by the rules of each company, but generally, well shut-in can be done in two ways:

- **Hard shut-in**
- **Soft shut-in**

2.5.1 Hard shut-in

In hard shut in method choke should be in closed position for drilling process. So, for shutting in the well by this method, operator should close the BOP. By closing BOP, the operator can measure the casing pressure, but if it is not possible to measure the casing pressure at the wellhead, it is possible to measure the pressure at the choke manifold. This method closes the well so fast, so the amount of kick that will be received by the well will be less, and consequently, the SICP will be less.

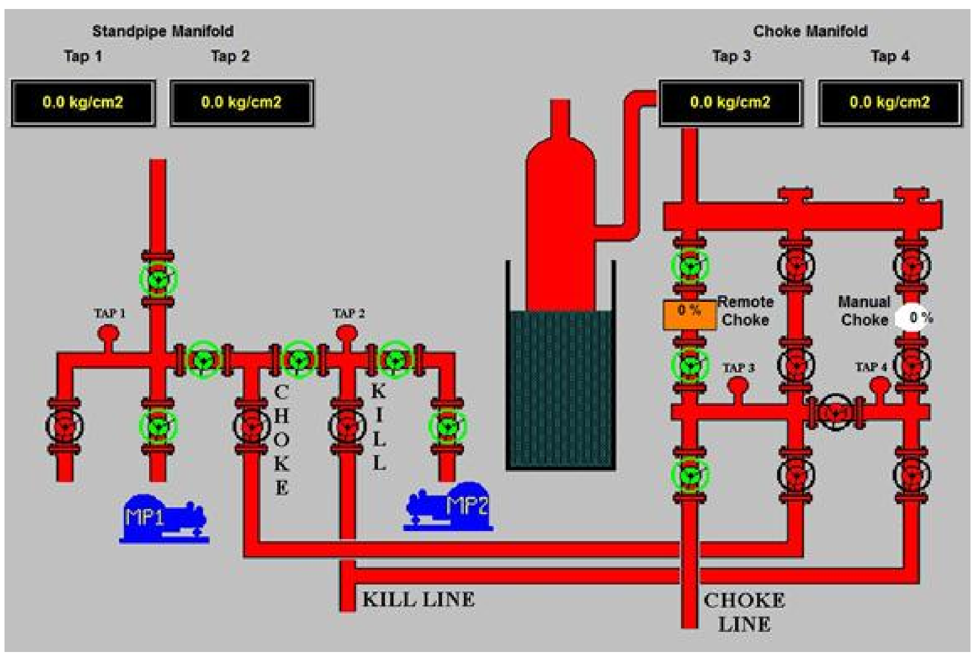


Figure 6- Hard shut-in line up

2.5.2 *Soft shut-in*

In soft shut-in method, choke should remain in open position. So, when this method is using for shut-in process of the well, the choke line valve is open, then BOP should be closed, and finally the choke should be closed. This method is not fast, and the size of kick will be bigger, because it takes more time to shut the well in, but the advantage of that is the possibility of monitoring the pressure build up during the process of well shut-in. Also, in this method the risk of fracture in the casing shoe is less than hard shut-in method. Also, it will cause to reduction of the water hammer phenomenon due to instant closure.

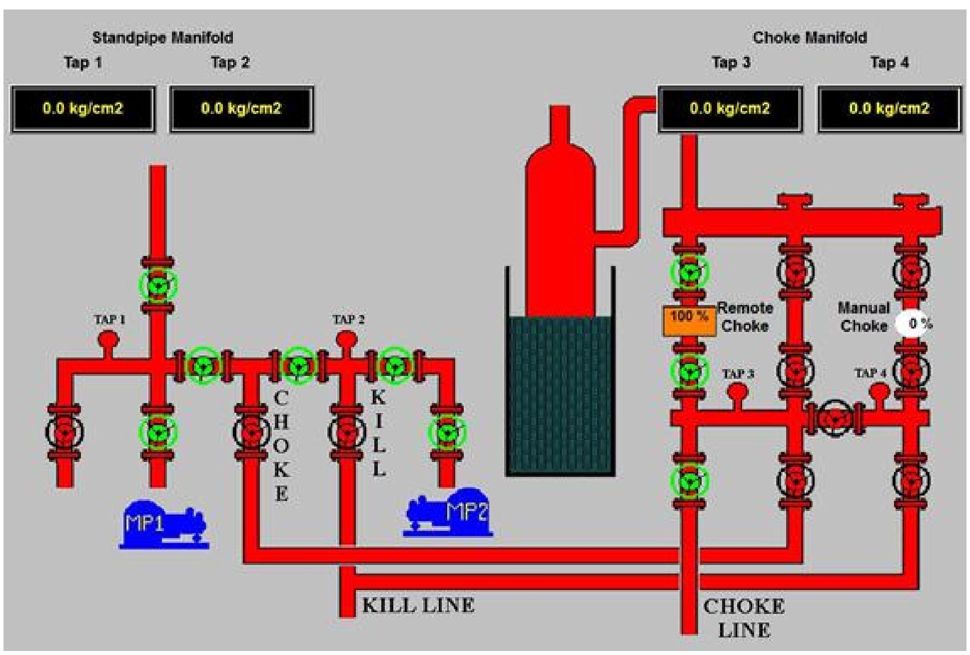


Figure 7- Soft shut-in line up

2.6 Well Control equipment

In the chapter 2 it is explained that BOP (blowout preventer) is the secondary barrier for well control during kick entrance into the wellbore. In the following sections, a short description about the function of BOP and other equipment which involve in well control operation and their rules is explained.

2.6.1 Control system

The preventers are activated by control system which using a hydraulic control fluid. Accumulators are the equipment for storing the energy, for closing and opening the blowout preventers. API RP53 indicates that accumulator's reservoir tank should have a total volume at least 2 times of usable volume to close the BOP equipment. The accumulator bottles store the accumulator fluid in very high pressure up to 3000 psi, which insures that the BOP equipment will close very fast. Accumulator is controlled from the control panel in the rig floor, but in emergency condition, rig crew can operate the BOP by the valve which positioned on the accumulator.

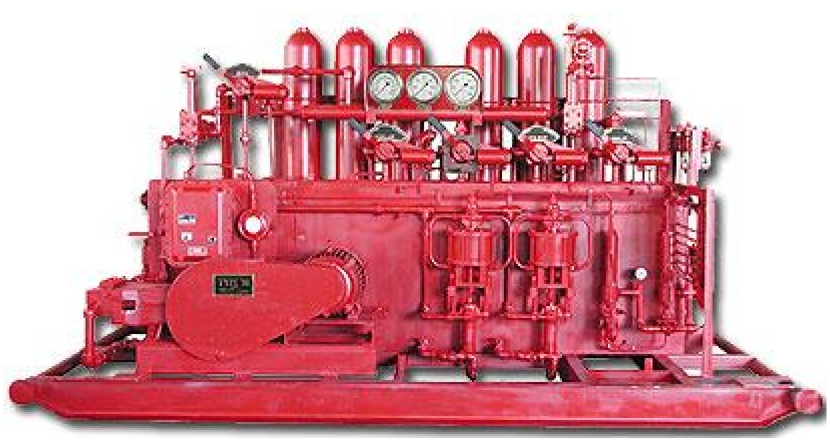


Figure 8- Accumulator for opening and closing the BOP system

2.6.2 Annular preventer

Annular Preventers positioned on the top of BOP stack and use the rubber –like element to seal the open hole or seal around the other elements like pipes and tool joints. Usually, when the kick has detected, the annular preventers are the first equipment that get close to secure the well. Their design is in such a way that they allow striping of the drill pipe while maintaining seal. In the following figure, the four types of annular preventer has been shown.

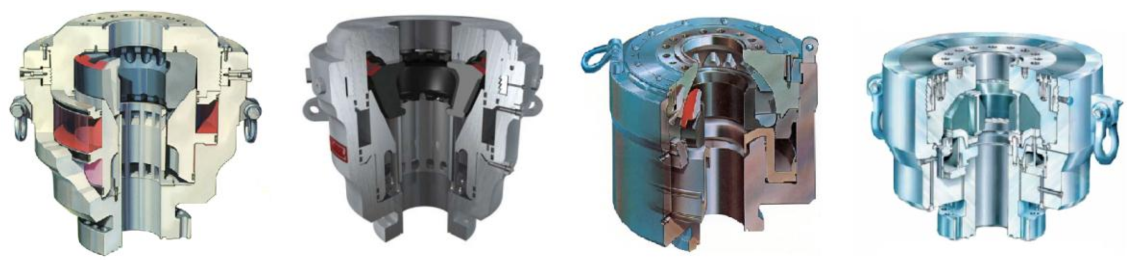


Figure 9- Annular preventers: Hydril GX, Hydril GL, Shaffer, Cameron D.

2.6.3 Ram preventer

Ram preventer are using to seal around the special size of pipe, and trapping the pressure blow them. Due to the functionality features of ram preventers, they can seal only around the special pipe diameters, and due to this fact that there are different range of pipe in the well, it is recommended that the BOP stacks should have the second ram preventer.

Blind rams, are on type of these rams, that can be used when there is no pipe in the well to close the open hole, but in some scenarios, that there is no other choice and there is the possibility of blowout, the operator can close them and cut the pipes.

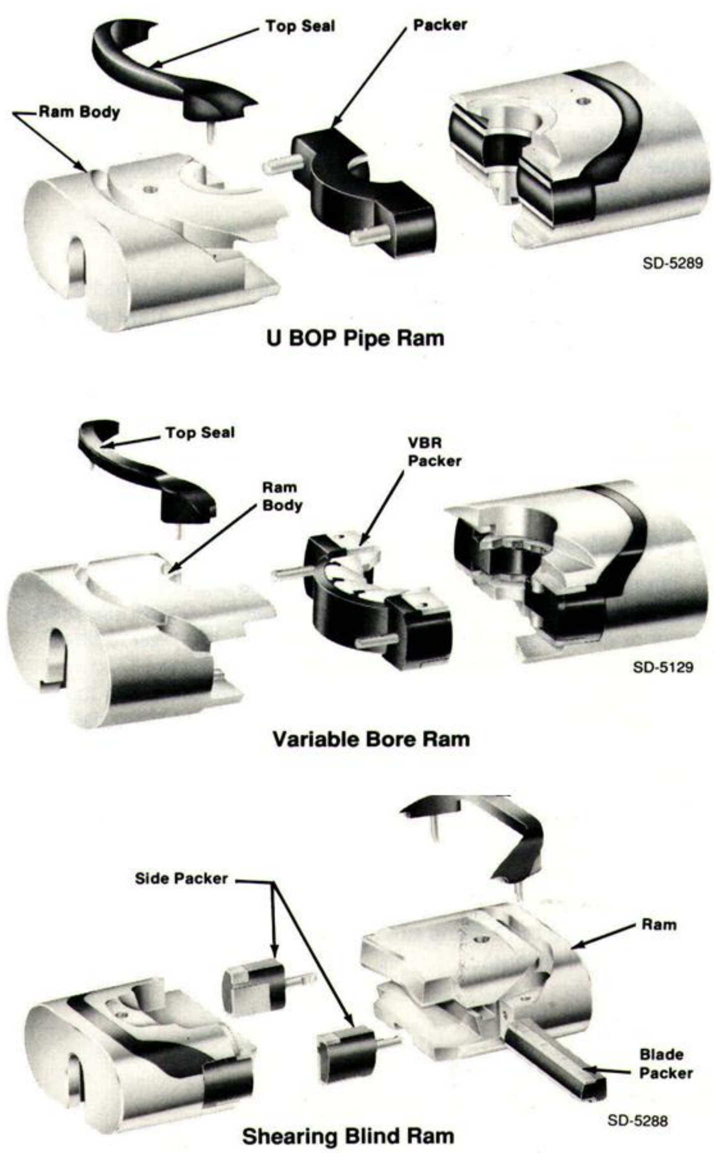


Figure 10- Cameron type ram preventers

2.7 The role of all green to go

There is role of thumb in drilling activity, which known as “all green to go”. In BOP stack, the opening or closing conditions of rams and valves are shown by red or green lights. If all these lights are green, which means the BOP stack is ready for drilling activity and it can be conduct by following the necessary steps of operations. In the following figure, this condition has been shown:

Figure 11- All green to go

CHAPTER 3. ANALYTICAL MODEL

In this chapter the analytical model and all the formulation package which will be considered during the simulation are discussed.

3.1 WOB, RPM, and ROP:

one the important parameters that needs to be considered and optimized for success and fast drilling activity is weight on bit. WOB, is the amount of weight that inserts to the bit by drill strings like drill collar to drill the holes. When the drill string has a clearance from the bottom hole, there is no weight on bit and whole the drill string is under the tension, and this tension force can be calculating by hydraulic gauge indicator on driller's console which is connected to deadline. Another way to calculate the WOB, is the MWD (measurement while drilling) equipment which in the downhole and can calculate the more accurate value of WOB. Then, by downward movement of drill string, it reaches to the bottom hole and by continuing the movement the weight on bit starts to increase. The optimized amount of this weight is depends to lots of parameters like, design and parameters of bit, mud weight, BHA, rock properties, and etc. there is no standard range for weight on bit amount, but for the drilling activities, it can be generally between 1000 to 100,000 lbs, and it is completely obtaining by local knowledge and experience.

On the other important reasons to optimize the rotary speed and weight on bit to avoid the wearing and damage to the bit. For this reasons, manufacturers provide the maximum rate of weight on bit that should be applied on bits, for having safe, fast, and effective drilling operations. Accordingly, the maximum weight on bit which declared by the manufacturer, considering 10-20% of safety factor can guaranty the optimize and safe drilling operation.

As explained the optimized amount for the WOB is coming from the local experience. One of the ways to obtain this optimized and proper value, is to increase the weight on bit step by step (usually in the range of 1000-2000 lbs) with an optimized RPM, and check the effect of this increment on the rate of penetration. Until the moment that by increasing the WOB, ROP increases the process should go on, and when the value of ROP has stopped to increasing by increment of WOB, it can be considered as optimized value.

In IADC drilling manual it is indicated that rate of penetration (ROP) is related to numerous parameters and perhaps important variables exist which are unrecognized until now. In qualitative point of view, it is quite obvious that rate of penetration is depended to WOB, RPM, strength of rock, type of bit, drilling fluid properties, existence of cutting, and etc. Diagrams of sensitivity of this parameters, which are provided by IADC is shown below:

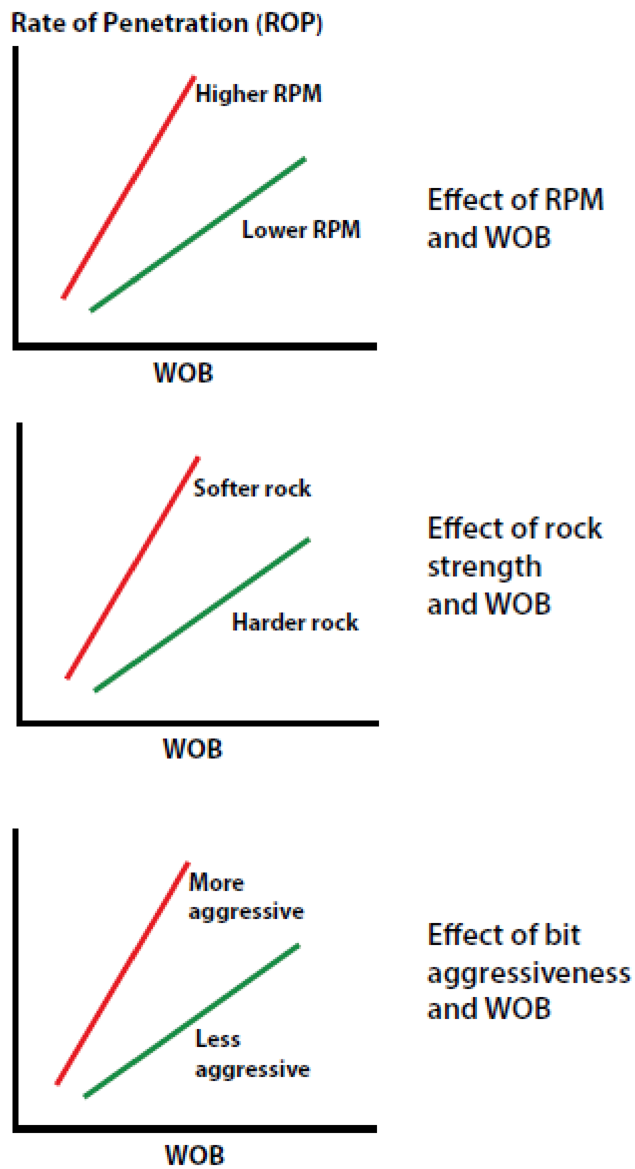


Figure 12- Different parameters' effect on ROP

Artificial neural networks can be useful, and by designing that according the real data, ROP can be predict. This research has done once on an Iranian oil field by R.Arabjamaloei and et al, in 2009, and the results was usable in those field.

The most famous model for estimating the rate of penetration is Bourgoyne and Young model which models the ROP according all the parameters which can have effect on that.

$$ROP = f_1 \times f_2 \times f_3 \times f_4 \times f_5 \times f_6 \times f_7 \times f_8$$

$$f_1 = e^{2.303\times a_1}, foirmation\ strength\ and\ bit\ type$$

$$f_2 = e^{2.303\times a_2\times(10000-TVD)}, depth\ and\ compaction$$

$$f_3 = e^{2.303\times a_3\times TVD^{0.69}\times(EPP-9)}, pore\ pressure$$

$$f_4 = e^{2.303\times a_4\times TVD\times(EPP-ECD)}, differential\ pressure$$

$$f_5 = \left\{\frac{\frac{WOB_{sf}}{OD_{bit}} - (\frac{WOB_{sf}}{OD_{bit}})_t}{4 - (\frac{WOB_{sf}}{OD_{bit}})_t}\right\}^{a_5}, drill\ bit\ diameter$$

$$f_6 = \left\{\frac{RPM_{sf}}{60}\right\}^{a_6}, RPM$$

$$f_7 = e^{-a_7\times h}, drill\ bit\ tooth\ wear$$

$$f_8 = \left\{\frac{F_j}{1000}\right\}^{a_8}, bit\ hydraulic\ jet\ impact$$

$$F_j = 0{,}01823 C_d q\sqrt{\rho \times \Delta P_b}$$

TVD = True vertical depth

EPP =Pore pressure gradient

ECD = Equivalent circulation density

h = Fractional tooth dullness

Fj = hydraulic impact force beneath the bit, lbf

$\frac{WOB_{sf}}{OD_{bit}}$ = threshold bit weight per inch of bit diameter, 1000 lbf/in

Table 1- Rate of penetration constants

Coefficient	Lower bound	Upper bound
a1	0,5	1,9
a2	0,000001	0,0005
a3	0,000001	0,0009
a4	0,000001	0,0001
a5	0,5	2
a6	0,4	1
a7	0,3	1,5
a8	0,3	0,6

3.2 Number of drill collars:

In the previous section the theory of WOB has explained. Also it is mentioned that this weight should be support by drill collars. Drill collars are the pipe with low ID, and high thickness which provide the WOB, and the number of them can be calculate by the following formula:

$$WDC = (WOB \times SF) \div (BF \times COS\,(\theta))$$

$$Number\ of\ Drill\ collars = WDC \div (weight\ of\ each\ drill\ collar)$$

$$Buoyancy\ Factor\ (BF) = (65.5 - mud\ weight\ in\ ppg) \div 65.5$$

WDC is drill collar weight in air, lb.

WOB is a **required** weight on bit, lb.

SF is a safety factor.

BF is mud buoyancy factor.

θ is inclination of the well.

65.5 = is density of steel in ppg.

3.3 WOH (Hook load):

In the WOB section it is mentioned that the tension force by the drill string can be seen driller’s console, and it calculating by hydraulic gauge which is connected to deadline. This number can be influenced by the buoyancy force of drilling fluid, because some part of this force are reduce due to the buoyancy of fluid. Also when the drill string reaches to the bottom hole, some part of this load transfers to the bit for providing the WOB. Hook load can be calculating by the following formula:

$$WOH(HOOK\ LOAD) = WDS \times BF \times COS\,(\theta) - WOB$$

WDS= Drill string weight

WOH = Hook load

BF is mud buoyancy factor.

θ is inclination of the well.

3.4 Pump pressure

In mud circulation system, the required pressure for circulation and overcome to all the frictional forces should be provide by mud pumps. This frictional loss can be the internal friction due to the fluid viscosity and external friction due to the pipe roughness. In applied drilling circulation system a pump pressure has defined according to the following formula:

$$P_{pump} = \Delta P_s + \Delta P_{dp} + \Delta P_{dc} + \Delta P_{mf} + \Delta P_{b+} \Delta P_{dca} + \Delta P_{dpa}$$

Ppump = pump pressure, psi or kPa

Δps = pressure loss in the surface equipment, psi or kPa

Δpdp = pressure loss inside drill pipe, psi or kPa

Δpdc = pressure loss inside drill collar, psi or kPa

Δpmt = pressure drop inside mud motor, psi or kPa

Δpb = pressure drop at bit, psi or kPa

Δpdca = pressure loss in the drill collar annulus, psi or kPa

Δpdpa = pressure loss in the drill pipe annulus, psi or kPa

The pressure loss equations are function of fluid type and their rheology properties, the flow regime (Turbulent or Laminar), and geometry of the path that mud is going to pass through circulation.

3.4.1 fluid type:

Rheology studies is one of the important concepts which needs to be considered for hydraulic study of fluid circulation. Rheology describes flow or deformation in terms of shear rate and shear stress. If shear rate of fluid is high, the friction of that fluid will be high. Fluids are categorized according to their rheological behavior , and they are divided to five main groups: Newtonian, Bingham-Plastic, Power Law, Herschel-Bulkley, Dilatant.

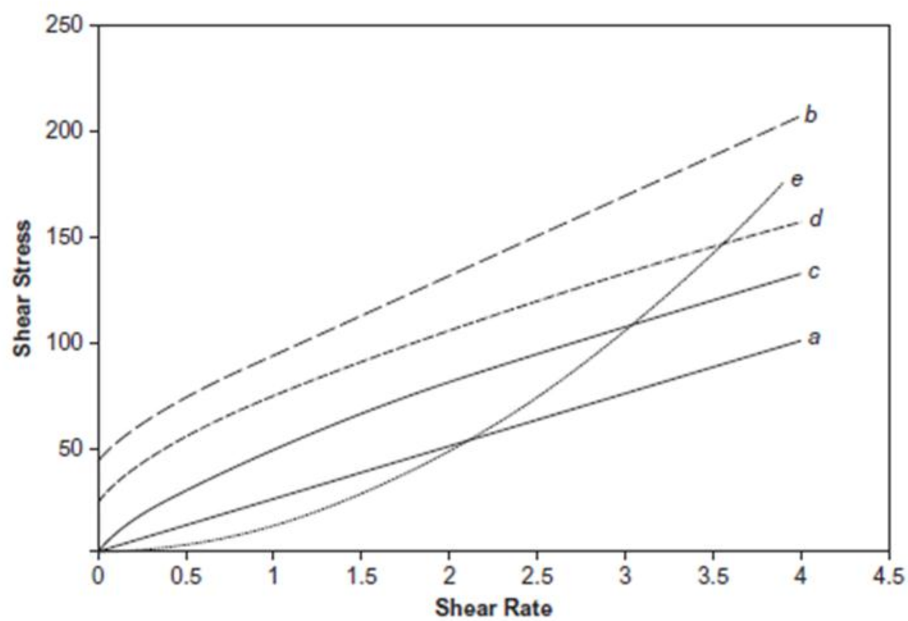


Figure 13- Different muds Rheology

When the flow regime is turbulent it can be helpful for removing the cutting, but on the other side it can cause erosion and damage to the equipment. Accordingly, it is suggested to have laminar flow in the annulus to move the cuttings upward and turbulent flow at the bottom of the hole for cuttings removal.

3.4.2 pressure loss in annular and inside of pipe:

For calculating the pressure loss in each part of circulation system, it is necessary to apply the pressure loss formula according to each fluid type. Therefore, in the following part of this section, the process for calculating the pressure loss in annular and tubular part of each segment for the Bingham Plastic fluids are explained. For other types of fluids, the formulas are explained in the Appendix A. In the simulator that model is simulated, assumes that fluid is Bingham Plastic fluid. This information has been driven from the drilling hydraulic manuals including, applied drilling circulation system, Drilling handbook of IFP.

In the first step the velocity of fluid should be calculate in the inside or annular part:

$$v = \frac{q}{2.448 \times d^2}$$

$$v = \frac{q}{2.448 \times (d_2^2 - d_1^2)}$$

q = flow rate, gpm

d = inside diameter of pipe, in

d_1 = inside diameter of casing or borehole, in

d_2 = outside diameter of pipe, in

Then apparent viscosity can be obtained, which the function of yield point and plastic viscosity:

$$\mu_a = \mu_p + \frac{6.66\, \tau_y d}{v}$$

$$\mu_a = \mu_p + \frac{5\,\tau_y(d_2 - d_1)}{v}$$

μ_a = apparent fluid viscosity, cp

τ_y = yield point

pressure loss depends on the friction factor, and friction factor is the function of fluid type and flow regime. First, the Reynold's number should be calculated for calculation the friction factor. For Bingham Plastic fluids, the Reynold number for the inside and annular part of pipe is calculating according the following formulas

$$N_{Re,inside} = 928 \times \frac{\rho v d}{\mu_a}$$

$$N_{Re,annular} = 757 \times \frac{\rho v(d_2 - d_1)}{\mu_a}$$

ρ = fluid density, ppg

μ_a =apparent fluid viscosity, cp

For the Bingham Plastic fluids, if N_{Re} < 2100, the flow is laminar. Otherwise, the flow regime is turbulent.

Laminar flow:

Inside: $\Delta P_f = (\frac{\mu_p v}{1500d^2} + \frac{\tau_y}{225d})\Delta L$

Annular: $\Delta P_f = (\frac{\mu_p v}{1000(d_2-d_1)^2} - \frac{\tau_y}{200(d_2-d_1)})\Delta L$

Turbulent flow:

Inside: $$\Delta p_f = \frac{\rho^{0.75}\, v^{1.75}\, {\mu_p}^{0.25}}{1800\, d^{1.25}} \Delta L$$

Annular: $$\Delta p_f = \frac{\rho^{0.75}\, v^{1.75}\, {\mu_p}^{0.25}}{1396\, (d_2 - d_1)^{1.25}} \Delta L$$

3.4.3 Pressure loss in surface equipment

For calculation of pressure loss in surface equipment, in most of the manuals and handouts, the method which has been considered, is same. Usually there are 4 common combination of surface equipment assembly which is mentioned in applied drilling circulation system and global oil field solution. The geometry for these combinations are according the following table which extracted from Applied drilling circulation system book:

Table 2- Surface equipment constants

	Combination 1				Combination 2				Combination 3				Combination 4			
	ID		Length		ID		Length		ID		Length		ID		Length	
Component	in	cm	in	cm	in	cm	in	cm	in	cm	in	cm	in	cm	in	cm
Standpipe	3	7.6	40	12.2	3.5	8.9	40	12.2	4	10.2	45	13.7	4	10.2	45	13.7
Rotary hose	2	5.1	45	13.7	2.5	6.4	55	16.8	3	7.6	55	16.8	3	7.6	55	16.8
Swivel	2	5.1	4	1.2	2.5	6.4	5	1.5	2.5	6.4	5	1.5	3	7.6	6	1.8
Kelly pipe	2.25	5.7	40	12.2	3.3	8.3	40	12.2	3.3	8.3	40	12.2	4	10.2	40	12.2
C_{se}	22				8				5				4			

3.4.4 Pressure loss in Bit

During the circulation, the major portion of pressure drop happens in bit nozzles, and it is useful for removing the cuttings and helping the drilling activity. This pressure loss can be calculated by the following formula:

$$\Delta P_b = \frac{\rho q^2}{12031 C_d^2 A_t^2}$$

Cd = nozzle discharge coefficient, dimensionless

ρ = fluid density, ppg

AT = total nozzle area, in^2

q = mud flow rate, gpm

3.4.5 Pump rate and mud density effect on pump pressure

As discussed, the general formula for pressure loss in pipe is the following formula:

$$\Delta P_f = \frac{f \rho v^2}{d} \Delta L$$

Considering this formula, the pump pressure is linear function of density and exponential function of rate. Accordingly, the formula will be as follow:

$$P_{pump\ new} = P_{pump\ old} \times \frac{\rho_2}{\rho_1}$$

$$P_{pump\ new} = P_{pump\ old} \times (\frac{SPM_2}{SPM_1})^2$$

3.5 Circulation rate

Circulation rate is controlling by the mud pump, and depending on the type of pump, and the size of its components, this rate can be different. Circulation rate can be obtained by calculating the volume that pump can send to the circulation system by one stroke. For the triplex pumps the equations for calculating the rate is:

$$Q = \frac{D^2 \times L \times N \times \pi}{308} \times E$$

Q = Flow Rate, gpm

D = Liner diameter, in

L = Stroke Length, in

N = Speed of pump in, Stroke/min

E = efficiency

3.6 Bottom hole pressure

Bottom hole pressure is the important parameter for well control purpose. It is explained in primary well control method the hydrostatic pressure of fluid should be higher than formation pressure at the bottom of well to avoid the fluid entrance into the well. Bottom hole pressure in static condition when the pumps are off, is different with the dynamic conditions. When the pumps are circulating the mud, annular pressure loss in the well should be added to the hydrostatic pressure of mud, because it acts like back pressure and due to that the value of BHP will be higher. Also, it should be considered that after shutting the well, due to the back pressure of choke the bottom hole pressure will be higher than the hydrostatic column of mud.

- Static condition: $BHP_s = 0.052 \times \rho \times TVD$

TVD = True Vertical Depth, ft

ρ = MUD Density, ppg

- Dynamic condition: $BHP_d = BHP_s + APL$

APL = annular pressure loss

- Shut-in condition: $BHP_{shut-in} = BHP_s + P_{choke} + APL$

For this condition, like the previous conditions, if the fluid is not circulating the APL will be zero, otherwise it should be including in the calculations.

Procedures for calculating the APL is explained in the mud pump pressure calculation part.

3.7 Kick flow rate into the well

It is important to know the exact amount of fluid that can enter to the well from the moment that the bit enters to the reservoir formation, until shutting in the well. For calculation of flow rate, the general formula of Darcy for the radial flow can be used.

$$Q_g = \frac{kh\left(P_i^2 - P_{wf}^2\right)}{1.422 \times T\overline{\mu z}\left[0.5 \times \ln \frac{2.637 \times 10^{-4} kt}{\mu \emptyset C_t r_w^2} + 0.80907\right]}$$

Q_g = *gas flow rate in standard condition, scf/day*

$K = permeability, md$

P_{wf} = *bottom-hole flowing pressure, psi*

P_e = initial reservoir pressure

t = time, hours

T = Reservoir temperature

r_w = wellbore radius, ft

h = thickness, ft

μ = gas viscosity at the initial pressure, cp

C_t = total compressibility coefficient at pi, psi−1

$\emptyset$ = porosity

These formula is calculating the rate at standard condition. For calculating the rate at reservoir condition it needs to be divided by gas formation volume factor. So, the final formula in the model will be:

$$B_g = \frac{0.0282\ zT}{P_{wf}}$$

$$q_g = \frac{kh\left(P_i^2 - P_{wf}^2\right)}{50.425 \times P_{wf}\left[0.5 \times \ln\frac{2.637 \times 10^{-4}kt}{\mu\emptyset C_t r_w^2} + 0.80907\right]}$$

$q_g = gas\ flow\ rate\ in\ reservoir\ condition, cf/day$

The model that is considered for gas intrusion in the well is single bubble model (LeBlanc, 1967), which is immiscible with mud (because the type of mud assumed to be water base mud). So according the Boyle's law, the multiplication of pressure and volume will be a constant number. Therefore, the volume of slug, and subsequently, the height of it can increase due to the pressure reduction.

3.8 Boyle's law

One the important basic laws in well control is the Boyle's law which says in ideal condition the multiply of pressure with volume is constant and by increasing of one of them, the other one will decrease with the same ratio:

$$P_1 \times V_1 = P_2 \times V_2 = constant$$

This formula is important for gas expansion during migration inside the annular and will be discuss in volumetric well control method in details.

CHAPTER 4. SIMULATION DATA, CALCULATION SAMPLES, AND SENSITIVITY ANALYSIS

In this chapter, the input data for conducing the simulation, calculation, and doing the sensitivity analysis are explained.

4.1 Well configuration

In the following part the geometrical parameters which are considered for the well control model calculation, has been shown. These parameters are the most important parameters which are necessary for calculation, and running the simulations.

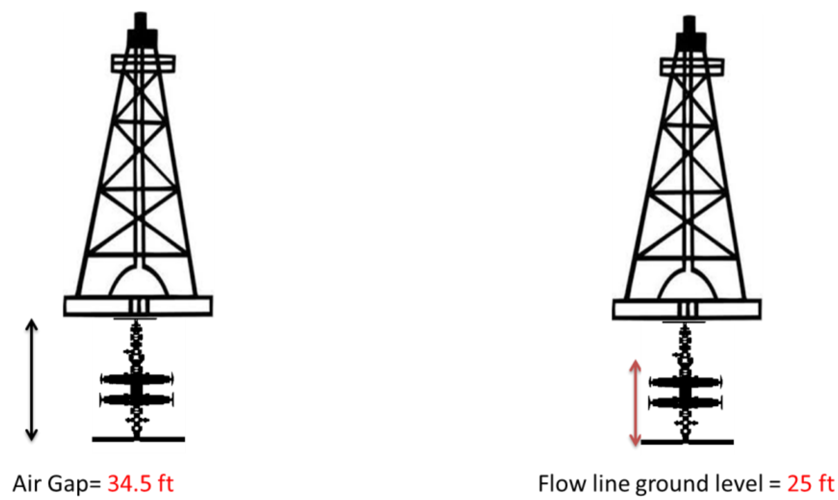


Figure 14- Well parameters

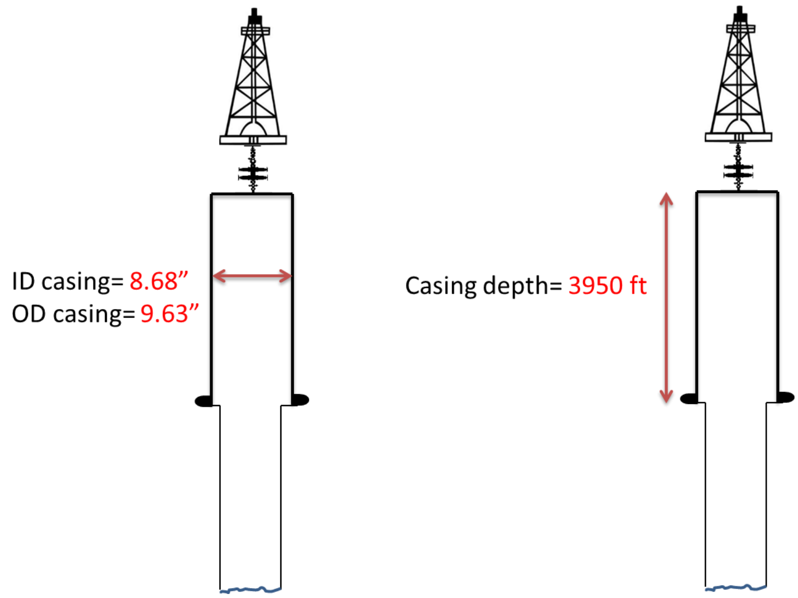


Figure 15- Casing depth and Diameters

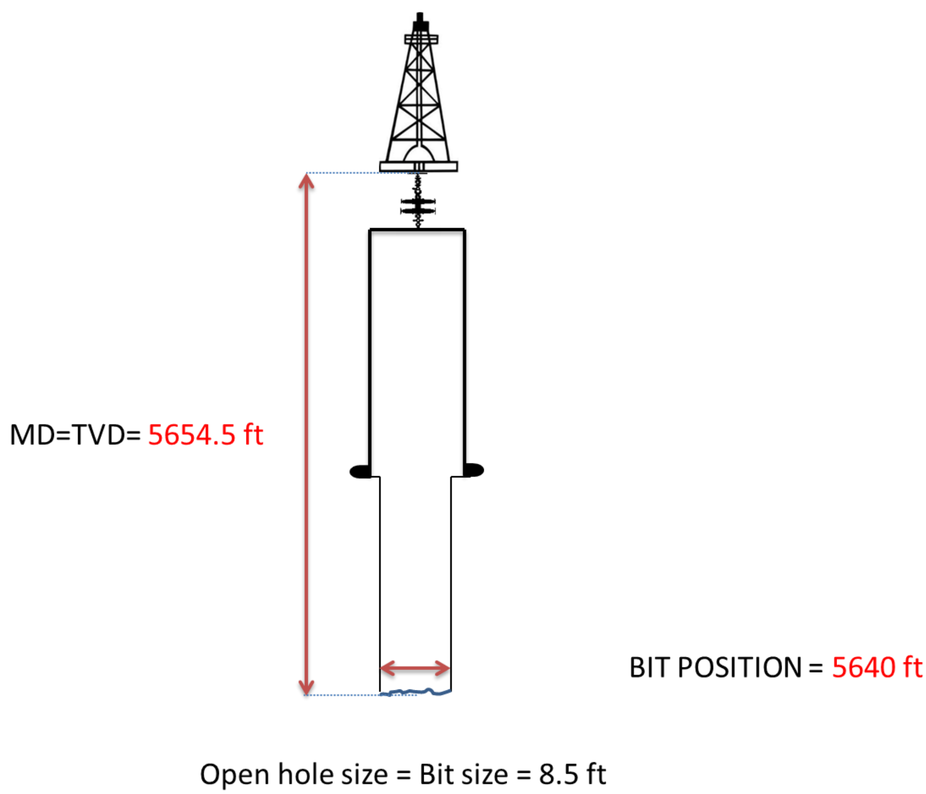


Figure 16- Well depth, and bit position

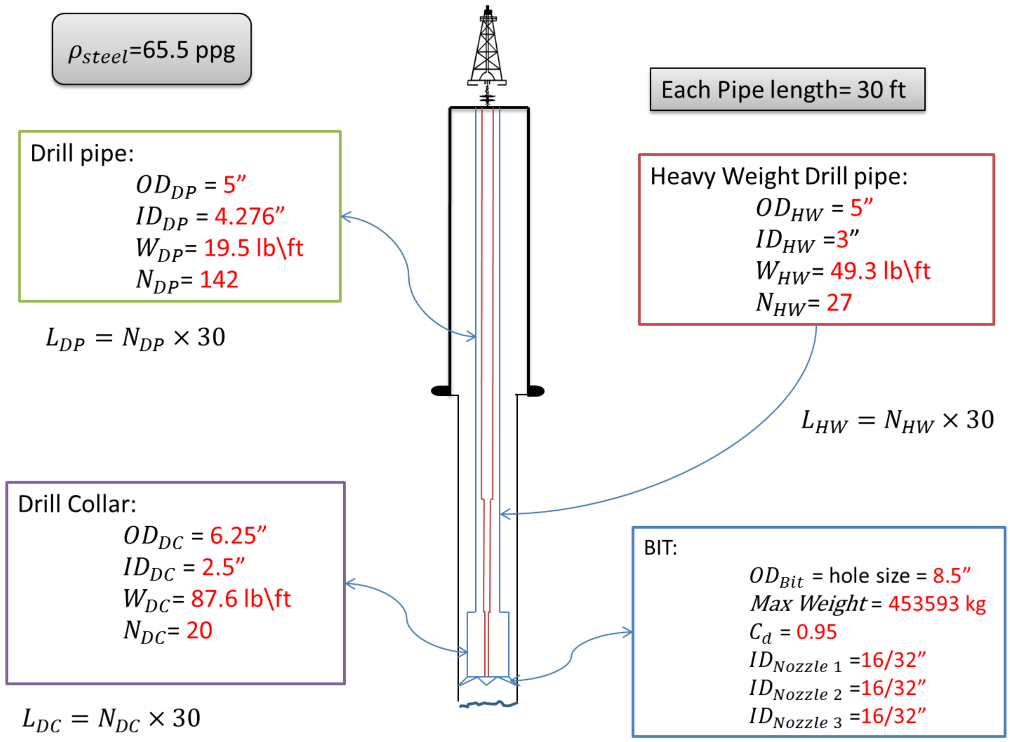


Figure 17- Drill string data

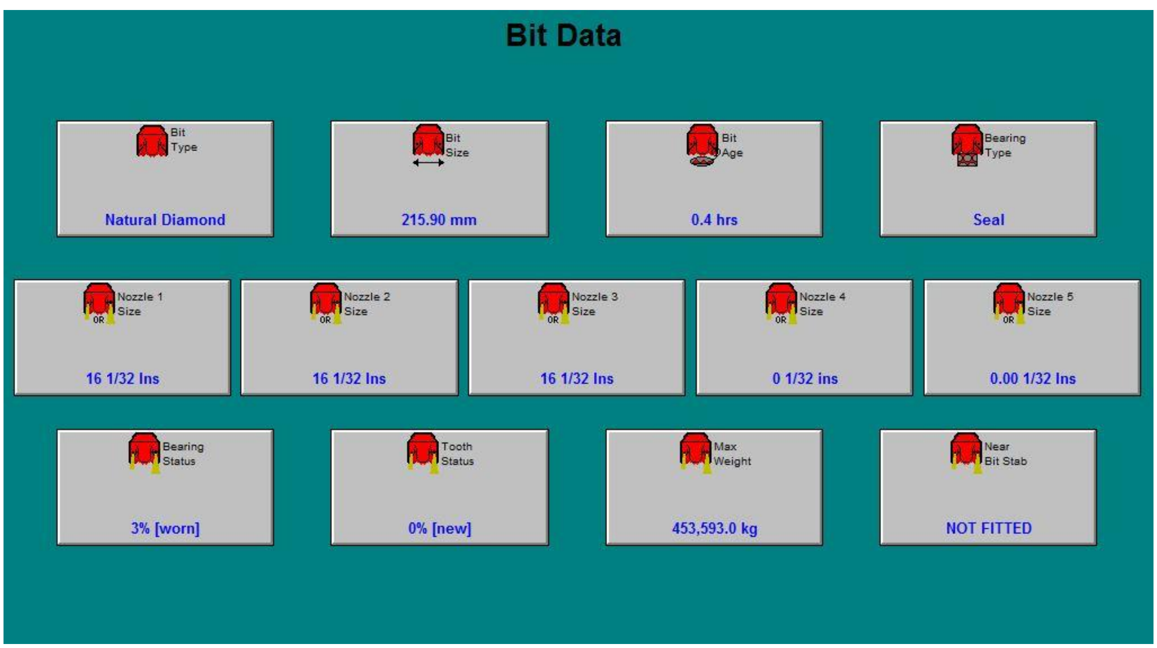


Figure 18- Bit Data

4.2 Formation data

After defining the data for the well geometries, which are important for static, and dynamic parameters' calculation, the configuration of formation should be defined to know in which depths, there are risk and possibility of parameter changes and warning signs during the drilling activity. For this purpose, a simple geological model for conducting the calculation is defined with these data:

- Formation 1:

  Depth at top = Air Gap= 34.5 ft

- Formation 2:

  Depth at top = 3937 ft

  Rock strength = 0.8

  K= 1mD

  Formation fluid= water □ 0.44 psi/ft

  Driller gradient= 0.55 psi/ft

- Formation 3:

  Depth at top = 5577 ft

  Rock strength = 0.8

  K= 1mD

  Formation fluid= water □ 0.44 psi/ft

  Driller gradient= 0.54 psi/ft

- Formation 4:

    Depth at top = 5638 ft

    Rock strength = 1.25

    K= 1mD

    Formation fluid= water □ 0.44 psi/ft

    Driller gradient= 0.48 psi/ft

- Formation 5:

    Depth at top = 5657 ft

    Rock strength = 0.3

    K= 1mD

    Formation fluid= water □ 0.44 psi/ft

    Driller gradient= 0.48 psi/ft

- Formation 6:

    Depth at top = 5662.5 ft

    Rock strength = 0.3

    K= 150 mD

    Formation fluid= gas □ 0.09 psi/ft

    Driller gradient= 0.62 psi/ft

- Formation 7:

    Depth at top = 5680 ft

    Rock strength = 1

    K= 10 mD

    Formation fluid= water □ 0.44 psi/ft

    Driller gradient= 0.62 psi/ft

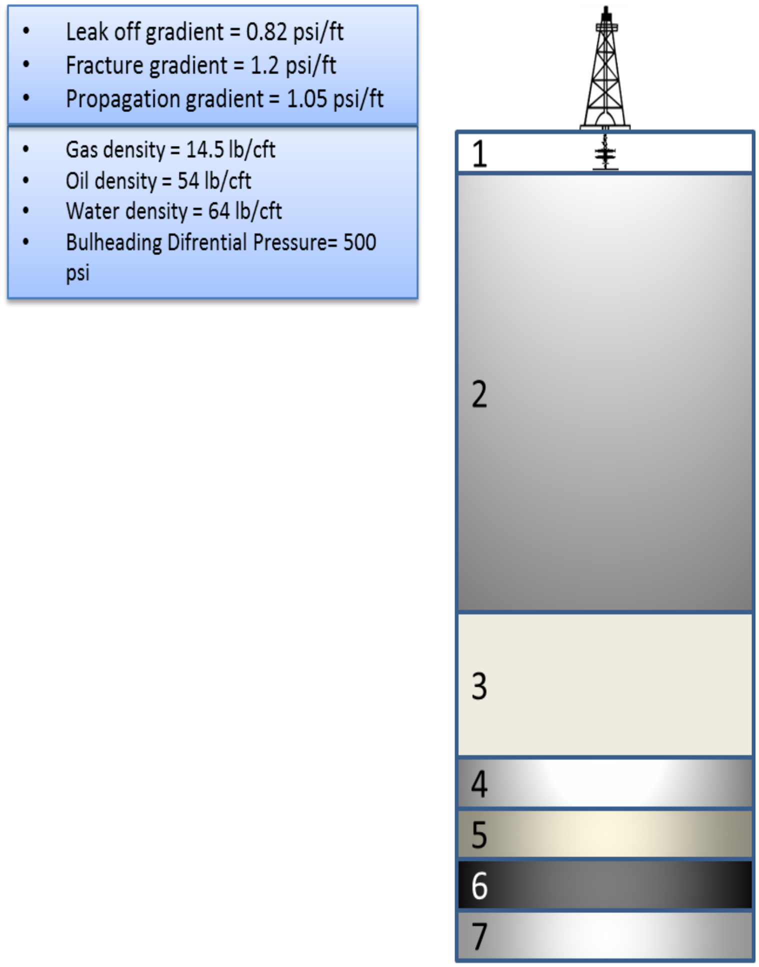


Figure 19- Formation data

4.3 Pump and mud data

Mud pump is one of the important prats of mud circulation system, which provides the sufficient pressure for compensating the pressure which is reducing due to the friction, in the mud circulation system. The pumps' type which is considered for these calculations is Triplex, and the important parameters of that, has been shown in the following figure:

Pumps:
Pump 1, 2, and 3:
Type: Triplex
Liner ID = 6"
Stroke length = 12"
Efficiency = 98%
Max Strokes= 120 SPM

MUD properties:
Density = 10ppg
Plastic Viscosity = PV = 10 cp
Yield point = YP = 20 $lb/100ft^2$

Pump Output = Formula = 4.31828 gal/Stroke

Surface equipment combination number = 3 → $C_{se} = 5$

Figure 20- Mud pump data

In the previous chapter the formula for calculation of circulation rate has explained, according to this data pump output will be:

$$Q = \frac{D^2 \times L \times N \times \pi}{308} \times E = \frac{6^2 \times 12 \times \pi \times N}{308} \times 0.98 = 4.3182N \ \ (gpm)$$

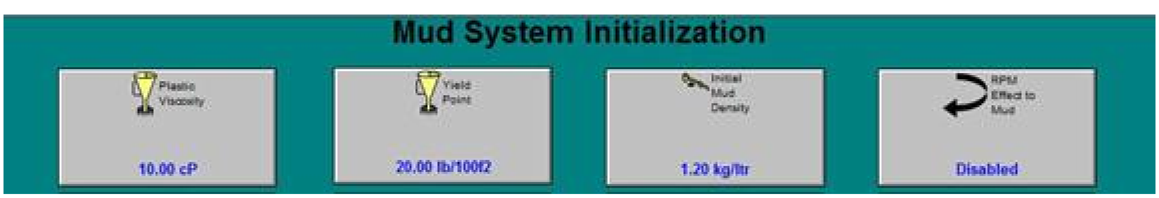


Figure 21- Mud Data

4.4 Hoisting Data

As mentioned in the previous chapter, for calculating the HL (hook load), it is necessary to consider the weight of all the equipment which are hanged by the crown block. If we neglect the weight of small connections, the main three parts which their weigh are important for our HL calculations are drill string weight, top derive weight, and travelling block.

$W_{Top\ Drive} = 22679.7\ kg$ $\qquad$ $W_{Traveling\ Block} = 15875.8\ kg$

$$Drag\ Coefficient = 1.5$$

Figure 22- Top drive and travelling block's weight

According to the data and calculations which has done, the hook load in static condition which the bit is in off bottom position, has obtained 106082.47 kg which is more than 99.9% same as the simulator's hook load and verified by the it.

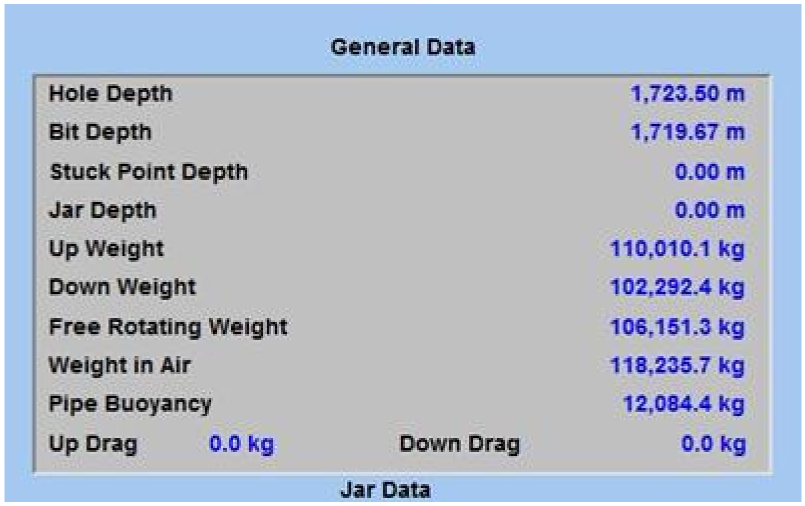


Figure 23- Hook load

4.5 sensitivity analysis

In any kind of studies, it is so important to have confidence about the reliability of reports. For this purpose, in this chapter, the simulations which has been done to study about the sensitivity of parameters to any change, and their degree of importance in the calculations, has presented.

4.5.1 Sensitivity analysis of parameters on ROP

In the previous chapters has mentioned that the rate of penetration is a parameter that many variables, can change it. In this part the sensitivity of ROP to the parameters including pumps rates, WOB, Rock strength, RPM, and density of mud discussed.

4.5.1.1 ROP vs pumps rates & ROP vs RPM

The simulations ran for three times according the following parameters in the table, and the results for ROP were according the following figures.

Table 3- Sensitivity analysis of ROP, 1

Number	Pumps Rate (strokes)	Flow rate (gpm)	WOB (tons)	Rock Strength (0-10)	RPM	Mud density (ppg)	ROP (m/hr)
1	45	194.3226	12	1.2	60	10.0144	7.7
	90	388.6452	12	1.2	60	10.0144	16.1
	135	582.9687	12	1.2	60	10.0144	23.2
2	45	194.3226	12	1.2	90	10.0144	10.6
	90	388.6452	12	1.2	90	10.0144	22.2
	135	582.9687	12	1.2	90	10.0144	31.5
3	45	194.3226	12	1.2	120	10.0144	13.5
	90	388.6452	12	1.2	120	10.0144	28.1
	135	582.9687	12	1.2	120	10.0144	40

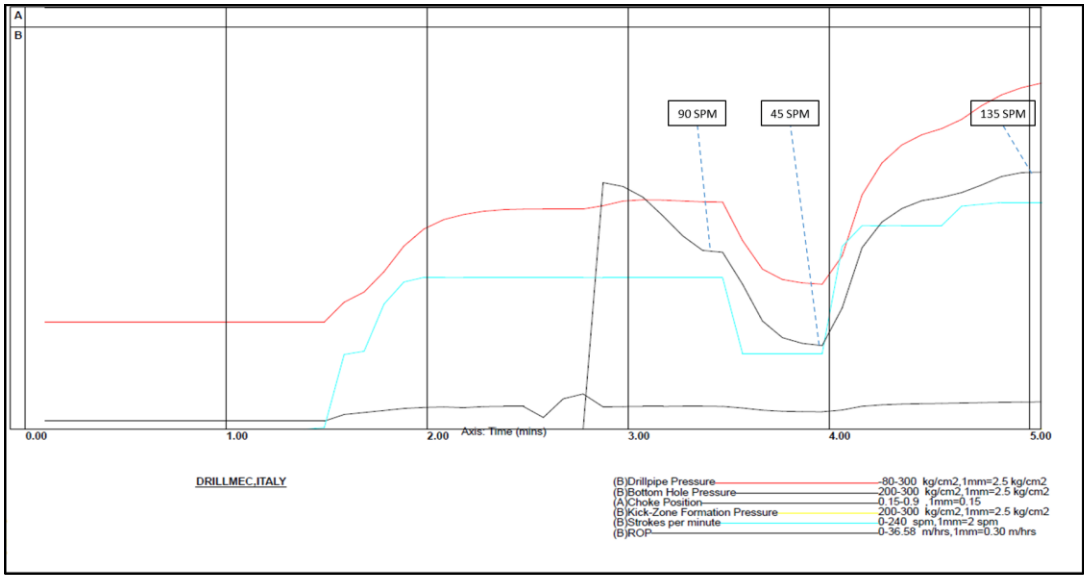


Figure 24- Change of SPM in 60 RPM

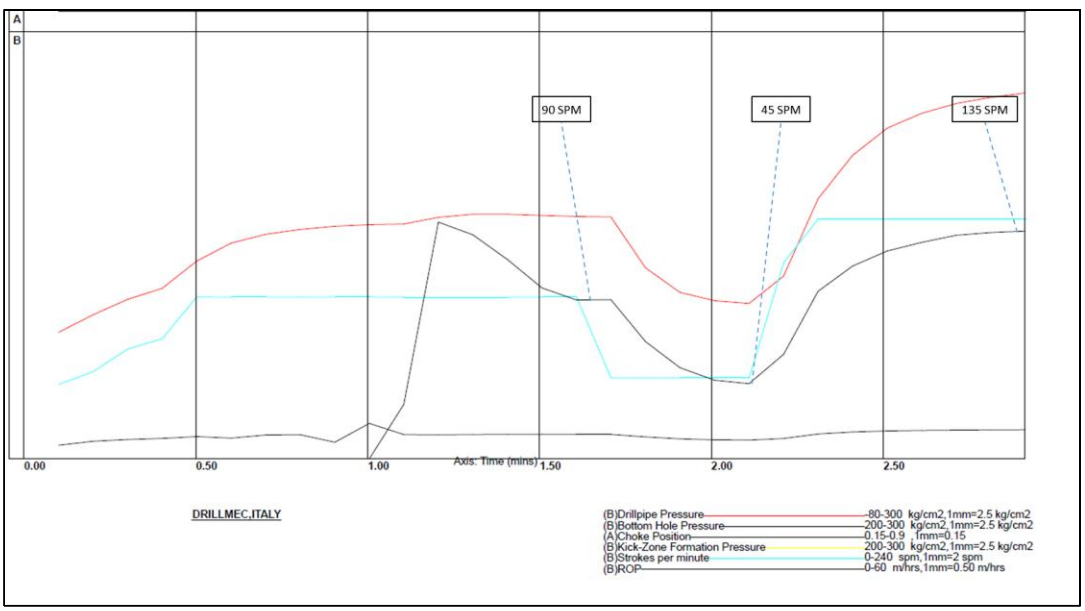


Figure 25- Change of SPM in 90 RPM

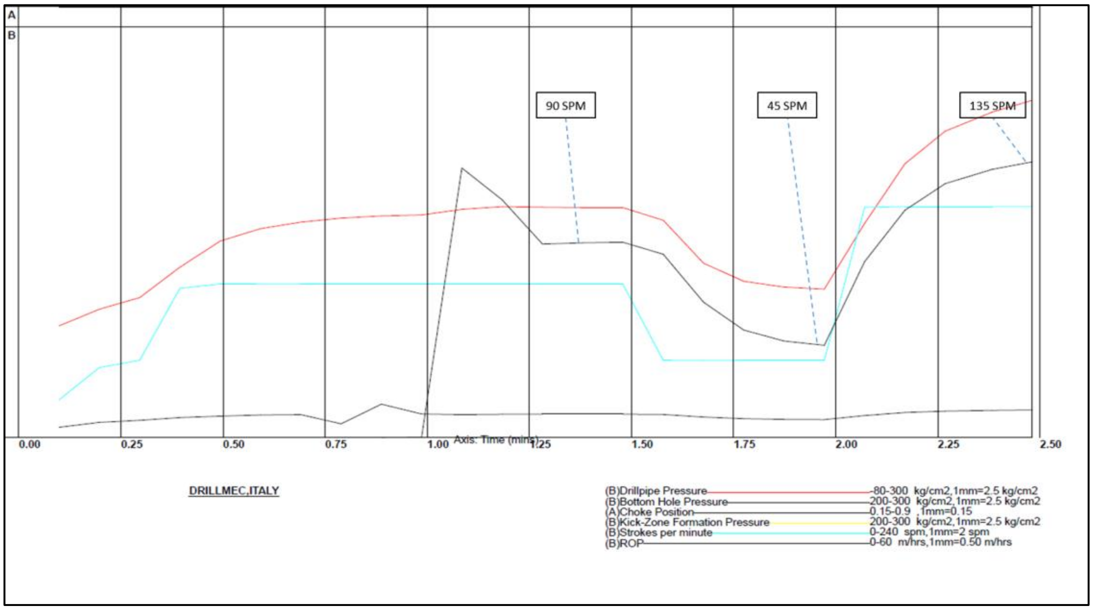


Figure 26- Change of SPM in 120 RPM

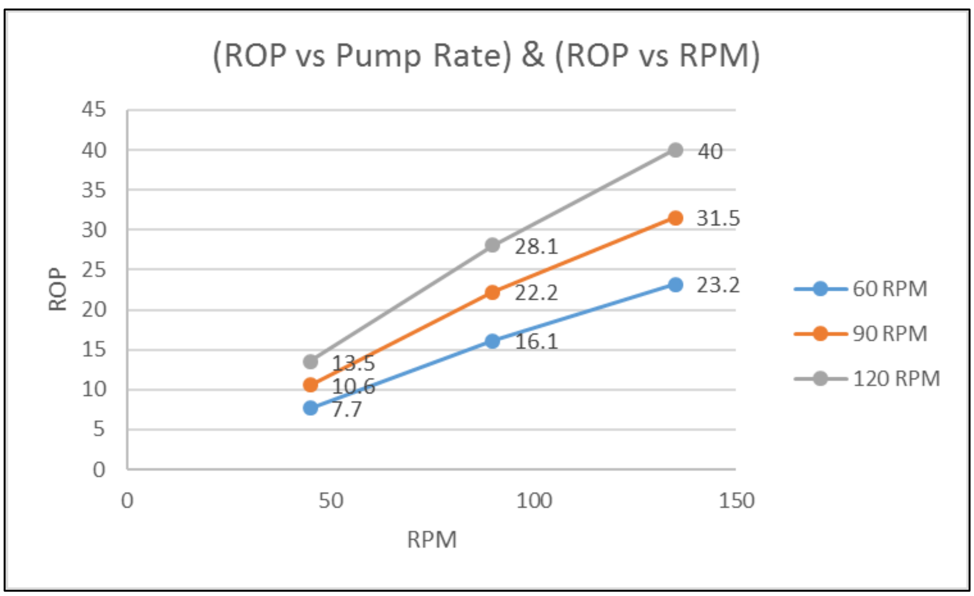


Figure 27- The effects of RPM and q on ROP

According to the Bourgoyne and Young model, the effects of RPM, and q on ROP explains by the following relations.

$$f_6 = \left\{\frac{RPM_{sf}}{60}\right\}^{a_6}, RPM$$

$$f_8 = \left\{\frac{F_j}{1000}\right\}^{a_8}, bit\ hydraulic\ jet\ impact$$

$$F_j = 0{,}01823 C_d q \sqrt{\rho \times \Delta P_b}$$

By changing these two parameters, the expect was increasing ROP. By assuming the $a_6$equal to 1, ROP will be function of RPM linearly, which can see in the results of simulator.

$$f_6 \alpha (RPM_{sf})^{a_6}, \qquad if\ a_6 = 0 \rightarrow f_6 \alpha RPM_{sf} \rightarrow ROP \alpha RPM$$

The effect of flow rate appears in bit hydraulic jet impact which pressure loss in the pit is function of flow rate. Accordingly, the ROP will be function of flow rate according the following formula:

$$F_j \alpha q^2 \rightarrow f_8 \alpha q^{2\times a_8}, \qquad if\ a_8 = 0.5 \rightarrow f_8 \alpha q \rightarrow f_8 \alpha\ SPM \rightarrow ROP \alpha SPM$$

4.5.1.2 ROP vs Rock Strength

The simulations ran for two times according the following parameters in the table, and the results for ROP were according the following figures.

Table 4- Sensitivity analysis of ROP, 2

Number	Pumps Rate (strokes)	Flow rate (gpm)	WOB (tons)	Rock Strength (0-10)	RPM	Mud density (ppg)	ROP (m/hr)
1	45	194.3226	12	1.2	120	10.0144	13.5
	90	388.6452	12	1.2	120	10.0144	28.1
	135	582.9687	12	1.2	120	10.0144	40
2	45	194.3226	12	0.75	120	10.0144	20
	90	388.6452	12	0.75	120	10.0144	41.6
	135	582.9687	12	0.75	120	10.0144	63

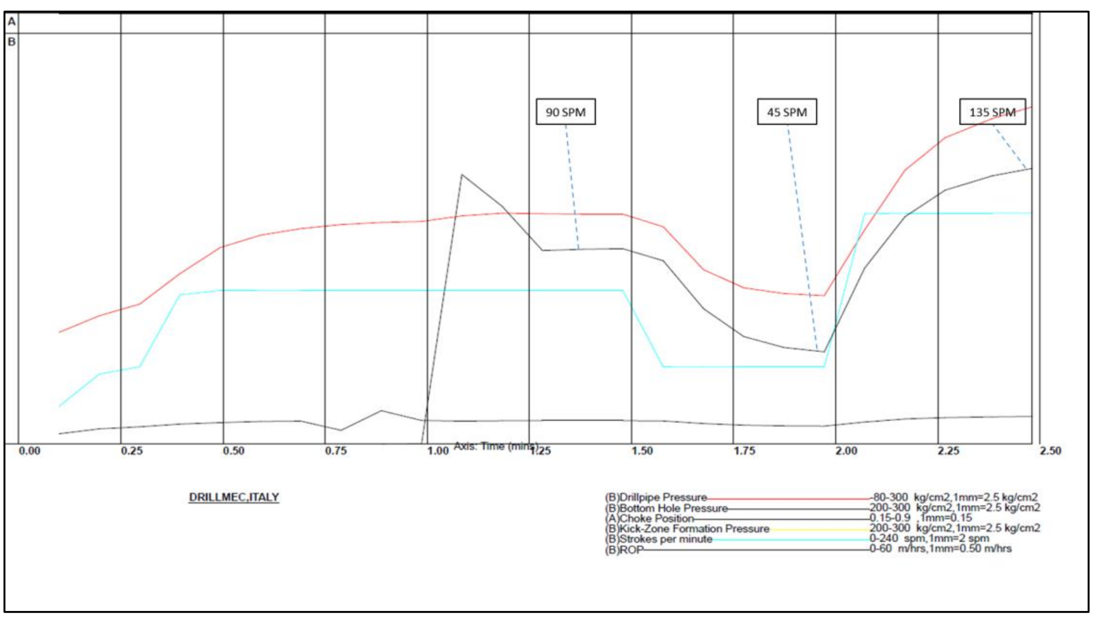


Figure 28- Change of SPM, rock strength is equal to 1.2

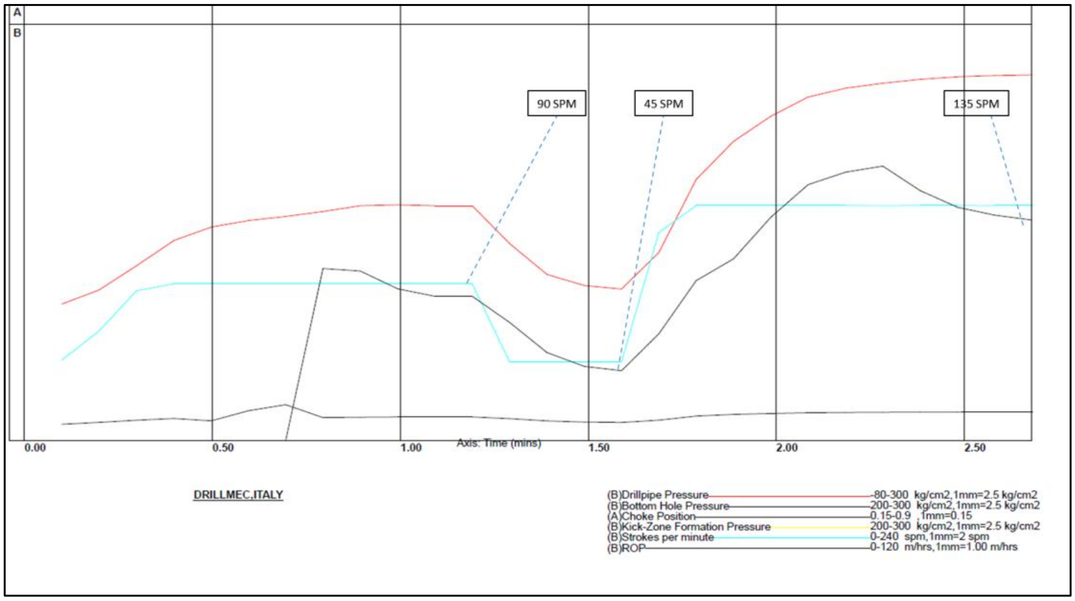


Figure 29- Change of SPM, when the rock strength is equal to 0.75

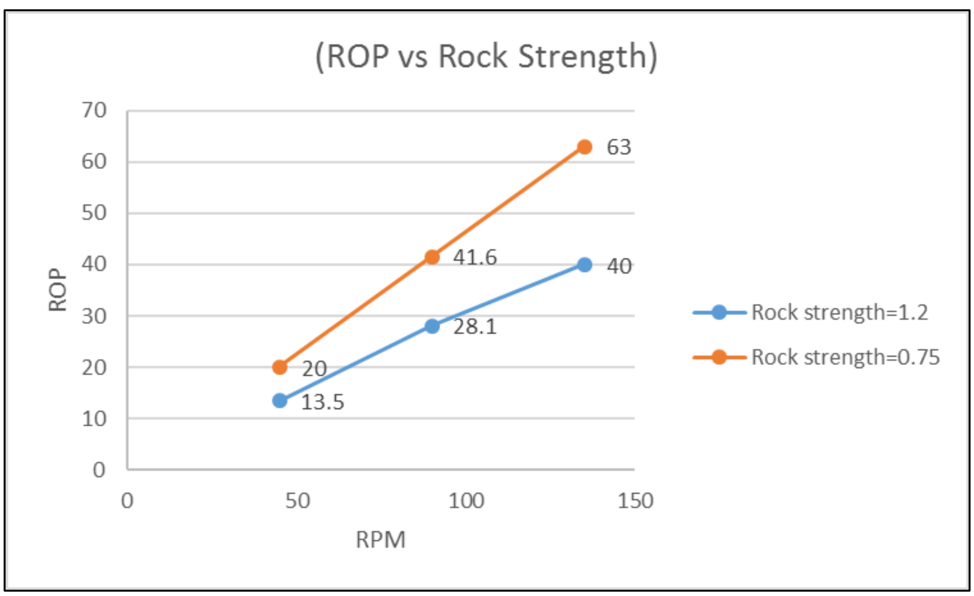


Figure 30- The effect of rock strength on ROP

According to the Bourgoyne and Young model, the effects of formation strength on ROP explains by the following relation.

$$f_1 = e^{2.303 \times a_1}, foirmation\ strength\ and\ bit\ type$$

By changing the formation strength, the expect was increasing ROP, which is confirm the results of simulator.

4.5.1.3 ROP vs WOB

The simulations ran for two times according the following parameters in the table, and the results for ROP were according the following figures.

Table 5- Sensitivity analysis of ROP, 3

Number	Pumps Rate (strokes)	Flow rate (gpm)	WOB (tons)	Rock Strength (0-10)	RPM	Mud density (ppg)	ROP (m/hr)
1	90	388.6452	12	1.2	120	10.0144	28.1
2	90	388.6452	15	1.2	120	10.0144	34
	90	388.6452	9.2	1.2	120	10.0144	20.5
	90	388.6452	5	1.2	120	10.0144	10

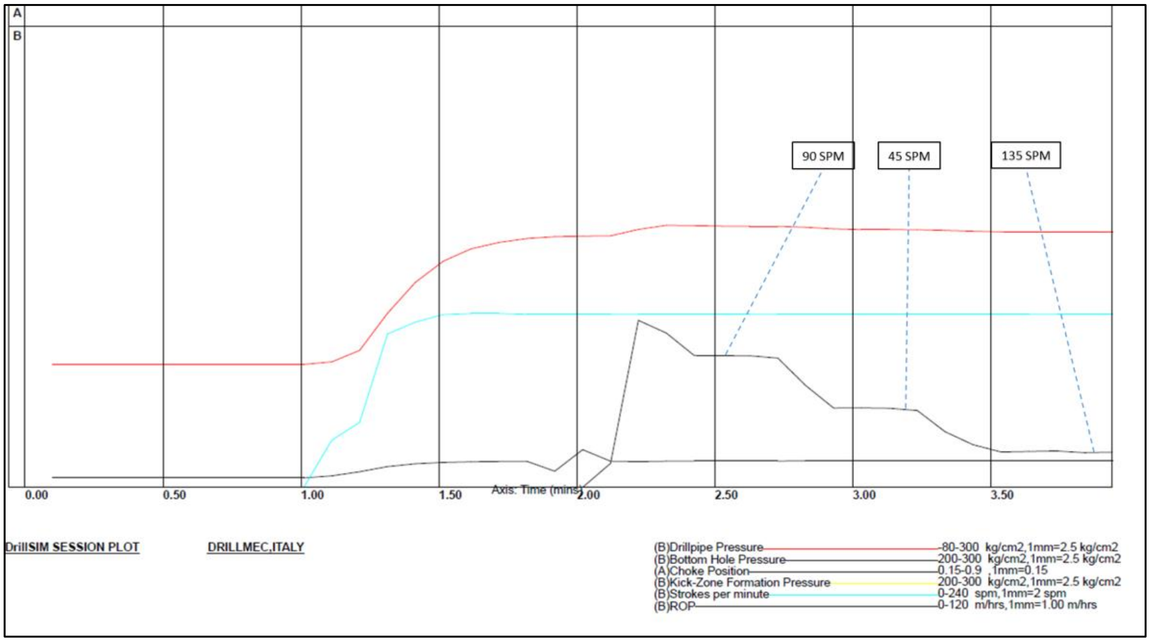


Figure 31- Change of WOB

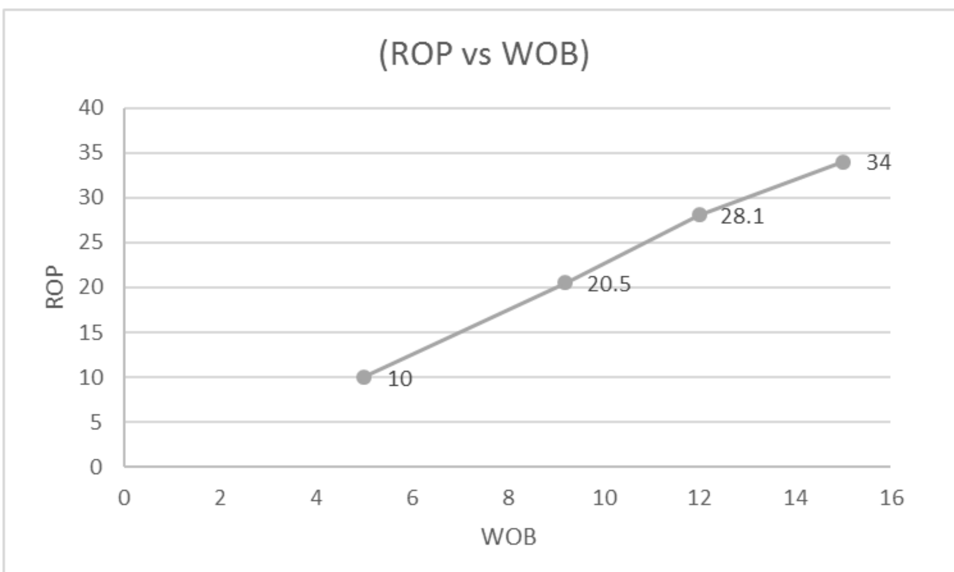


Figure 32- The effect of WOB on ROP

4.5.2 Sensitivity analysis of pump pressure with different flow rates

One of the important parameters in drilling operation is the pressure which is providing by pump for circulation of mud and it is important to be controlled for many reasons which one of them is not to exceeding the formation leak of pressure due to high annular pressure loss. For the mentioned configuration of model, the pump rate has been calculated by the simulator as the following diagram.

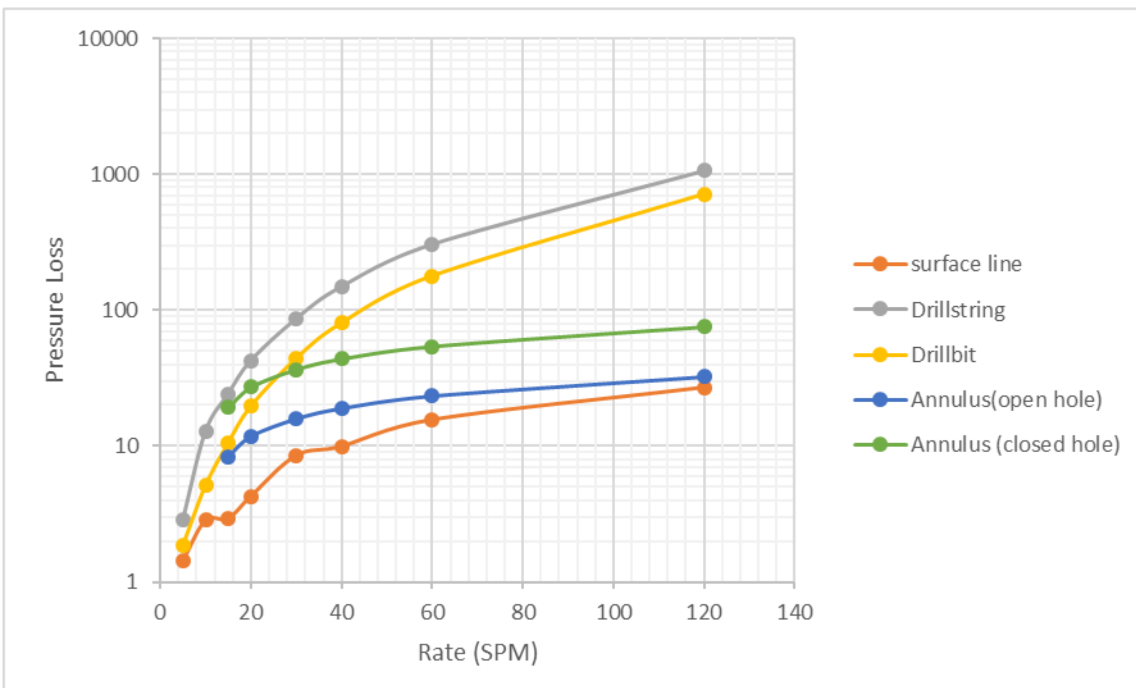


Figure 33- Pressure loss in different parts of model

According to the figure 27, the majority of pressure loss has been occurring in drill string due to small cross sectional area, and drill bit. By increasing the pump rate the pressure loss in each part has increased.

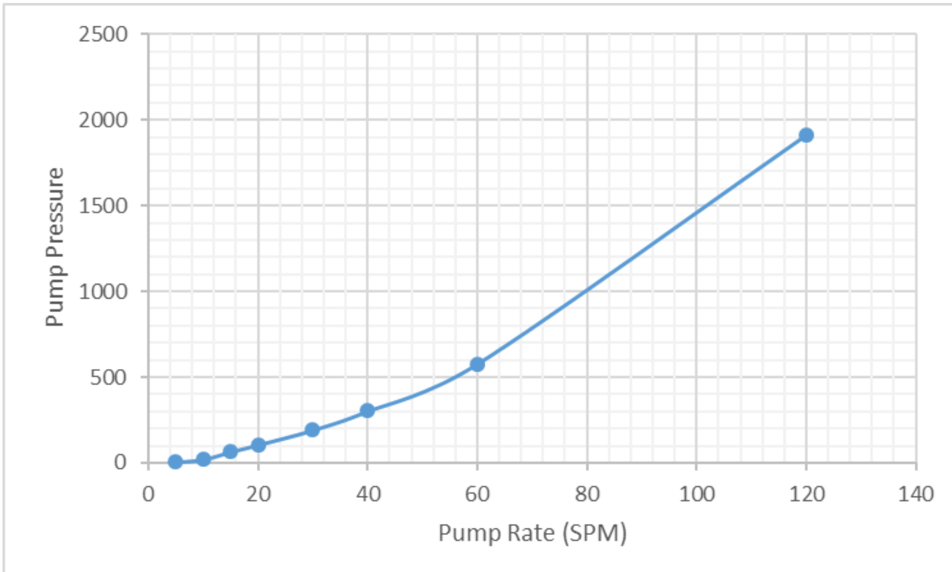


Figure 34- Pump pressure

In the figure 28, can find the relation between pump pressure and pump rate. This relation in the calculation is rounding to power two, according to following formula.

$$\Delta P_{2,Pump} = \Delta P_{1,Pump} \times (\frac{SPM_2}{SPM_1})^2$$

For more accurate calculation in the field, it is proposed that by using to pump rate and obtaining two pump pressure, it is possible to calculate the exact number for the power, which can be less than two in reality.

CHAPTER 5. SIMULATION OF KILL METHODS

When the well received a kick, it means the primary well control has lost, and by using BOP, the secondary well control barrier is using to control the well. After controlling the kick flow into the well, it is time to change the mud inside the well to provide new primary barrier which can control the entrance of kick to the well by its hydrostatic pressure. Accordingly, the operators should calculate the new weight of mud that should be use during the rest of operation, which known as kill mud. For calculating the necessary weight of kill mud, it is necessary to obtain the formation pressure, and then, develop a mud which can provide a pressure equal or higher than formation pressure, to control the flow.

$$P_{formation} = P_{hydrostatic\ of\ mud} + SIDPP(\ or\ SICP)$$

SIDPP= Shut in drill pipe pressure

SICP= Shut in casing pressure

It should be taken into account, that in the case of using SICP, if there are cuttings inside the mud the hydrostatic pressure of mud will be different with clean mud.

After calculating the formation pressure, it is possible to obtain the weight of kill mud by using the simple hydrostatic formula:

$$\rho_{kill\ mud} = \frac{P_{formation}}{TVD} = \frac{SIDPP\ (\ or\ SICP)}{TVD} + \ \rho_{initial\ mud}$$

In the following sections, the methods and processes for killing the wells, and simulations for each one of the methods which conducted, has been explained.

5.1 Conventional Methods

5.1.1 Driller's method

This method is the most widely used method in well control processes. The main concept in this method is to keep the BHP constant during the operations, and the nozzles should be at the bottom of the well to be able to circulate the kick from the bottom of the well to the surface. For reaching to the purpose of having constant BHP, remotely controlled choke is using to control the back pressure. At the beginning, by using the original mud, the kick circulates out of the well, and in the second circulation, the new mud (kill mud) replaces with the original mud to have the well under control by the primary well control barrier. Because of using the same mud that exist inside the well, in the first circulation process the SIDPP remains constant in the value of ICP (initial circulating pressure), but SICP starts to increase due to the expansion of gas (kick). When the gas reaches to the surface, SICP is in the highest value, and by circulating it to out of the well, SCIP starts to decrease. During the second circulation, the kill mud replaces with the previous mud, and the hydrostatic pressure of mud column starts to change. In the beginning the hydrostatic pressure inside the drill pipe start to increase which leads to decrease the SIDPP and reaches to FCP (final circulation pressure), but meanwhile the hydrostatic pressure inside the annular is stay constant, so SICP remains constant. Then, after reaching the kill mud to the nozzles, it starts to enter the annular space, and cause to decrease in SICP. Then the well should be closed and if the SIDPP, and SICP are equal to zero, it means that the well is killed properly and the operation for well control was successful.

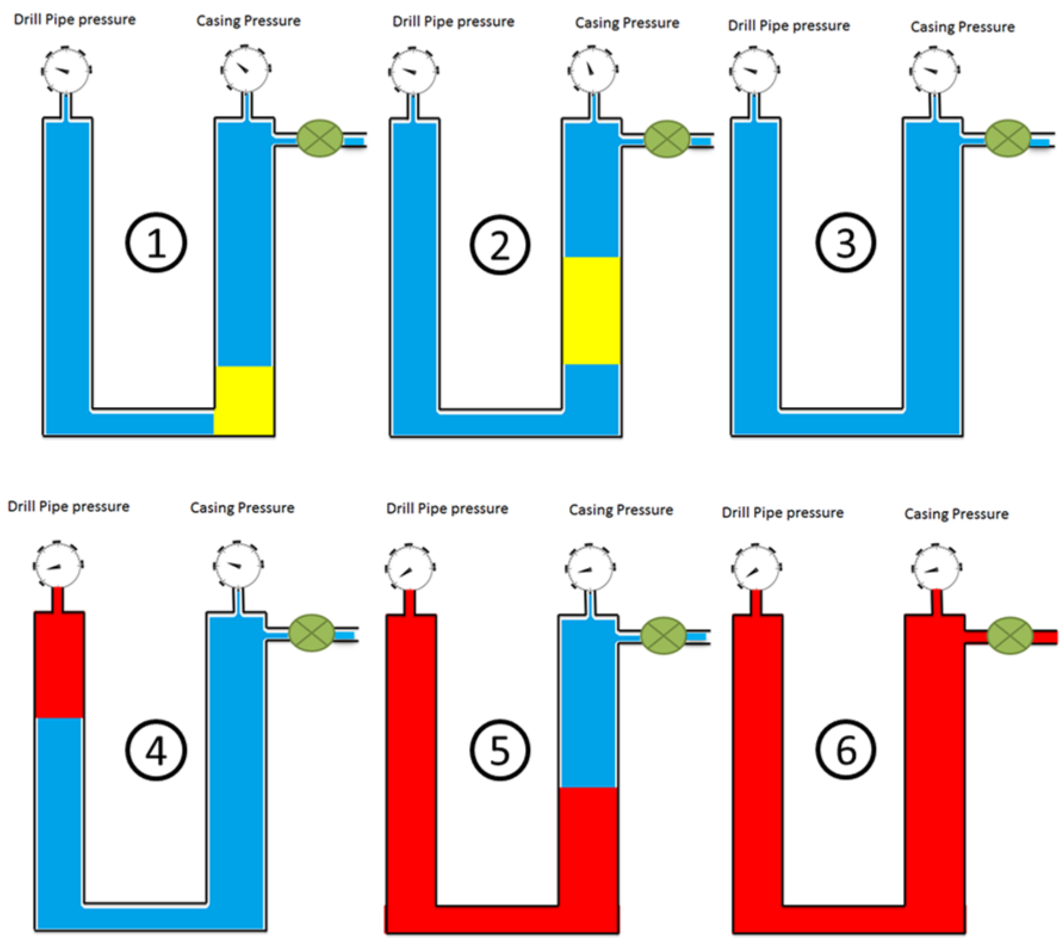


Figure 35- Schematic of drill pipe and casing pressure during the Driller's method

For simulating this method with the software, the following steps has been followed.

At the beginning, the pumps start circulation with 30, and 40 SPM to obtain the pressure loss amount for slow circulation rate during killing the well. After that, drilling process has start, and after a while the first drilling break has been seen by increasing ROP. Drilling has stopped to check the return flow, and because the return flow became zero after stopping the drilling and switching off the pumps, it is concluded that the drilling break was due to the formation change, and the drilling process can continue. Drilling process continued until the second drilling break, and in this point, after switching off the pumps, it has been concluded that the well is flowing due to kick entrance, so the well closed with hard shut-in method, and first circulation of mud with slow circulation rate has been done. During all this step, by controlling the choke the bottom hole pressure kept constant. After flowing the gas out the mud the kill mud replaced with old mud and by circulation of that the SICP, and SIDP start to decrease, until they became zero after finishing the circulation and killing the well. All the steps and response of the system is visible at the following graph.

The parameters for drilling purpose were assumed to be according the following table:

Table 6- Drilling data

Parameter	Value
Pump 1 (rate)	45 SPM
Pump 2 (rate)	45 SPM
WOB	12 tons
RPM	120

After reaching to the formation which contains higher pressure than hydrostatic column of mud gas entrance into the reservoir had start, and the first action which conduct was to move up the bit, stop the rotation and then stop the mud circulation to check the flow rate in the surface, because the well was flowing in the surface, the hard shut in method used to kill the well, and first step of circulation by keeping the SICP in a constant value has start. After flowing the gas out of the well the new mud has started to circulate in to re-establish the primary barrier. The new mud density are calculated by following formula:

$$\rho_{mud,kill} = \rho_{mud,old} + \frac{SIDPP \times 10}{TVD} = 1.2 + \frac{41.5 \times 10}{1725} = 1.44\ kg/cm^2$$

The reason the conversion factor (1/0.052) is 10, is because that in this case we used the KGM units, not the field's ones.

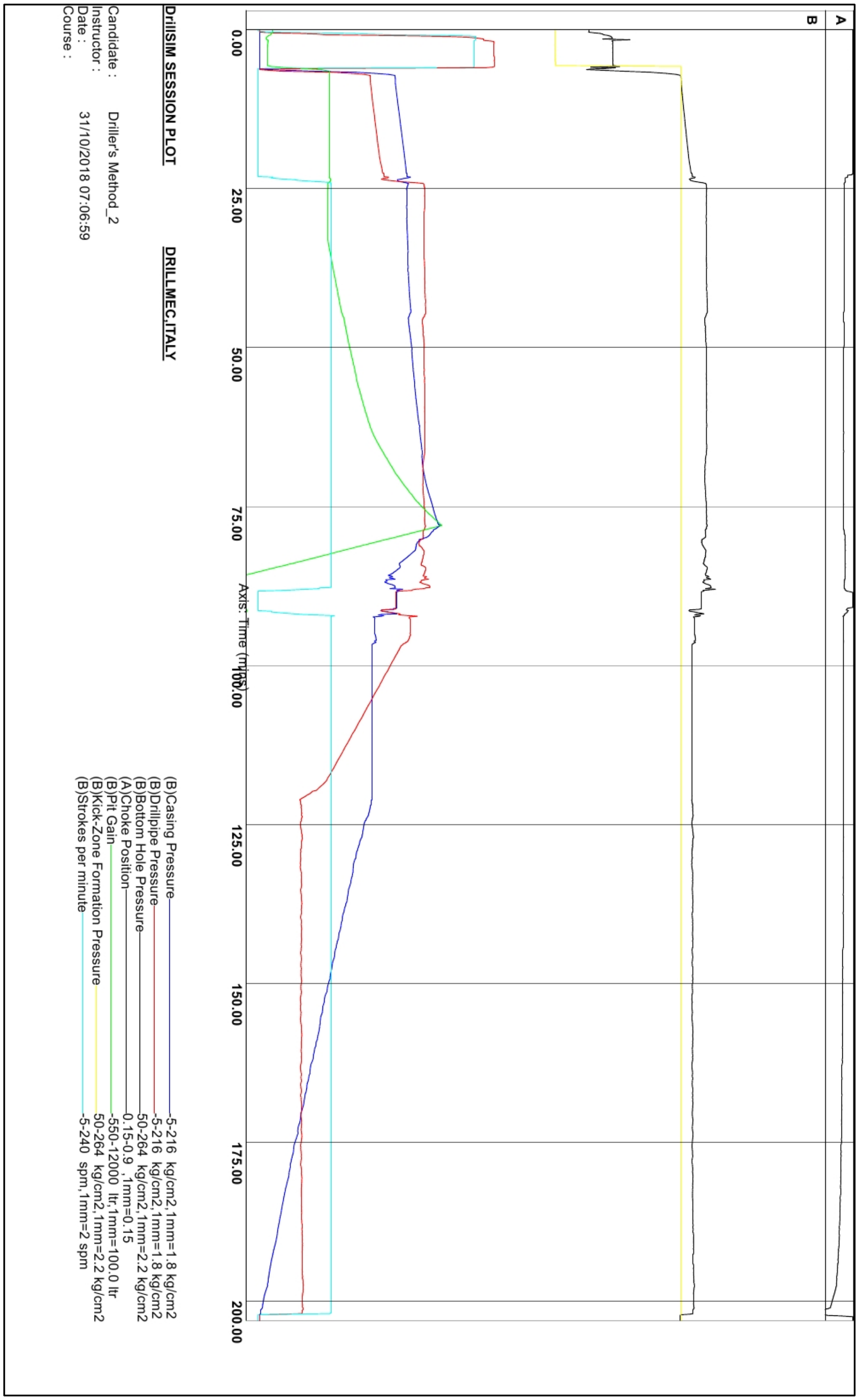


Figure 36- Driller's Method

For having more idea about the calculation, you can refer to kill shit which has been provided in Appendix C.

5.1.2 Wait & Weight Method

This method is also known as engineering method, and like the driller's method, the main concept is to keep the BHP constant, and having the nozzles at the bottom of the well to be able to circulate the kick from the bottom of the well to the surface. In this method, there is only one circulation process and from the beginning of the process, the weight of kill mud should be calculated, and then by circulating of that through drill pipe toward annular space, the kick should be circulated out of the well. Because of using the different and heavier mud the SIDPP starts to decrease, but meanwhile due to the movement of gas inside the annular area and expansion of the SICP starts to increase. When the kill mud reaches to the nozzles the SIDPP remains constant, because the after this moment the fluid inside the drill pipe will be same for the rest of operation. On the other hand, the gas is circulating toward upward and due to the expansion of it the SICP increases. Like the Driller's method the maximum SICP will be reached, when the gas reaches to surface, and after sending it out of the well, the hydrostatic pressure in the annulus will increase, which will cause to reduction of SICP. It should be taken into account that SICP will not reach to zero when all the gas is circulated out of the well, but also the remaining old mud in the annulus should be replace with the kill mud as well.

For simulating this method with the software, the following steps has been followed.

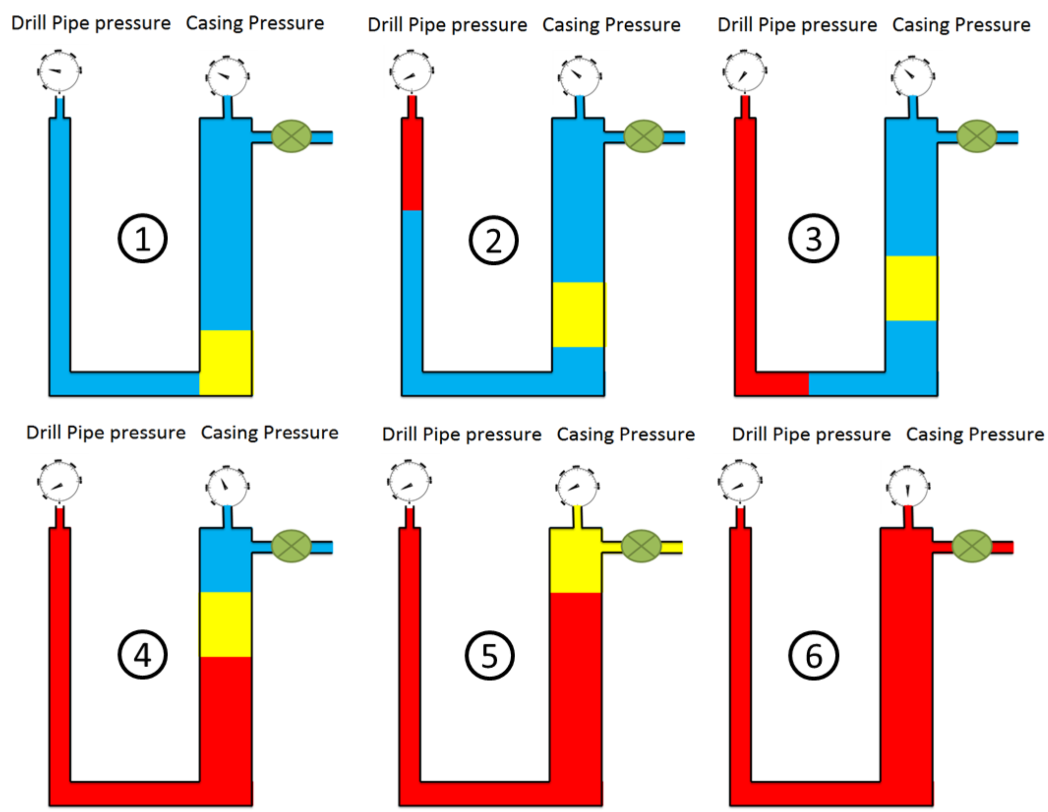


Figure 37- Schematic of drill pipe and casing pressure, Wait and Weight's method

At the beginning, the pumps start circulation with 30, and 40 SPM to obtain the pressure loss amount for slow circulation rate during killing the well. All the process followed in a same way with Driller's method, until having kick in the well, so the well closed with hard shut-in method, and wit one circulation of kill mud with slow circulation rate the kick has been flowed out of the well and kill mud replaced with the old mud. All the steps and response of the system is visible at the following graph.

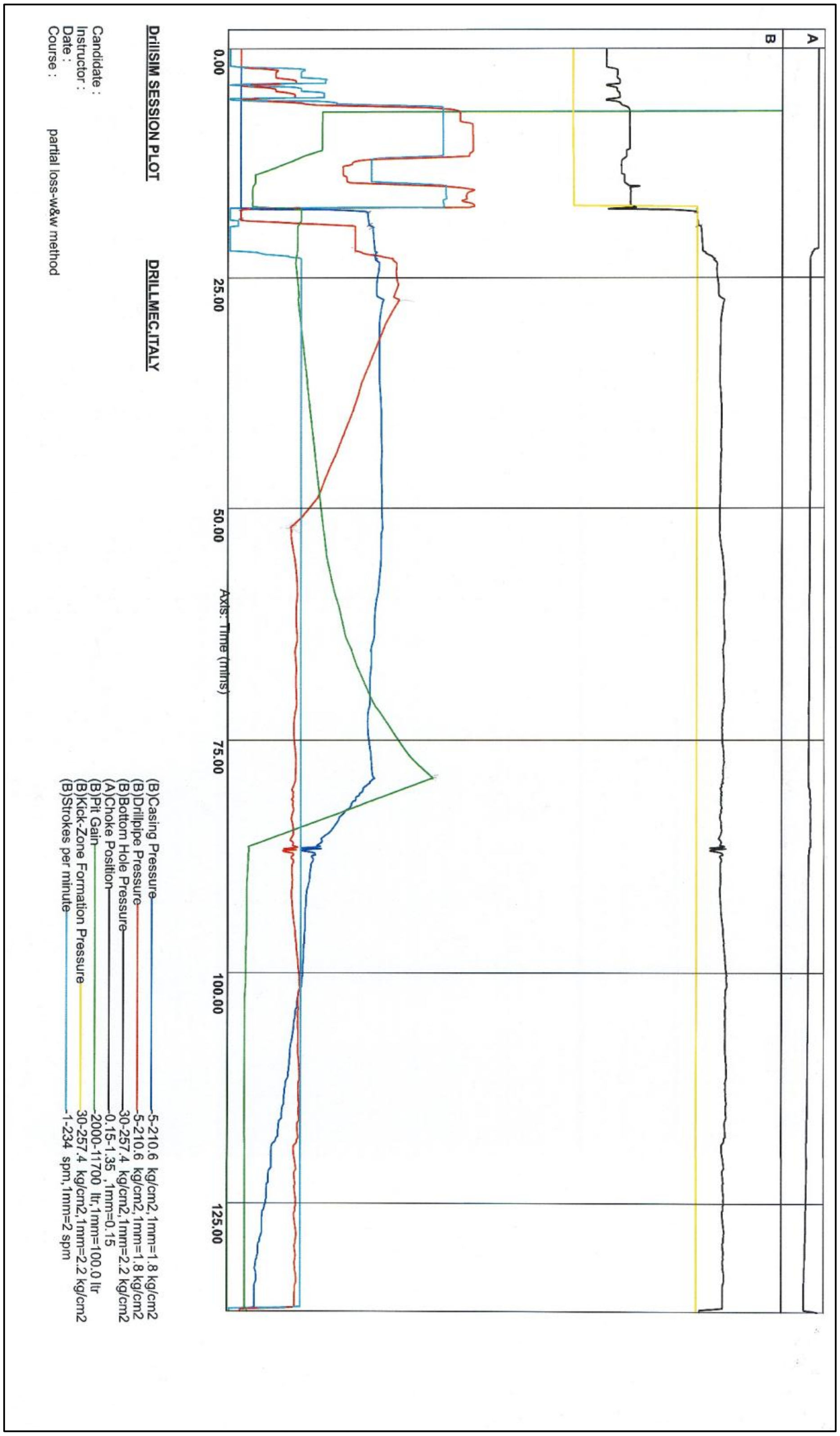


Figure 38- Wait and Weight Method

5.2 Unconventional methods

In unconventional methods, we have kind of situations that makes it impossible for us to use the BHP constant methods, so we need to increase the BHP, during the killing well but it should be taken into account that in all the operation processes, the range of BHP should not pass the limits (Formation pressure, and Fracture pressure).

5.2.1 Volumetric method

In some operations there is no possibility to use the previous methods. For example, during tripping out the drill string and swabbing, the gas can enter to the well, and the first action that should be done is to bringing back the string inside the well, but when it is not an option to bring the string back, the volumetric method is using for well control operation. The main concept in this method is to allow the gas to expand which will cause the reduction of gas pressure, but on the other hand it will increase the back pressure at the surface. So, the extra pressure at the top of the well should bleed off by using the choke valve, and after flowing all the gas out of the well, the drill string should be send back to continue the operation. It should be taken into account that in this method, it is not necessary to circulate the mud with kill mud because the mud weight was proper to avoid kicking and the reason for having kick inside the well was the swabbing phenomena.

In the first step of simulation it is assumed that the drill string is blocked and there is no possibility to circulate through to kill the well. Accordingly, the volumetric method used for flowing the gas out of the well.

It should be taken into account that these simulations had run until reaching the gas kick volume to the BOP. In the first simulation, as mentioned the idea was to keep the pressure in safety range, means upper than bottom hole pressure and lower than fracture pressure, by controlling the SICP. In the second simulation, we considered that the SIDPP gauge is working and we can control the BHP through that.

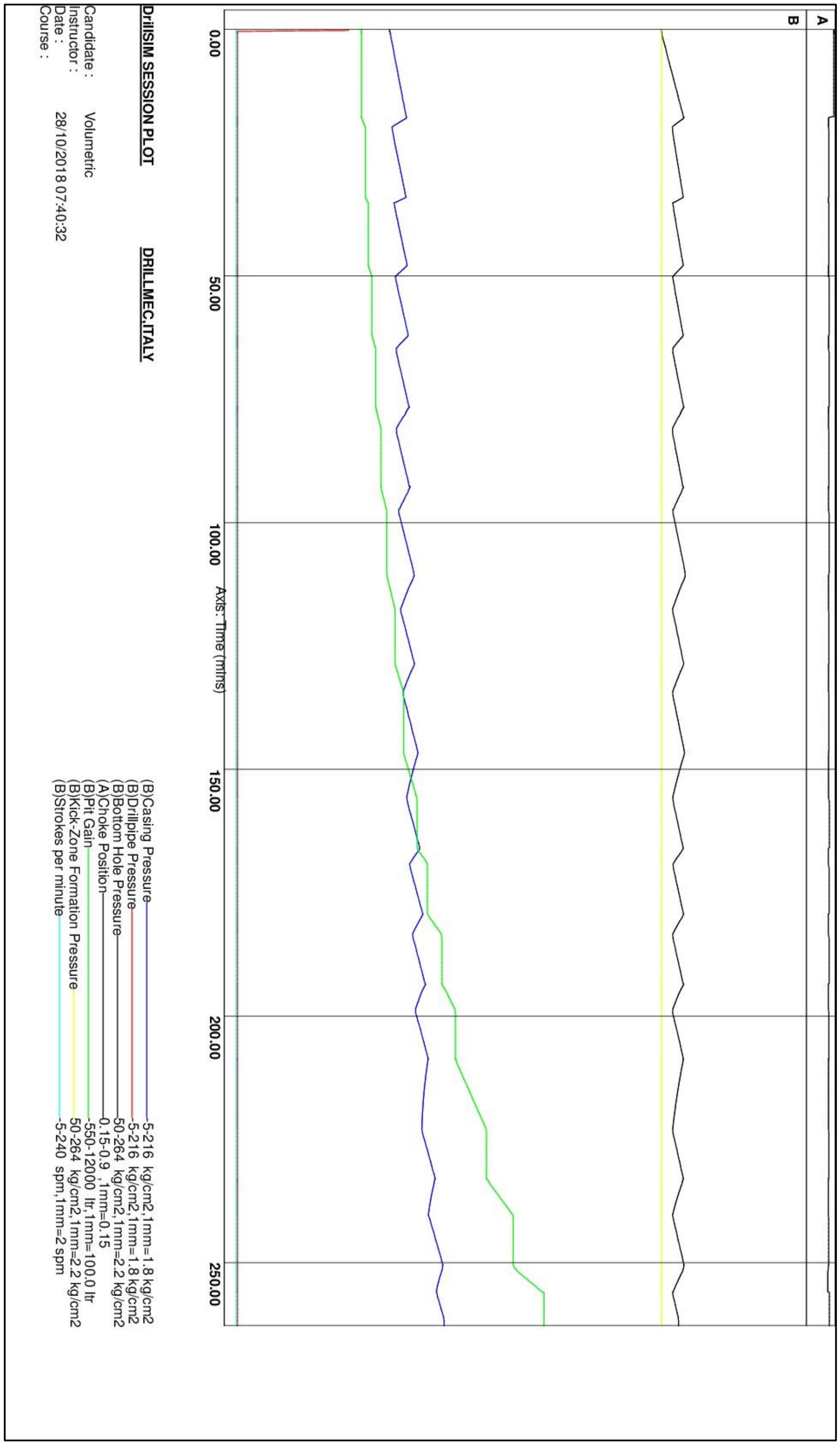


Figure 39- Volumetric method with controlling the BHP by SICP

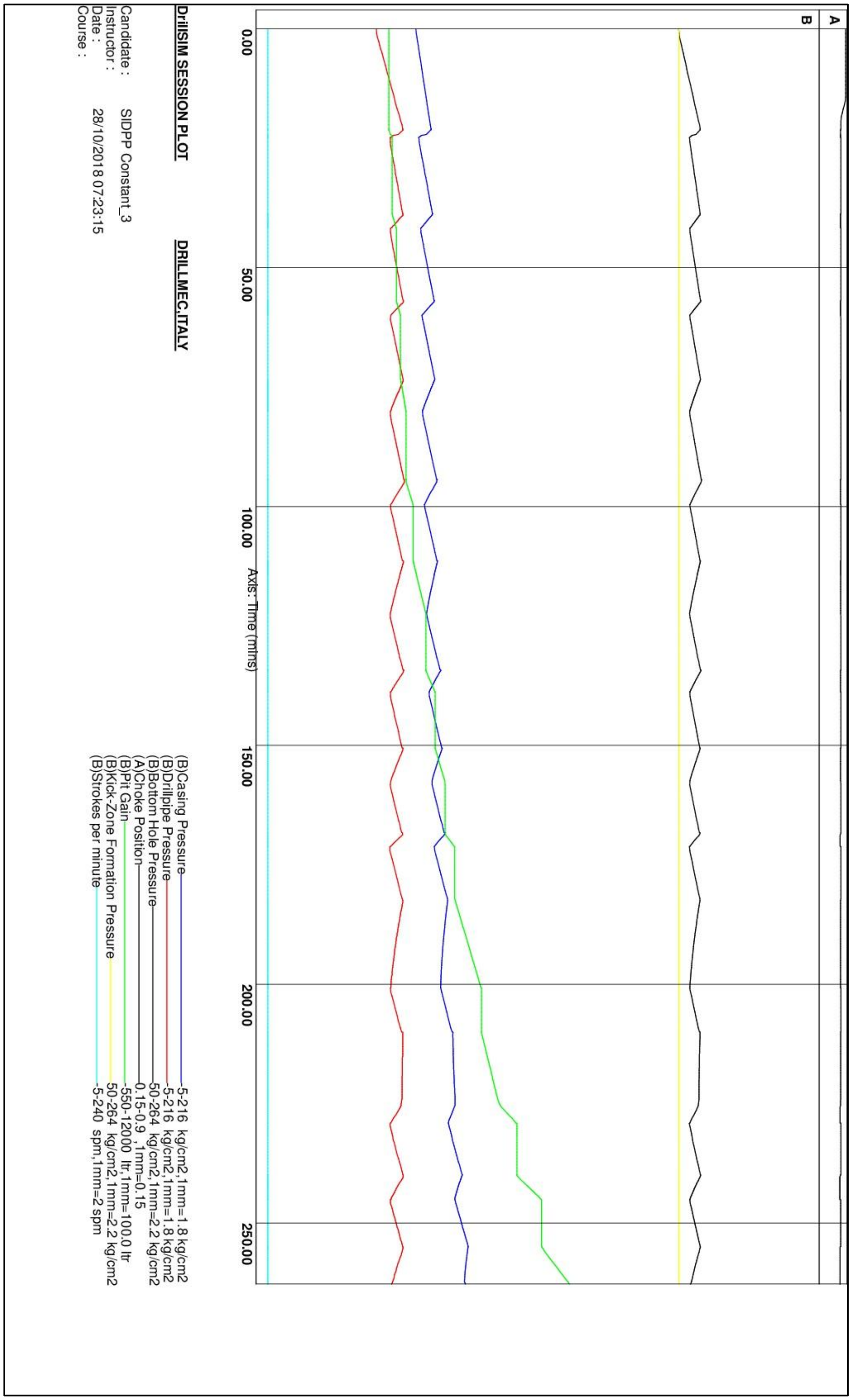


Figure 40- Volumetric method with controlling the BHP by SIDPP

5.2.2 Bullheading

Sometimes none of the mentioned methods are feasible to be consider as a well control method. For example, if the kick has high amount of H2S which it is not possible to control it on the surface, there is possibility of breaking the casing in the shoe, or the volume of kick is higher than amount that can be handle by surface facilities, the alternative method should be chosen. Bullheading is the method that can help to control the well in the mentioned conditions. In this method by using the pumps, the wellbore pressure increases and became overbalance, and transfers back the kick to the formation.

In the last step, the simulation for this method has done, by assuming the gas migration ratio is zero. It should be taken into account that the pump rate should provide a flow rate for mud which is higher than gas migration, and with the data which had been considered for the previous simulations, the required flow rate could provide higher pressure than fracture pressure, in the casing shoe. The second important point in this method which needs to be taken into account is the pumping flow line, which in this method the mud should be pumped through kill line, so the standpipe manifolds needs to be modified.

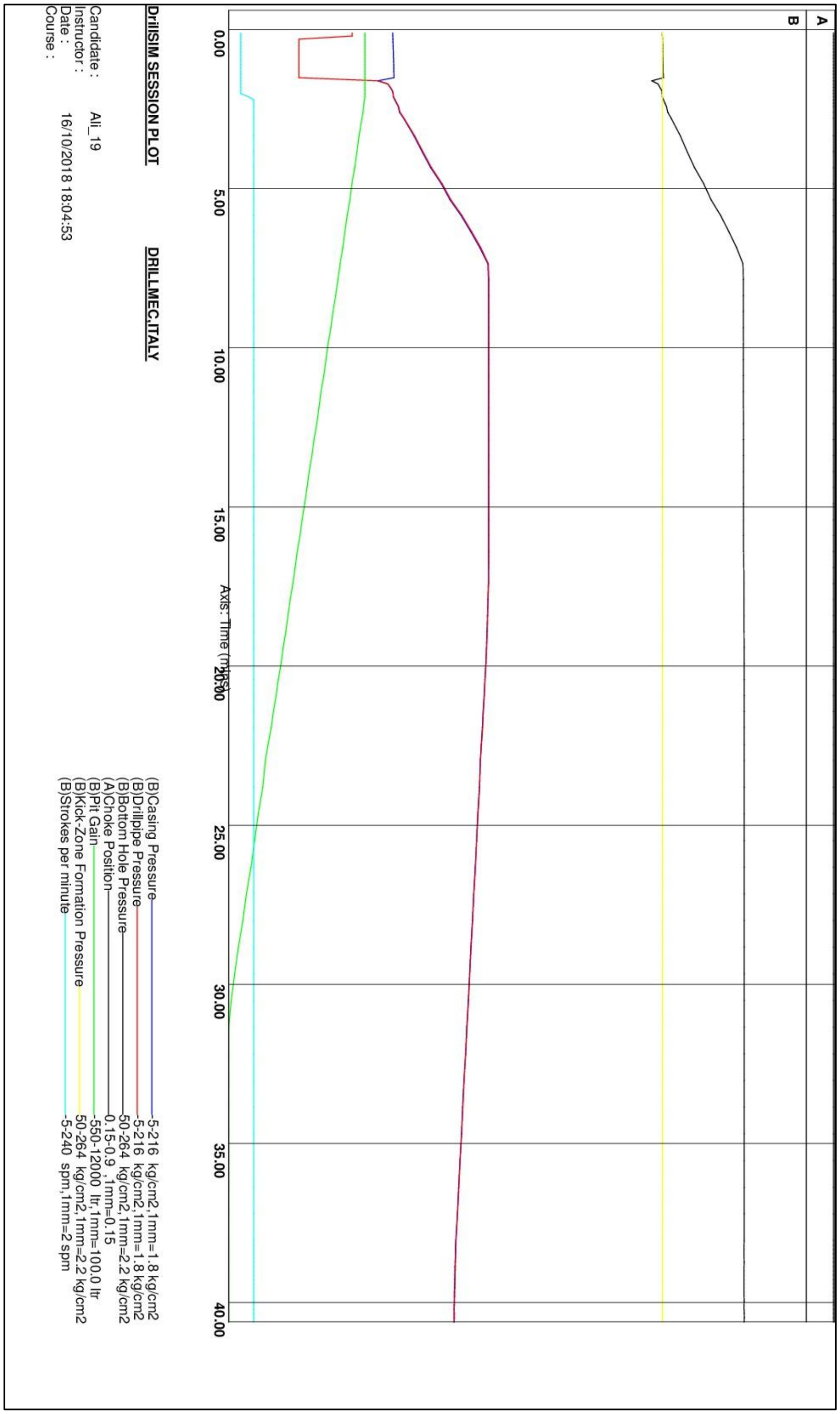


Figure 41- Bullheading method

CHAPTER 6. CONCLUSION AND RECOMMMENNDATIONS

6.1 Conclusions

The period which is spent in Drillmec for this project, was divided into two phases: a first phase was for preparation and training the essential topics for the development of the work in progress. The first phase had the final goal of transferring all the practical and professional skills to specialize in the drilling, well control and simulation sectors. Initial phase ended after obtaining the certificates in “IWCF well control, Level 4 (supervisor)", and "IWCF well intervention Level 4 (supervisor)" mandatory for those working in the Oil & Gas sector.

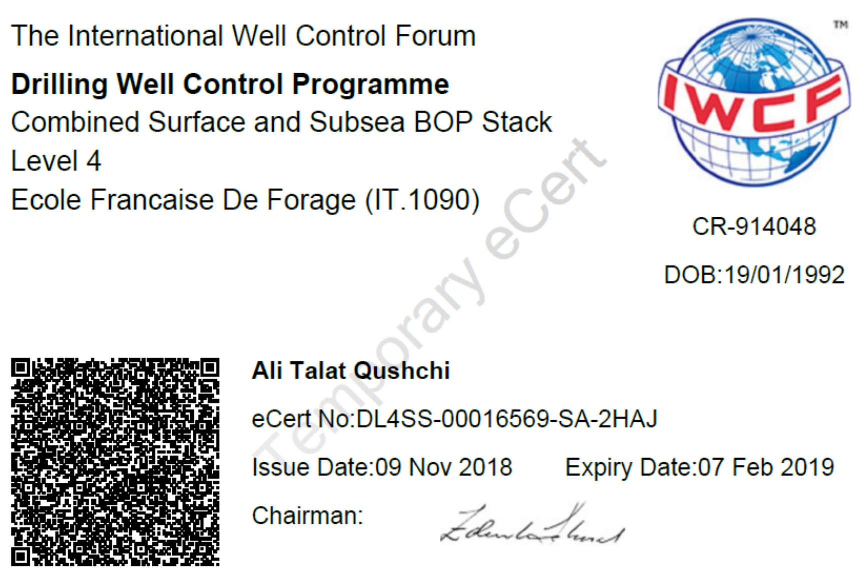
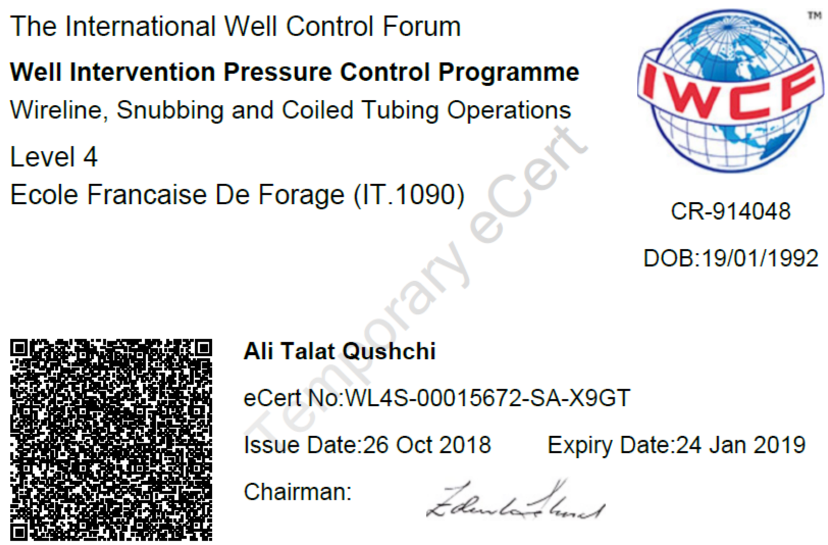

The International Well Control Forum
Drilling Well Control Programme
Combined Surface and Subsea BOP Stack
Level 4
Ecole Francaise De Forage (IT.1090)
Temporary eCert
IWCF ™
CR-914048
DOB:19/01/1992
Ali Talat Qushchi
eCert No:DL4SS-00016569-SA-2HAJ
Issue Date:09 Nov 2018 Expiry Date:07 Feb 2019
Chairman:

Figure 42- Well control Level 4



The International Well Control Forum
Well Intervention Pressure Control Programme
Wireline, Snubbing and Coiled Tubing Operations
Level 4
Ecole Francaise De Forage (IT.1090)

CR-914048
DOB:19/01/1992

Ali Talat Qushchi
eCert No:WL4S-00015672-SA-X9GT
Issue Date:26 Oct 2018 Expiry Date:24 Jan 2019
Chairman:

Temporary eCert

Figure 43- Well intervention pressure control Level 4

The objectives achieved where the second phase began, which was the application of the principles and procedures of conventional well control with the most common well control methods in the case of kick (driller's method and wait & weight method), and applications of unconventional well control principles and procedures (bullheading, volumetric method) and analysing the killing methods by designing a proper model with simulator.

The main idea for following both methods are same which is the circulation of kick out of well and reconstruction of primary barrier with new heavier mud. As mentioned before, the main difference between these methods are the steps which kill mud involves in process. It is crystal clear that in Wait and Weight method the time which is necessary for killing the well is less than Driller’s method as you can see in the result of simulation, because in one circulation the gas is circulating out of the well and the new kill mud reconstruct the primary barrier. In Driller's method, controlling the pressure by choke is simpler, because in each circulation there are maximum two type of fluids and in one section of U-tube (casing or drill string) there is only one type of fluid so static hydrostatic pressure of one section is always constant, but in Weight and Wait method, always there are two types of fluid until displacing the primary mud with new one in the drill string.

The plots obtained during the simulations have shown both advantages and disadvantages with Driller, and Weight and Wait methods. By the use of simulators, we can gain knowledge of dangers and outcomes before they happen.

The circulation rate is an important parameter, because it is direct relation with APL (annular pressure loss), and gas circulation rate. If the rate is too much, it is true that the circulation of gas out of the well will speed up but it will increase the dynamic hydrostatic pressure which can lead the fracture in weak points like casing shoes. The optimized value for SCR should be decided, before any kind of operation.

Another important thing about having good knowledge about the reaction in well control phenomena, is reducing the kick volume, which has very important effect on getting a successful result before failing the operations.

6.2 Recommendations

Well control situation is common in the oil and gas field operations on the site, and a good training for the people who involved in this operation is urgent. Due to this fact lots of times by the training centers and organizations is allocating for training the personnel, to be aware about the right action that they should take in case of emergency. Experience of this kind of phenomenon is not possible due to the existed risks, so the best way to show the operations is by simulating.

During this work all the parameters which are engaged in the calculation has collected and it is ready for programming by the Drillmec's expert to simulate this phenomenon in the full scale simulator of this company. Therefore, it is recommended that future research should be conducted to investigate in this area.

Some parts of workflows for calculation of different parameters are included in Appendix B.

APPENDIX A. PRESSURE LOSS CALCULATIONS ACCORDING DIFFERENT TYPES OF FLUIDS

A.1 Newtonian fluids:

The rheological model for Newtonian fluid is the simplest one, which is a linear relation between shear stress and shear rate and shear rate at zero shear stress zone is equal to zero. This relation is according the following formula:

$$\tau = \mu \times \gamma$$

τ = shear stress, lb/100 ft2 or Pa

μ = viscosity, cp or Pa-s

γ = shear rate, s-1

In the first step the velocity of in each part of system should be calculate.

$$v = \frac{q}{2.448 \times d^2}$$

$$v = \frac{q}{2.448 \times (d_2^2 - d_1^2)}$$

V= velocity, ft\sec

q = flow rate, gpm

d = inside diameter of pipe, in

d_1 = inside diameter of casing or borehole, in

d_2 = outside diameter of pipe, in

for flow regime, like the Bingham Plastic fluids, it is necessary to calculate the Reynolds number, for the inside and annular, it can be obtain by following formula:

$$N_{Re,inside} = 928 \times \frac{\rho v d}{\mu}$$

$$N_{Re,annular} = 757 \times \frac{\rho v(d_2 - d_1)}{\mu}$$

ρ = fluid density, ppg

μ = fluid viscosity, cp

According to general descriptions in manuals, if Reynold number is higher than 4000, the flow is turbulent, and if it is less than 2100, the flow is laminar. Between these two numbers, the flow is in transitional condition.

In the next step the velocity of in each part of system should be calculate.

$$v = \frac{q}{2.448 \times d^2}$$

$$v = \frac{q}{2.448 \times (d_2^2 - d_1^2)}$$

q = flow rate, gpm

for calculating the pressure loss due to the friction the general formula based on Funning equation, expressed by Bourgoyne et al., 1986. After that, lots of correlation for calculating of friction factor has developed which, using Fanning friction factor for laminar flow, and Chen friction factor for the turbulent flow, leads to accurate prediction of pressure loss. In the following section, this formula has provided:

$$\frac{dp_f}{dL} = \frac{f\,\rho\,\overline{v^2}}{25.8\,d}$$

pf = frictional pressure, psi

L = pipe length, ft

f = Fanning friction factor, dimensionless

v = average velocity, ft/s

d = equivalent pipe inner diameter, in

Laminar flow:

$$f = \frac{16}{N_{Re}}$$

$$\Delta P_f = \frac{\mu v}{1500 d^2} \Delta L$$

$$\Delta P_f = \frac{\mu v}{1000(d_2 - d_1)^2} \Delta L$$

Turbulent flow:

$$f = \frac{0.0791}{N_{Re}^{0.25}}$$

$$\Delta p_f = \frac{\rho^{0.75}\, v^{1.75}\, \mu^{0.25}}{1800\, d^{1.25}} \Delta L$$

$$\Delta p_f = \frac{\rho^{0.75}\ v^{1.75}\ \mu^{0.25}}{1396\ (d_2 - d_1)^{1.25}} \Delta L$$

A.2 Power Law fluids:

In the first step the velocity of fluid should be calculate in the inside or annular part:

$$v = \frac{q}{2.448\ \times\ d^2}$$

$$v = \frac{q}{2.448\ \times\ (d_2^2 - d_1^2)}$$

q = flow rate, gpm

d = inside diameter of pipe, in

d_1 = inside diameter of casing or borehole, in

d_2 = outside diameter of pipe, in

Then apparent viscosity can be obtained, which the function of yield point and plastic viscosity:

$$\mu_a = \frac{K d^{(1-n)}}{96 v^{(1-n)}} \left(\frac{3 + \frac{1}{n}}{0.0418}\right)$$

$$\mu_a = \frac{K (d_2 - d_1)^{(1-n)}}{144 v^{(1-n)}} \left(\frac{2 + \frac{1}{n}}{0.0208}\right)$$

K= consistency index of Power Law fluids

n= flow behavior index of Power Law fluids

μ_a = apparent fluid viscosity, cp

$$N_{Re} = 89100\frac{\rho v^{2-n}}{K}(\frac{0.0416d}{3+\frac{1}{n}})^n$$

$$N_{Re} = 109000\frac{\rho v^{2-n}}{K}(\frac{0.0208(d_{2}-d_1)}{2+\frac{1}{n}})^n$$

$$N_{Rec} = 3470 - 1340n$$

If Reynold number is higher than critical Reynolds number, the flow regime is turbulent, otherwise it is laminar.

Laminar flow:

$$\Delta P_f = \left[\left(\frac{96v}{d}\right)\left(\frac{3n+1}{4n}\right)\right]^n \frac{K}{300d}\Delta L$$

$$\Delta P_f = \left[\left(\frac{144v}{d_2-d_1}\right)\left(\frac{2n+1}{3n}\right)\right]^n \frac{K}{300(d_2-d_1)}\Delta L$$

Turbulent flow:

$$\Delta P_f = \frac{f\rho v^2}{25.8d}\Delta L$$

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

A.3 Herschel-Buckley fluids:

In the first step the velocity of fluid should be calculate in the inside or annular part:

$$v = \frac{q}{2.448 \times d^2}$$

$$v = \frac{q}{2.448 \times (d_2^2 - d_1^2)}$$

For calculating the Reynolds number, C_c for the inside part of pipe, and C_a^* for the annular part should be calculate:

$$C_c = 1 - (\frac{1}{2n+1}) \frac{\tau_y}{\tau_y + K \left\{\frac{(3n+1)q}{n\pi (d/2)^3}\right\}^n}$$

$$C_a^* = 1 - (\frac{1}{n+1}) \frac{\tau_y}{\tau_y + K \left\{\frac{(3n+1)q}{n\pi \left[\left(\frac{d_2}{2}\right) - \left(\frac{d_1}{2}\right)\right]\left[\left(\frac{d_2}{2}\right)^2 - \left(\frac{d_1}{2}\right)^2\right]}\right\}^n}$$

Then, Reynolds number will be calculating by following formula:

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

$$N_{Re} = \frac{4(2n+1)}{n}\left[\frac{\rho v^{(2-n)} \left(\frac{d_2 - d_1}{2}\right)^n}{\tau_y \left(\frac{d_2 - d_1}{2v}\right)^n + K \left(\frac{3n+1}{nC_a^*}\right)}\right]$$

If Reynold number is higher than critical Reynolds number, the flow regime is turbulent, otherwise it is laminar.

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

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

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

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

Laminar flow:

$$\Delta P_f = \frac{4K}{14400d}\left\{\left(\frac{\tau_y}{K}\right) + \left[\left(\frac{3n+1}{nC_c}\right)\left(\frac{8q}{\pi d^3}\right)\right]^n\right\}\Delta L$$

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

Turbulent flow:

$$f_c = \gamma (C_c N_{Re})^{-z}$$

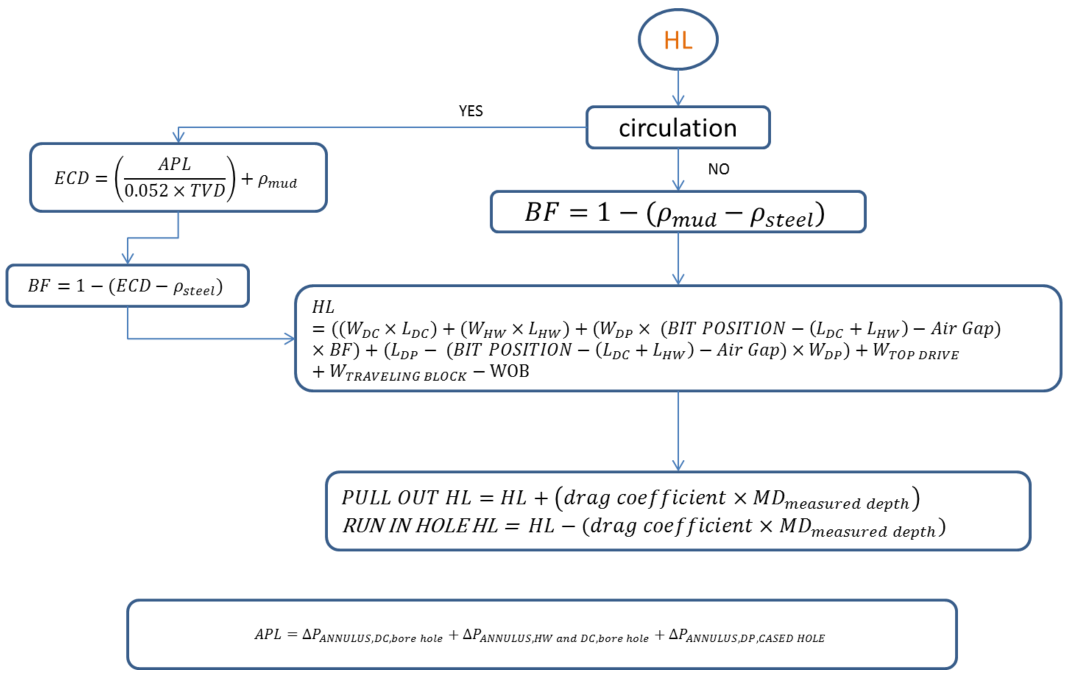
$$f_a = \gamma (C_a^* N_{Re})^{-z}$$

$$\Delta P_f = \frac{f_c \, q^2 \rho}{1421.22 d^5} \Delta L$$

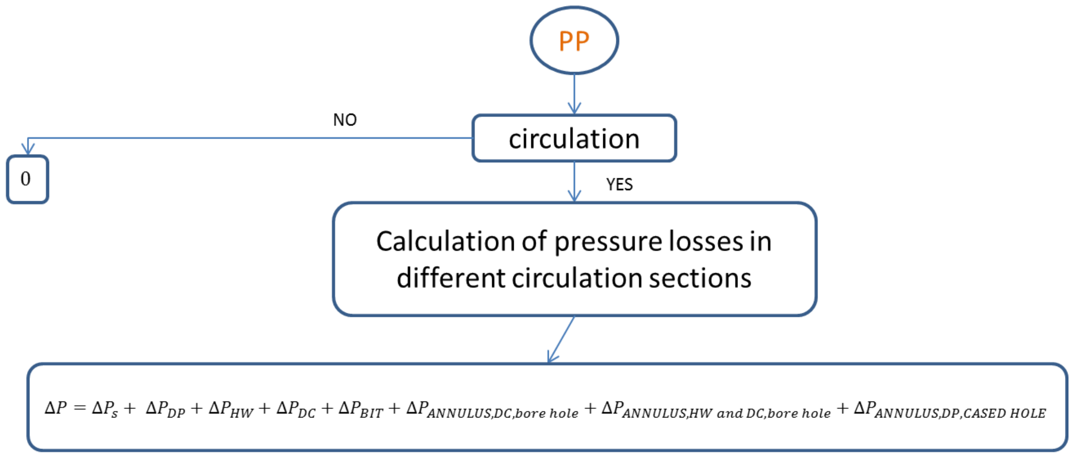
$$\Delta P_f = \frac{f_a \, q^2 \rho}{1421.22 (d_2 - d_1)(d_2^2 - d_1^2)^2} \Delta L$$

APPENDIX B. WORKFLOWS FOR CALCULATION OF DIFFERENT PARAMETERS

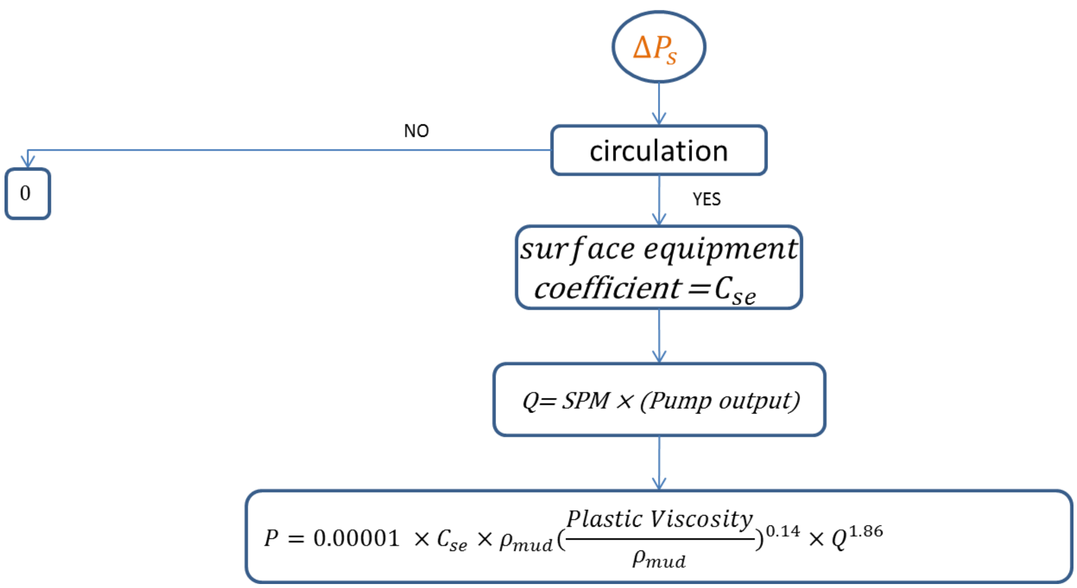
B.1 Hook Load Calculations

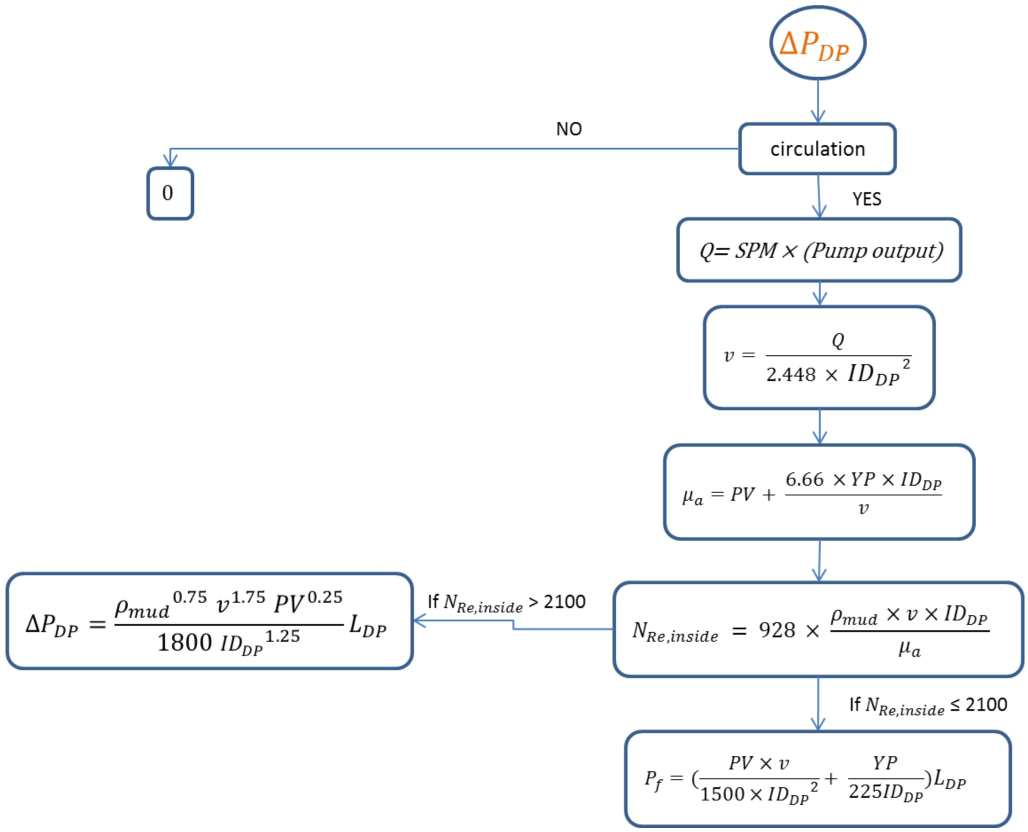


B.2 Pump pressure calculation workflow

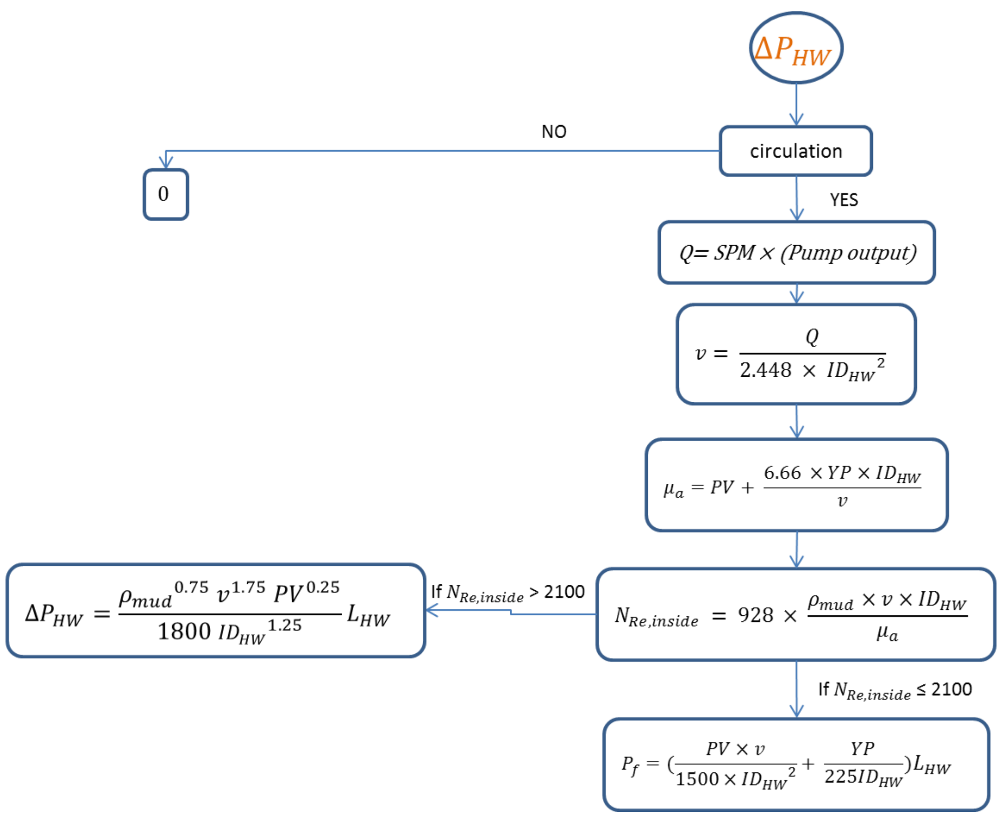


Procedure for calculation of pressure losses are explained in the next slides.

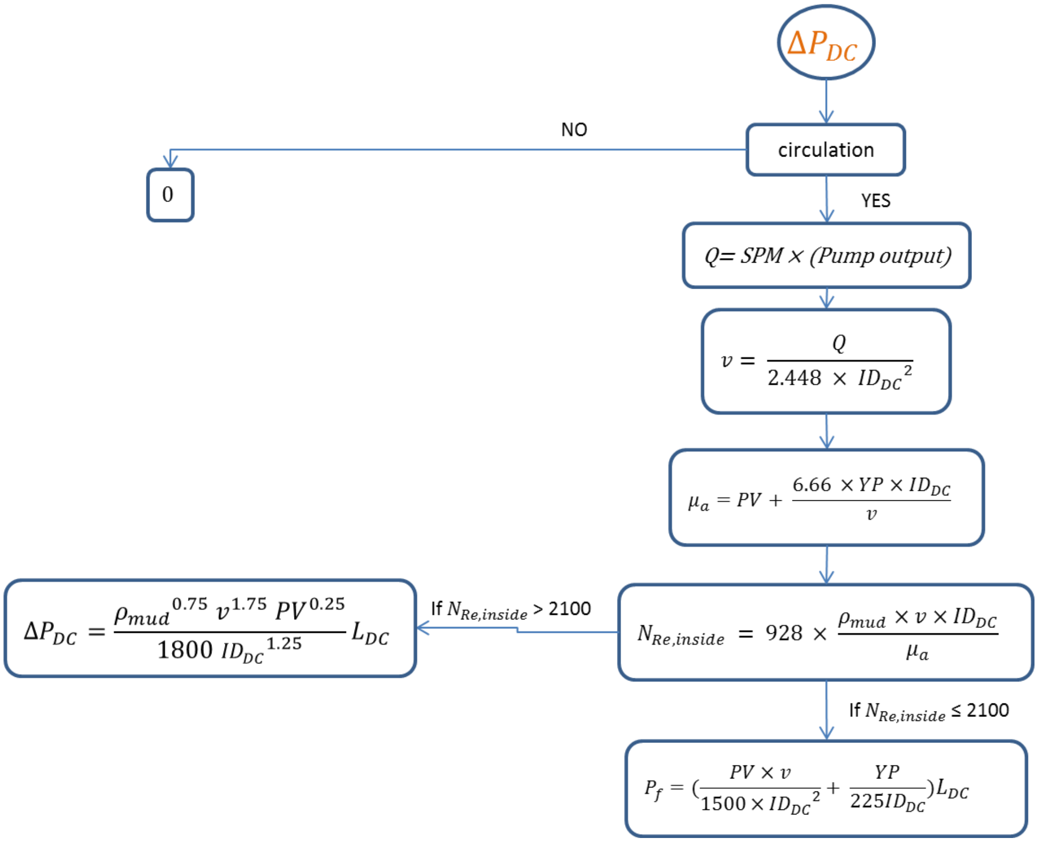


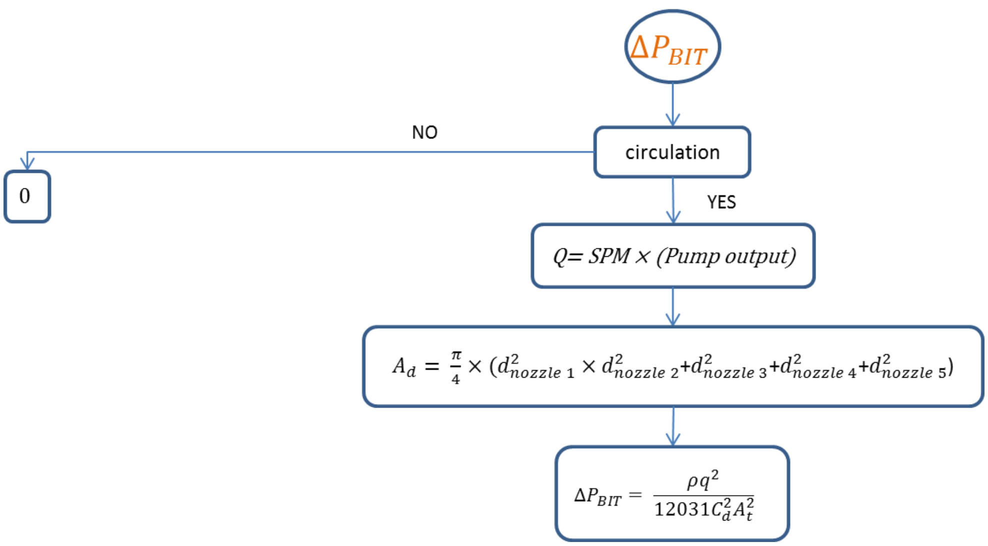


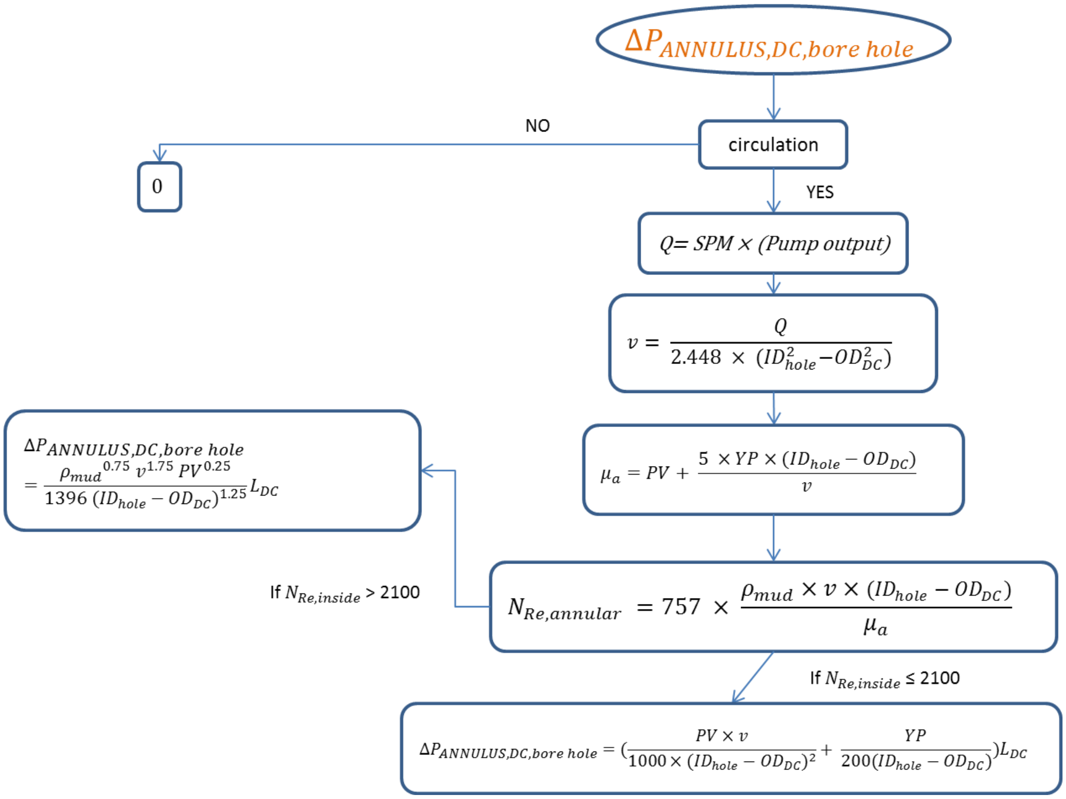
ΔP_{DP}
circulation
NO
0
YES
$Q = SPM \times (Pump\ output)$
$v = \frac{Q}{2.448 \times ID_{DP}^2}$
$\mu_a = PV + \frac{6.66 \times YP \times ID_{DP}}{v}$
$N_{Re,inside} = 928 \times \frac{\rho_{mud} \times v \times ID_{DP}}{\mu_a}$
If $N_{Re,inside} > 2100$
$\Delta P_{DP} = \frac{\rho_{mud}^{0.75} v^{1.75} PV^{0.25}}{1800\ ID_{DP}^{1.25}} L_{DP}$
If $N_{Re,inside} \leq 2100$
$P_f = (\frac{PV \times v}{1500 \times ID_{DP}^2} + \frac{YP}{225 ID_{DP}}) L_{DP}$



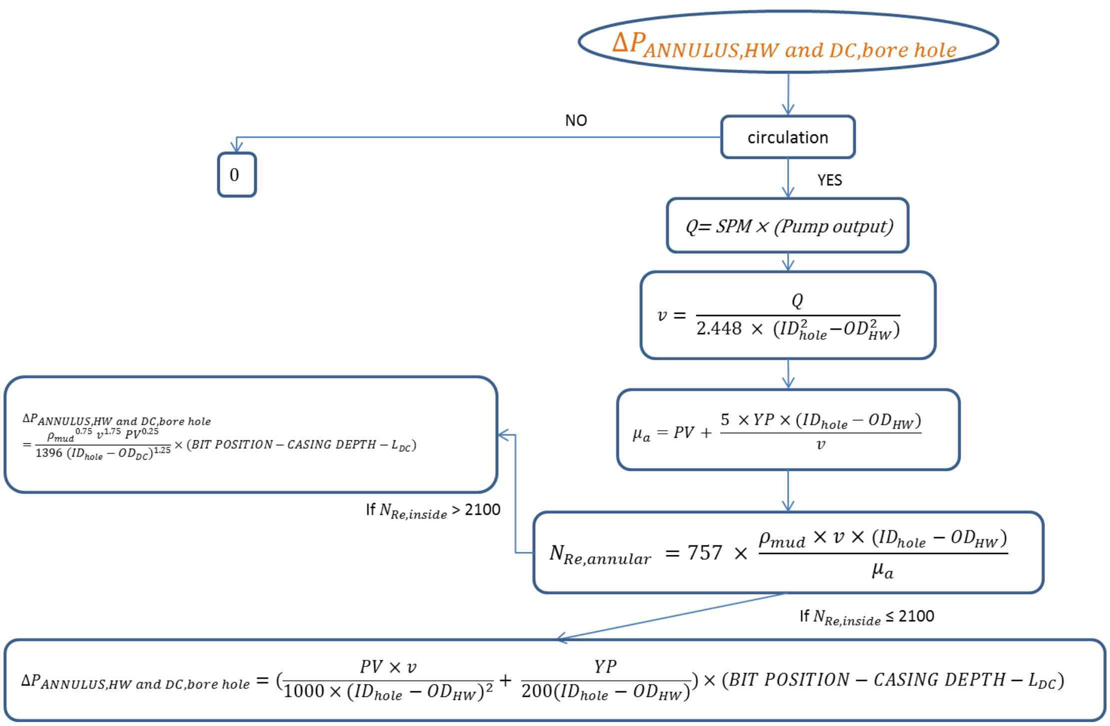
ΔP_{HW}
circulation
NO
0
YES
$Q = SPM \times (Pump\ output)$
$v = \frac{Q}{2.448 \times ID_{HW}^2}$
$\mu_a = PV + \frac{6.66 \times YP \times ID_{HW}}{v}$
$N_{Re,inside} = 928 \times \frac{\rho_{mud} \times v \times ID_{HW}}{\mu_a}$
If $N_{Re,inside} > 2100$
$\Delta P_{HW} = \frac{\rho_{mud}^{0.75} v^{1.75} PV^{0.25}}{1800\ ID_{HW}^{1.25}} L_{HW}$
If $N_{Re,inside} \leq 2100$
$P_f = (\frac{PV \times v}{1500 \times ID_{HW}^2} + \frac{YP}{225 ID_{HW}}) L_{HW}$


ΔP_{DC}
circulation
NO
0
YES
$Q = SPM \times (Pump\ output)$
$v = \frac{Q}{2.448 \times ID_{DC}^{2}}$
$\mu_a = PV + \frac{6.66 \times YP \times ID_{DC}}{v}$
$N_{Re,inside} = 928 \times \frac{\rho_{mud} \times v \times ID_{DC}}{\mu_a}$
If $N_{Re,inside} > 2100$
$\Delta P_{DC} = \frac{\rho_{mud}^{0.75}\, v^{1.75}\, PV^{0.25}}{1800\, ID_{DC}^{1.25}} L_{DC}$
If $N_{Re,inside} \leq 2100$
$P_f = (\frac{PV \times v}{1500 \times ID_{DC}^{2}} + \frac{YP}{225 ID_{DC}}) L_{DC}$

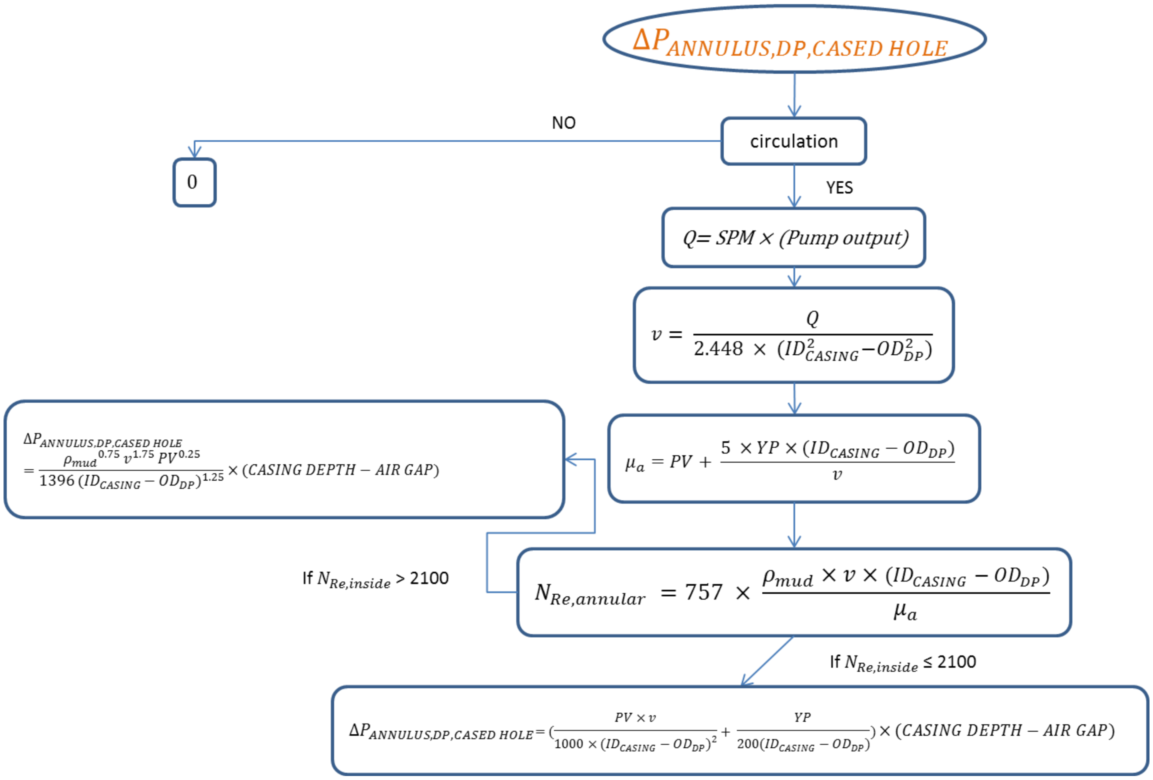

ΔP_{BIT}
circulation
NO
0
YES
$Q = SPM \times (Pump\ output)$
$A_d = \frac{\pi}{4} \times (d_{nozzle\ 1}^2 \times d_{nozzle\ 2}^2 + d_{nozzle\ 3}^2 + d_{nozzle\ 4}^2 + d_{nozzle\ 5}^2)$
$\Delta P_{BIT} = \frac{\rho q^2}{12031 C_d^2 A_t^2}$



$\Delta P_{ANNULUS,DC,bore\ hole}$
circulation
NO
0
YES
$Q = SPM \times (Pump\ output)$
$v = \frac{Q}{2.448 \times (ID_{hole}^2 - OD_{DC}^2)}$
$\mu_a = PV + \frac{5 \times YP \times (ID_{hole} - OD_{DC})}{v}$
$N_{Re,annular} = 757 \times \frac{\rho_{mud} \times v \times (ID_{hole} - OD_{DC})}{\mu_a}$
If $N_{Re,inside} > 2100$
$\Delta P_{ANNULUS,DC,bore\ hole} = \frac{\rho_{mud}^{0.75}\ v^{1.75}\ PV^{0.25}}{1396\ (ID_{hole} - OD_{DC})^{1.25}} L_{DC}$
If $N_{Re,inside} \leq 2100$
$\Delta P_{ANNULUS,DC,bore\ hole} = \left(\frac{PV \times v}{1000 \times (ID_{hole} - OD_{DC})^2} + \frac{YP}{200(ID_{hole} - OD_{DC})}\right) L_{DC}$



$\Delta P_{ANNULUS,HW\ and\ DC,bore\ hole}$
circulation
NO
0
YES
$Q = SPM \times (Pump\ output)$
$v = \frac{Q}{2.448 \times (ID_{hole}^2 - OD_{HW}^2)}$
$\mu_a = PV + \frac{5 \times YP \times (ID_{hole} - OD_{HW})}{v}$
$N_{Re,annular} = 757 \times \frac{\rho_{mud} \times v \times (ID_{hole} - OD_{HW})}{\mu_a}$
If $N_{Re,inside} > 2100$
$\Delta P_{ANNULUS,HW\ and\ DC,bore\ hole} = \frac{\rho_{mud}^{0.75}\ v^{1.75}\ PV^{0.25}}{1396\ (ID_{hole} - OD_{DC})^{1.25}} \times (BIT\ POSITION - CASING\ DEPTH - L_{DC})$
If $N_{Re,inside} \leq 2100$
$\Delta P_{ANNULUS,HW\ and\ DC,bore\ hole} = \left(\frac{PV \times v}{1000 \times (ID_{hole} - OD_{HW})^2} + \frac{YP}{200(ID_{hole} - OD_{HW})}\right) \times (BIT\ POSITION - CASING\ DEPTH - L_{DC})$


$\Delta P_{ANNULUS,DP,CASED\ HOLE}$
circulation
NO
YES
0
$Q = SPM \times (Pump\ output)$
$v = \frac{Q}{2.448 \times (ID_{CASING}^2 - OD_{DP}^2)}$
$\mu_a = PV + \frac{5 \times YP \times (ID_{CASING} - OD_{DP})}{v}$
$N_{Re,annular} = 757 \times \frac{\rho_{mud} \times v \times (ID_{CASING} - OD_{DP})}{\mu_a}$
If $N_{Re,inside} > 2100$
$\Delta P_{ANNULUS,DP,CASED\ HOLE} = \frac{\rho_{mud}{}^{0.75} v^{1.75} PV^{0.25}}{1396\,(ID_{CASING} - OD_{DP})^{1.25}} \times (CASING\ DEPTH - AIR\ GAP)$
If $N_{Re,inside} \leq 2100$
$\Delta P_{ANNULUS,DP,CASED\ HOLE} = (\frac{PV \times v}{1000 \times (ID_{CASING} - OD_{DP})^2} + \frac{YP}{200(ID_{CASING} - OD_{DP})}) \times (CASING\ DEPTH - AIR\ GAP)$

APPENDIX C. KILL SHEET OF OPERATION

Kill sheet:

DRILLMEC DRILLING TECHNOLOGIES WELL CONTROL CENTER

Exercise_Surface_1

INSTRUCTOR

INTERNATIONAL WELL CONTROL FORUM
BOP SURFACE KILL SHEET
VERTICAL WELL (kg/cm² Units)

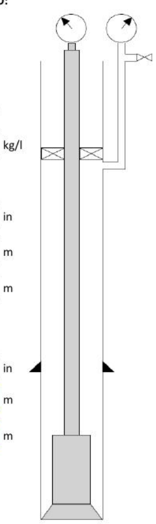
NOME: ____________________

DATA: ____________________

DATI FORMAZIONE SCARPA:

PRESSIONE DI LEAK-OFF IN SUPERFICIE	(A)	98	kg/cm²
DENSITA' FANGO AL TEST	(B)	1,1	kg/l
MASSIMA DENSITA' FANGO AMMISSIBILE:			
(A) X 10 / PROFONDITA' VERTICALE SCARPA + (B) =	(C)	1,91	kg/l
MAASP INIZIALE =			
((C) - DENSITA' ATTUALE) x PROFONDITA' VERT. SCARPA / 10 =		85,5	kg/cm²

DATI ATTUALI DEL POZZO:



DENSITA' FANGO ATTUAL	1,20	kg/l
DATI CASING E SCARPA:		
DIMENSIONE:	9 5/8	in
MD	1204	m
TVD	1204	m
DATI FORO:		
DIMENSIONE:	8 1/2	in
MD	1726	m
TVD	1726	m

CAPACITA' POMPA No.1	CAPACITA' POMPA No.2
16,35 litri/colpo	16,35 litri/colpo

DATI PORTATA RIDOTTA	PRESSIONE A PORTATA RIDOTTA (PL) kg/cm² POMPA No.1	POMPA No.2
30 colpi/min	13,2	13,5
40 colpi/min	21,1	20,8

DATI VOLUME PRE-REGISTRATI	LUNGHEZZA m	CAPACITA' l/m	VOLUME litri	COLPI POMPA colpi	TEMPO minuti
DRILL PIPE		x	=	VOLUME / CAPACITA' POMPA	COLPI POMPA / PORTATA RIDOTTA
HEAVY WALL DRILL PIPE		x	= +		
DRILL COLLARS		x	= +		
VOLUME INTERNO BATTERIA			(D) l	(E) 840 colpi	28,0 min
DC x FORO LIBERO		x	=		
DP/HWDP x FORO LIBERO		x	= +		
VOLUME FORO LIBERO			(F) l	670 colpi	22,2 min
DP x CASING		x	= (G) +	1862 colpi	62,1 min
VOLUME ANULARE		(F + G) = (H)	l	2532 colpi	84,6 min
VOLUME TOTALE IN POZZO		(D + H) = (I)	l	3372 colpi	112,4 min
VOLUME ATTIVO DI SUPERFICIE		(J)	l	colpi	
TOTALE SISTEMA FLUIDO ATTIVO		(I+J)	l	colpi	
LINEE DI SUPERFICIE			l	97	

Figure 44- Kill sheet, first page

DRILLMEC DRILLING TECHNOLOGIES
WELL CONTROL CENTER

INTERNATIONAL WELL CONTROL FORUM
BOP SURFACE KILL SHEET
VERTICAL WELL (kg/cm² Units)

NOME: ____________________

DATA: ____________________

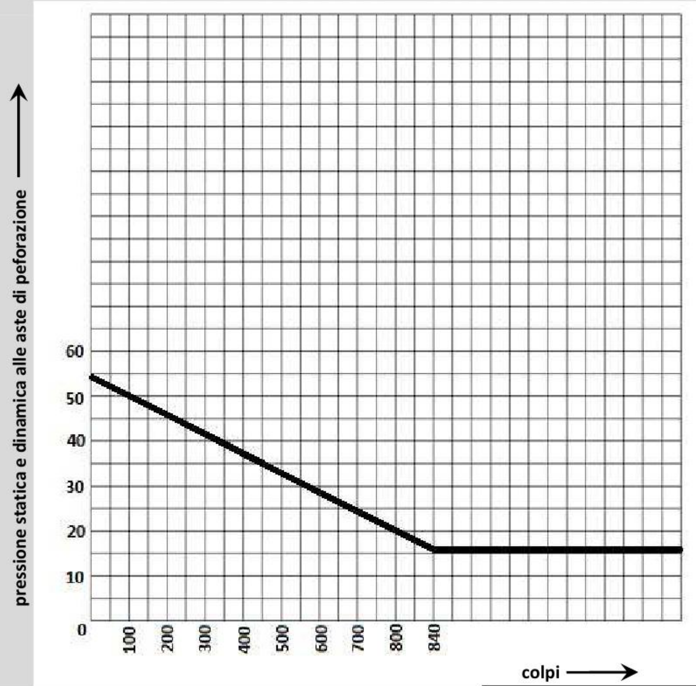
DATI DEL KICK: SIDPP: 41,1 Kg/cm² SICP: ____ Kg/cm² AUMENTO VOLUME IN VASCA ____ litri

DENSITA' FANGO PESANTE **KMD**	DENSITA' FANGO ATTUALE + $\frac{10 \times SIDPP}{TVD}$ = 1,2 + $\frac{10 \times 41,1}{1726}$ = 1,44 kg/l
PRESSIONE INZIALE DI CIRCOLAZIONE **ICP**	PRESSIONE A PORTATA RIDOTTA + SIDPP = 13,2 + 41,1 = 54,3 kg/cm²
PRESSIONE FINALE DI CIRCOLAZIONE **FCP**	$\frac{\text{DENSITA' FANGO PESANTI}}{\text{DENSITA' FANGO ATTUALE}}$ x PRESSIONE A PORTATA RIDOTTA = $\frac{1,44}{1,2}$ x 13,2 = 15,8 kg/cm²

(K) = ICP - FCP = 54,3 - 15,84 = 38,5 kg/cm²

$\frac{(K) \times 100}{(E)}$ = $\frac{38,5 \times 100}{840}$ = 4,58 $\frac{kg/cm^2}{100\ colpi}$

COLPI	PRESSIONE kg/cm²
0	54,30
100	49,72
200	45,14
300	40,56
400	35,98
500	31,40
600	26,82
700	22,24
800	17,66
840	15,82



Firma:

Figure 45-Kill sheet, second page

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