Effects of Drill String Movement and Changes in PDC Bit Geometry on Mud Flow Behavior

By

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CERTIFICATION OF APPROVAL

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A project dissertation report submitted to the
Petroleum Engineering Program Universiti Teknologi PETRONAS
In partial fulfillment of the requirements for the
Bachelor of Engineering (Hons) Petroleum Engineering

Approved

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JANUARY 2015 SEMESTER

CERTIFICATION OF ORIGINALITY

I hereby confirm that this project is my own original work and responsibility. Furthermore, all the report work is my own unless other authors are stated in the references. Project work that was done and written in this report had been done by me not by any unspecified people or sources.

…………………………….

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ABSTRACT

Drill bit is the most pivotal component of the bottom-hole assembly and a successful hydraulic design of it will confidently contribute to an efficient drilling performance with a better cuttings transport especially at the downhole zone. That could be achieved by a combination of managing pressure drop and flow rates across the drill bit.

In this project, Computational Fluid Dynamics is used in the form of ANSYS CFX Simulation to investigate the effect of changing geometry for PDC (Polycrystalline Diamond Compact) bit on the drilling fluid flow behavior in terms of pressure drop and velocity trends. Additionally, the bit rotational movement effect is simulated for different RPM and different inlet velocities to study the effect of the movement on pressure drop of the system.

Six different PDC bit geometries were created to achieve the objective of the project and different rotational speeds were used ranging from 10 RPM to 110 RPM and compared with the stationary condition of the bit.

Results showed that changing geometry has a significant effect on pressure drop and velocity profile. Fluid rheological properties played an important role in influencing the hydrodynamic properties as the simulation was conducted using Water, Foam of 90% quality, and Herschel-Bulkley fluid with the different geometries. Highest pressure drop was observed with the Herschel-Bulkley fluid followed by Foam and then Water. The result proved that increasing either RPM or inlet velocity will always lead to increased pressure drop which is due to the more faced resistance and lost pump energy.

CHAPTER 1

INTRODUCTION

1.1 Background

Time considerations are very important in the drilling and exploration industry and reducing drilling and tripping time which will have a significant impact on the total well cost. That can be achieved by avoiding any delay caused by mechanical issues, slow rate of penetration, or a problematic cutting transport behavior at the bottom-hole. Therefore, a special attention is given to bit hydraulic design of drill bits since drilling is always preferred to be run at a cost reduced and time efficient manner. Quite a number of studies and research have been carried out to enhance the hydraulic performance of drill bits through improving the design, and understanding the drilling mud behavior around the bit.

According to Smith International Inc. (Drill bit manufacturer), there are multiple types of drill bits depending on the application in the oil field. However, they are mainly divided into two big categories as shown in **FIGURE 1**: Roller cone or Fixed head drill bits. Fixed head bits such as PDC bit which is the most popular tool used in drilling to shear the rock with its continuous scraping rotation with no separately moving parts like its roller-cone counterpart for different applications. PDC bits have been used for oil and gas drilling since their first production in 1976 with increased popularity which resulted in tremendous technological studies for bit improvements. However, a lot more design enhancements are needed to achieve more economical and operational goals in mud flow/wellbore cleaning and multilayer drilling.

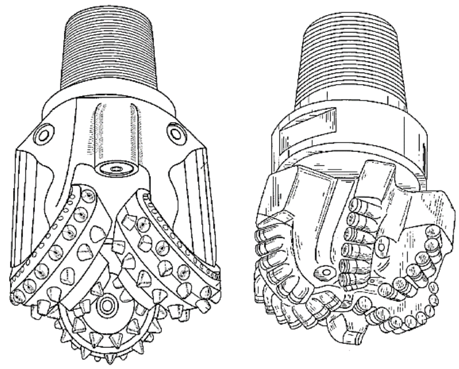


FIGURE 1**.** Roller cone bit shape vs. fixed head PDC bit shape (Smith International)

The whole mud circulation process should be looked at from different perspectives that are associated directly with the success of the drilling such as the mud viscosity/rheological model and how fast and smoothly could be transported at the lower portion of the drill string. The mud behavior directly affects carrying the cutting, cleaning the hole and cooling down the bit cutters.

A successful bit hydraulic system can be achieved by a combination of pressure drop and flow. Therefore, a fair understanding of flow distribution around bit and pressure drop trends will determine the areas that need improvements in the bit design. Improvements can be made by doing some geometric modification with considering factors like the movements of the drill string [8].

Numerical Simulations for innovative PDC bits designs were performed before field experimentation to improve the overall performance of PDC bits for Changbei Gas Field in China [1]. Computational Fluid Dynamics (CFD) software such as ANSYS has been used to simulate the drilling mud behavior such as velocity trends like shown in **FIGURE 2.** The use of CFD algorithms enables the investigation process to almost visualize the real drilling operation.

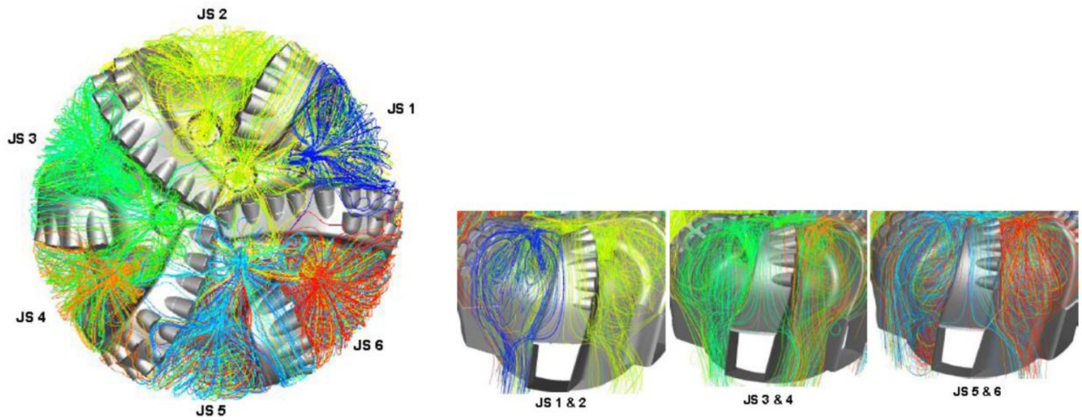


FIGURE 2. The use CFD simulation to improve PDC bit design, Changbei Gas Field, China

While drilling a well, both drill string and the whole bottom hole assembly make a number of full rotations per minute. These different rotational speeds need to be considered when doing a CFD simulation to be more realistic about the actual drilling operation.

1.2 Problem Statement

There are no systematic known method to measure or calculate the numerical or experimental value of PDC bit hydraulics after changes in the bit geometry. Availability is limited for PDC bit solid geometry that can undergo modifications or CFD simulation model that could be used for investigation and analysis.

1.3 Objectives

- To develop CAD models of 6 alternative PDC bit geometries.
- To investigate the effect of PDC bit geometric change on the mud flow behavior.
- To investigate the effect of rheological properties on pressure drop.
- To simulate the effect of drill string rotation on pressure drop.

1.4 Scope of Study

The scope is limited to:

- CAD Modelling of 6 different PDC bit geometries.
- Hydrodynamic simulation of the flow.

- Conducting the simulation using different rheological models such as water, Foam of 90% quality and Herschel-Bulkley Fluids.
- Rotational Speeds applied are 10,30,50,70,90,110 RPM only

The work doesn't include cutting transport or simulation or any change in the junk slot area other than the created geometries. Additionally, high temperature and high pressure conditions are not considered.

CHAPTER 2

LITERATURE REVIEW

2.1 PDC Bits development

Every part of the drilling rig is assisting the drill bit to crush the rock formation and penetrate the subsurface layers to extract hydrocarbons. It is always in contact with the rock formation and such a component must be equipped with other tools and subs at bottom-hole assembly (BHA). The assembly will have a certain rotational speed to help the bit teeth to scrap or crush the formation [4, 5]

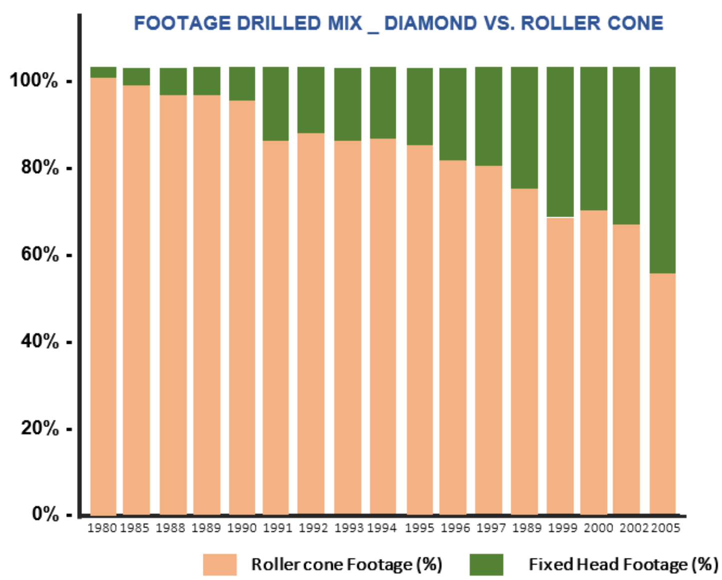


FIGURE 3. Increased reliability of fixed head cutters over years, Oil and Gas Journal Courtesy

According to Oil and Gas Journal in the article (Roller Cones vs. Diamonds: A Reversal of Roles, 2006) PDC bits are four times more costly than roller cone bits. Therefore, the choice of bit type contributes to how economical the drilling operation and performance will be and the reliability on PDC bit is increasing by years as shown in **FIGURE 3.**

To meet this criteria, PDC drill bit must justify its additional cost by increasing the rate of penetration or by staying longer in the hole without being replaced for longer drilling time. Fixed cutter bits has no moving parts and they can drill for longer time than roller cone bits. PDC bits is the major type of fixed head bits. They have a diamond dusk attached on a tungsten carbide stud. They are famous for drilling as fast as 100 ft. /hr. and for great distances [5].

PDC bits' steer-ability has also improved due to design and cutter innovations, further eroding the old advantage of roller cones in motor applications. It's a simple fact. PDCs are supplanting roller cones in many formation applications on a daily basis [6].

2.2 Bit Hydraulic Design Objectives

The main objectives of any bit hydraulic design are to rapidly transport the mud into the annulus, cool down the cutters and keep the body of the bit clean. Higher WOB or higher RPM can increase the rate of penetration which is desired by the operator to reduce the drilling time but it will as well affect the lifetime of the bit [6]. **FIGURE 4** shows an example of the drilling mud streamlines in a PDC bit which carry along the cuttings to the surface simulated using computational fluid dynamics.

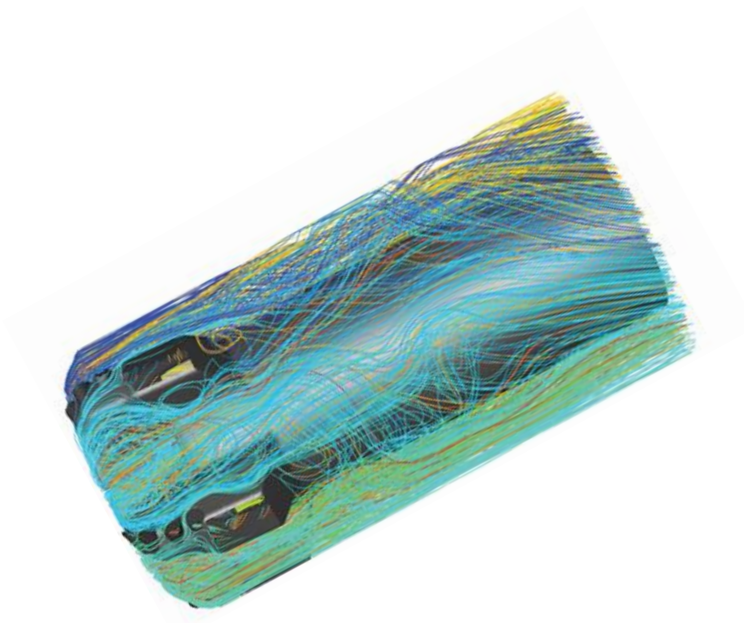


FIGURE 4. Drilling mud keeps bit cutters cool and transport cuttings, Drilling Contractors

Drilling time is very important since it is very costly (150$k per day for offshore) and around (30k$) for a land rig. However, higher ROP can cause the PDC bit to wear faster which will make it a dull bit in a shorter period of time and here comes the importance of the Drilling hydraulic optimization to make the bit drill the longest period of time with a high ROP [4].

Design criteria of drill bits is what influences the bit hydraulics as modifying the bit profile and distribution of nozzles will lead to effective hydraulic utilization which will maximize the drilling performance [7].

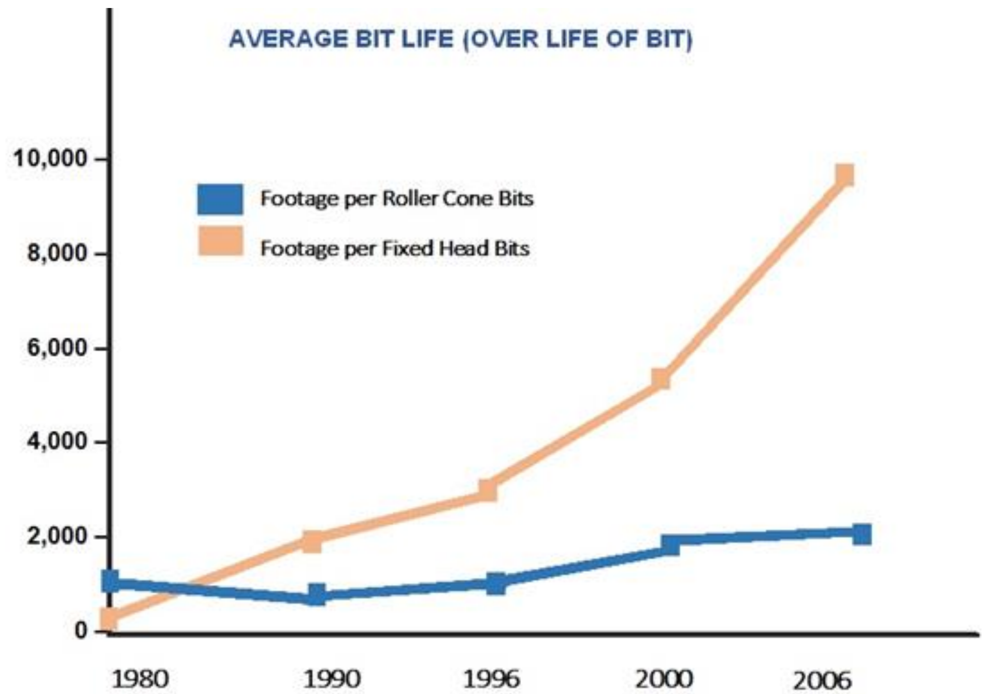


FIGURE 5. Average bit life for different depth along the years, Oil and Gas Journal Courtesy

FIGURE 5 shows that Diamond bit footage (over the life of a bit) took off rapidly in 1996 due to the growing rental/repair of PDCs. Roller cone footage drops in 2000 because softer, longer runs with roller cones were taken over by PDCs, leaving roller cones to drill harder formations more likely to produce shorter runs.

2.3 Drilling mud rheological properties

The behavior of the mud is the main contributor to a successful drilling. Therefore, studying the mud rheology is important. The mud's rheological model is described by the relationship between its shear stress and shear rate. Newtonian fluids like water would follow Newton's law of viscosity which is also called Newtonian model because the shear rate is directly proportional to the shear stress. However, the drilling mud are non-Newtonian so the previous model doesn't apply on it. The description is complex that there are several rheological models that can precisely describe the characteristics of the drilling mud such as Herschel Bulkley [5].

A. **Water**

Newtonian fluid with a density 999.97 kg/m³ and molar mass of 18.01528 g/mol. The relationship between the shear stress and shear rate is linear as shown in Figure 7.

B. **Foam**

Foam is formulated when water, surfactants, and air are combined to create such a stiff foam. The foam is then circulated as a drilling fluid. It's believed to have an excellent carrying capacity with some limitations and it behaves like a non-Newtonian fluid and it's used in underbalanced drilling operations [9-5]

C. **Herschel Bulkley Model**

The Herschel–Bulkley fluid is a generalized form of the non-Newtonian fluid where the strain experienced by the fluid is related to the stress in a complicated. As shown in **FIGURE 6** the fluid need to achieve a minimum value of stress called yield stress. The relationship is non-linear where 3 parameters characterize this relationship which are the yield shear stress, the flow index *n*, and consistency *k* [9].

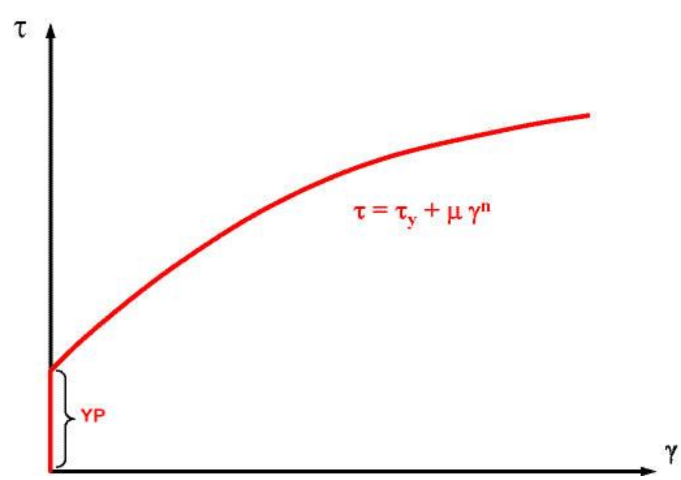


FIGURE 6. Shear stress / shear rate relationship in Herschel Bulkley Model, Drilling Contractors

In 2004, Souza Mendes and Dutra (SMD) developed a viscosity function that is free of discontinuities for Power Law fluids for highly shear thinning fluids. This model is convenient for numerical simulations as it has continuous derivatives.

The right choice of the drilling mud would make the simulation more accurate that is close to the real case during drilling.

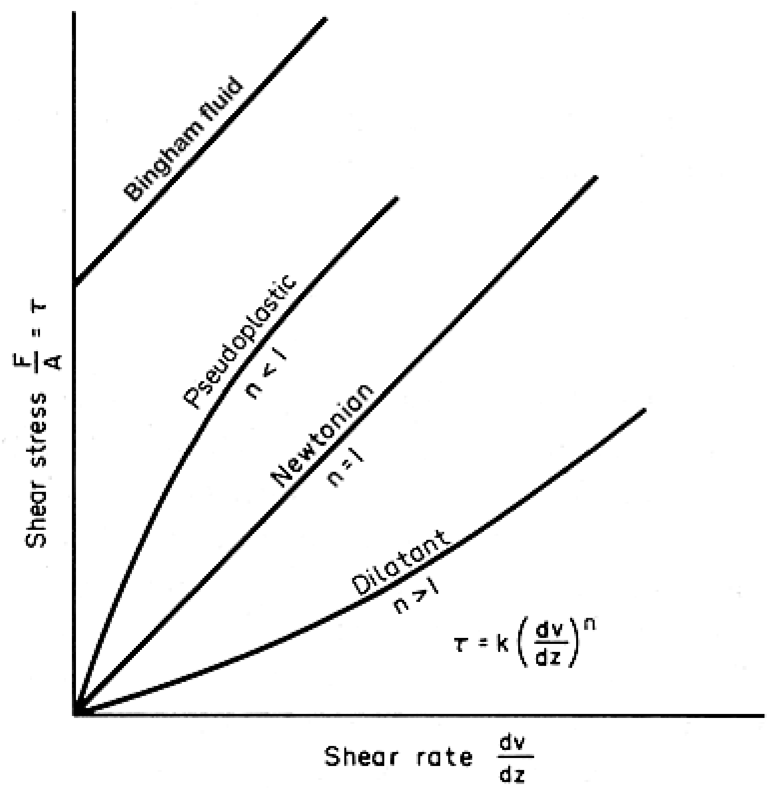


FIGURE 7. Shear stress vs. shear rate for majority of rheological models, Drilling Contractors

Design falls of bit would cause troubles such as accumulation of cuttings if not transported fast or balling. A balled-up bit has an almost equal diameter to the borehole diameter where the action of tripping the pipe out of hole will behave like a piston. Fluid is sucked in from the formation below the bit if mud cannot fall in the hole and displace the pipe as fast as it is being pulled. Lower part of the formation has always been abrasive and very hard like quartz sandstone which will have a high pressure as 26,000 psi which will affect bit durability and directional drilling [7]

The author [1] claimed that the operator of the Changbei gas field in China experience a series of transitional formations with different rock stability at the upper sections of the wells which affect the stability of the bit due to the imbalance forces that are created that will lead to downhole vibrations. It could be enhanced by laying out the cutters of the bit so that the lateral forces are balanced. Middle parts has always been the soft clay stone which will cause the PDC bit to experience balling which will reduce the ROP.

2.4 CFD based Investigation of PDC bit

CFD is computational fluid dynamics which is a well-known and validated tool which is used on a wide scale to investigate the fluid flow in very diverse applications such as F1 racings and filtration systems. It is often used to replace the experimental testing and it's famous for being able to quickly and economically produce a lot of information about the fluid flow when experiment is hard to make or not feasible .CFD simulation was used to model PDC bits before but on a limited manner since it will require a lot of time and investment to produce accurate information that could replace the real experiment. The complexity of meshing and computer becomes an obstacle even when using super computers [2].

The optimized design of the improved shows lower velocity which is good to avoid erosion of the blades but it should also be fast enough to transport the cuttings. An improved drill-bit design should consider so many goals such as optimizing the tool to consider the formation challenges. Using computational hydraulics software is also effective in improving the bit Hydraulics. Improvements in the cutter technology can increase the resistance of the bit without experiencing impact resistance. The study claimed that after optimizing PDC drill bit using CFD simulation it resulted in 12% greater depth of the well with a faster 15% ROP than the nearest offset well in the Changbei field well 22. Other wells showed improvements as 63% greater depth with same ROP which shows higher durability of the PDC bit [1].

FIGURE 8 shows an example of fluid simulation using ANSYS-FLUENT is particle tracking simulation method could be used to investigate the transportation of cuttings from the drill bit to the annulus by modeling the evacuations, spherical particles with a ranging diameter from .1 to 10mm. The particles were injected at the bottom-hole to the surface. The range of particle diameters were chosen to represent the real case of drilling. The study considered water as a flowing material which is a Newtonian fluid instead and it considered a stationary BHA [3].

According to [10] evaluation of bottom-hole flow of the mud through a bi-center bit was achieved using ANSYS FLUENT based on considering the geometry of the bit and considering boundary conditions. The simulation showed some characteristic analysis of the bit flow field, influence of the distribution between the reaming and piloted sections of the bi center bit. The study also shows the influence of the nozzle spray angle on the fluid flow in the bit. The study concluded that using FLUENT to do a hydraulic analysis to propose new design.

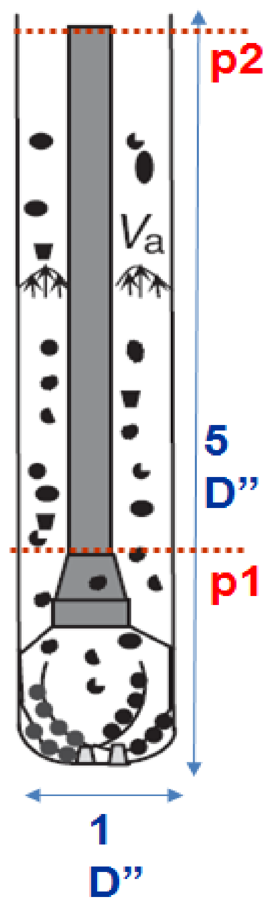


FIGURE 8. Particle tracking simulation method for PDC bits

2.5 Summary

The literature review was a great tool to understand and get an insight about PDC bit developments and previous numerical simulations that was done in this field. The literature also showed how effective is CFD in improving PDC bit. For more details about the literature, please refer to **Appendix -1**.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology is the process followed to achieve the objectives of this study that are listed in section 1.3 using ANSYS CFX. The flow chart for the project methodology is as shown in **FIGURE 9** followed by the details behind the main activities. Additionally other information such as 'Gantt Chart' and 'Study Milestones' are attached in **Appendix 2** and **Appendix 3**.

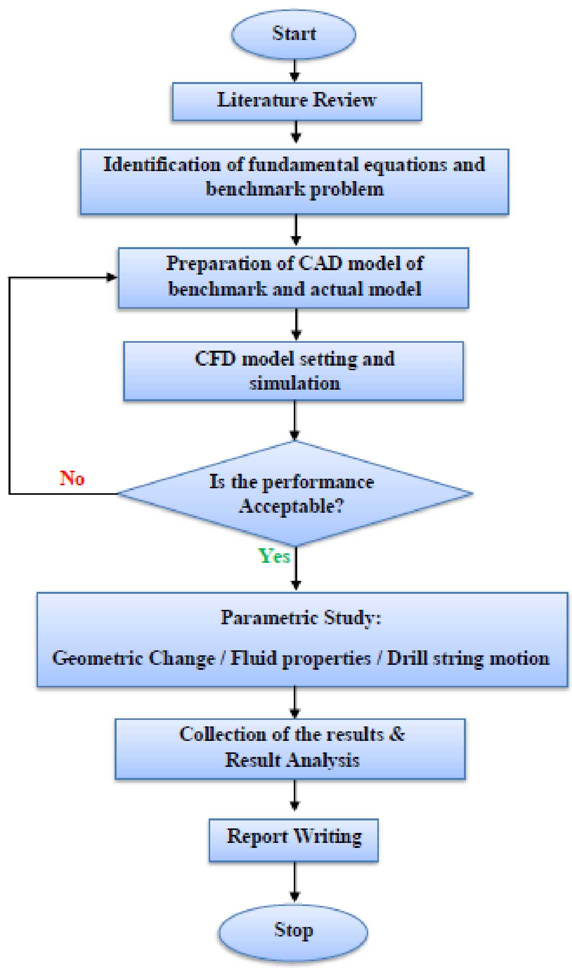


FIGURE 9. Project Flow Chart

3.1.1 Literature Review

At this point of the project different recourses were used to obtain knowledge about PDC bit different features and previous simulation attempts that were done trying to improve the performance of it. The literature is to evaluate these information, describe and summarize it in a way that it could benefit this project. Fluid properties, PDC geometry, drill string motion, and CFD simulation studies are considered are the main points of this literature review.

3.1.2 Identification of fundamental equations and benchmark problem

A benchmark problem is chosen that was done before using ANSYS CFX which is about CFD analysis of viscous non-Newtonian flow under the influence of a superimposed rotational vibration [11]. This benchmark problem was particularly selected because it was made using the same software and code with variety of rheological models and for simplicity. The selected part from the results was validated and it's shown in this document.

- **Navier-Stokes Equation**

To solve any fluid problem, the physical properties of the fluid should be determined implementing fluid mechanics. Navier-Stock equation and it is governing equation of CFD (the continuity, momentum and energy equation) can be used to describe the physical properties of the fluid mathematically applying the conservation law of physical properties of fluid.

- **Continuity equation**

Mass conservation is the physical principle of continuity equation, where the rate at which mass entering the system is equal to the rate at which mass leaving the system assuming isothermal flow condition, for the fluid phase the equation can be expressed as follow:

$$\frac{\partial \rho_l}{\partial t} + \nabla \cdot (\rho_l v_l) = 0$$

- **Benchmark problem setting up**

The selected benchmark problem was validated according to the following set up:

1) Geometry: A cylindrical pipe with a diameter of 4mm X 6mm length as shown in **FIGURE 10.**

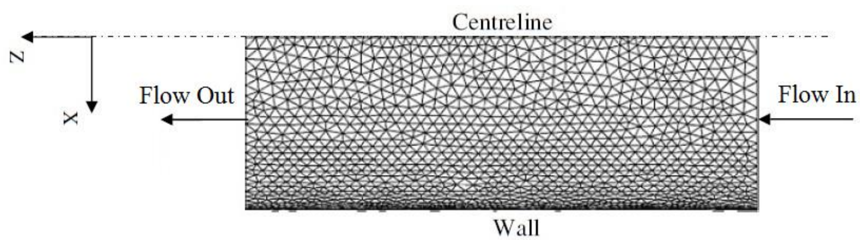


FIGURE 10. Geometry of the benchmark problem

2) Fluid Type:
   Non-Newtonian fluids were chosen which are Bingham Plastic and Herschel Bulkly with the following rheological properties:

TABLE 1. Fluid Properties for benchmark problem

Parameters	**Symbol**	**Unit**	**Bingham plastic**	**Herschel-Bulkley**
Yield Stress	τ_o	Pa	1, 3, 5	1, 3, 5
Flow consistency index	K	Pa/s	1.0	1.47
Fow behavior index	n	-	-	0.56
Density	ρ	kg/m3	1000	1000
Dp/L		kPa m-1.	9.81	9.81

3) Pipe Rotation: The validation was made for the stationary pipe with no rotation
4) Solver Control: ANSYS CFX was used with application of steady state flow.

TABLE 2. Solver options set up for benchmark problem

Parameter	**Unit**	**Value**
Maximum No. Iterations	-	500
Residual Target	-	1*10^-6
Inlet Pressure	Pa	58.86
Outlet Pressure	Pa	0

For the benchmark problem, geometry is created using ANSYS and meshed to prepare for the set up for simulation. Non-Newtonian fluid such as Bingham Plastic and Herschel-Bulkley are used for validation.

3.1.3 CAD Models creation and CFD Simulation

This is considered the backbone of the project which is creating 6 different geometries for PDC bits and modeling the fluid flow through them.

3.1.4 Parametric Study

Change on the models are done many times and recording the result is obtained by trying different bit geometries, inlet velocities and changing rotational speeds and observing velocity profiles and pressure drops.

3.1.5 Further Analysis and Report Writing

After all the previous work, further analysis on the findings should be made and be explained in a report form.

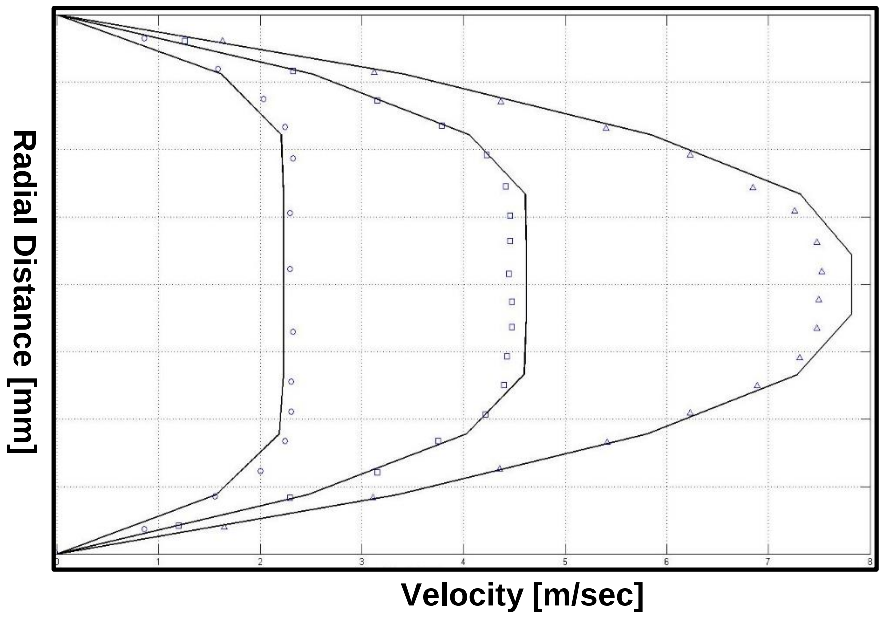
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Benchmark Problem

Computational Fluid Dynamics is a widely used and trusted tool in several fields of engineering to predict fluid flow in a certain domain. In this project, ANSYS WOKRBENCH and ANSYS 15.0 CFX are used to validate the results of the benchmark problem and to be used to investigate the mud flow behavior after considering the drill string movements and geometric modifications.

By tracking the flow velocity of the flow for each case with the radial position of the pipe (Diameter 4mm) the following results are obtained and it's compared on the same chart with the results obtained by M. Eesa for Bingham Plastic Rheological Model as in **FIGURE 11.**



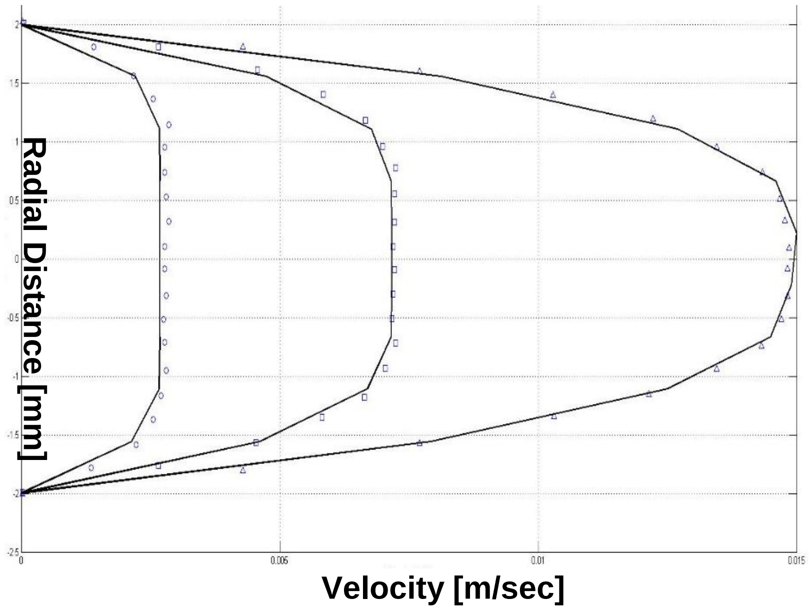
Experimental Value at $T_{0}= 1Pa$ ——— △ **Obtained Value at** $T_{0}= 1Pa$

Experimental Value at $T_{0}= 3Pa$ ——— □ **Obtained Value at** $T_{0}= 3Pa$

Experimental Value at $T_{0}= 5Pa$ ——— ○ **Obtained Value at** $T_{0}= 5Pa$

FIGURE 11. Benchmark Problem Validation (Velocity Profile, Bingham Plastic)

It could be noticed that the obtained result after simulation is matching with the original results of the benchmark problem with a very slight difference that could be noticed in the graph. The following is the original comparison between experimental value and CFD simulation by M. Eesa. Following the same procedure for Herschel-Bulkley and here is the result obtained. The values of velocity magnitude matches with the values from the benchmark problem



Experimental Value at T_{0}= 1Pa — **Obtained Value at** T_{0}= 1Pa
Experimental Value at T_{0}= 3Pa — **Obtained Value at** T_{0}= 3Pa
Experimental Value at T_{0}= 5Pa — **Obtained Value at** T_{0}= 5Pa

FIGURE 12. Benchmark Problem Validation (Velocity Profile, Herschel–Bulkley)

The results shows a good match with the experimental value.

4.2 Geometry Creation of the bit

Six different geometries were created locally using ANSYS Geometry Drawing and they are with different profile and gauge orientations. The geometries are shown in **FIGURE 13** and the description is provided in **TABLE 3.**

FIGURE 13. Different PDC bit designs that were created for simulation using ANSYS

TABLE 3. PDC Bit design descriptions

Design	Design Description	Code	Remarks
1	Concave Design with straight gauge	R1C1	Without Cutters
2	Concave Design with spiral gauge	R1C2	Without Cutters
3	Double Cone Design with straight gauge	R2C1	Without Cutters
4	Double Cone Design with spiral gauge	R2C2	Without Cutters
5	Parabolic Design with straight gauge	R3C1	Without Cutters
6	Parabolic Design with spiral gauge	R3C2	Without Cutters

4.3 Meshing of the model

For the 6 different geometries, the mesh slightly varies because of the geometry change using tetrahedral grids with inflation layers created near wall regions and nozzles to resolve the meshing around the near wall region and accurately capturing the flow effects in that region after that a mesh independence study was made to choose the right mesh that will be accurate and economical, refer to **FIGURE 14.**

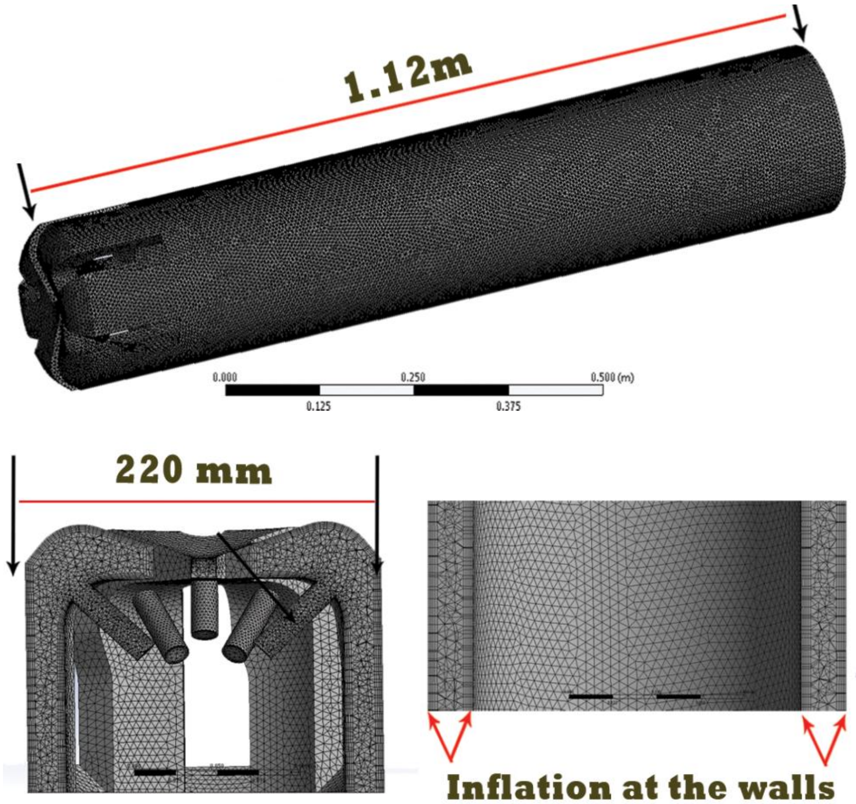


FIGURE 14. Mesh, dimensions of the fluid model, and inflation at the walls and nozzles

Inflation could also be shown at the following figure to make sure the calculation is more accurate and representative of the case

4.3.1 Grid independence study

Mesh independence study was worked to optimize the number of elements in the mesh to reduce the simulation time without affecting the results of the simulation. It was achieved using Geometry R1C1 and water as the flowing material and tracking pressure drop.

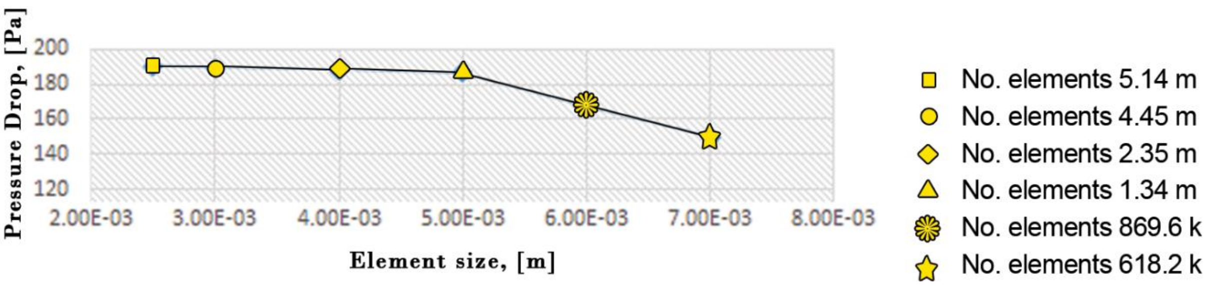


FIGURE 15. Mesh Independence Study

The used element size is 5.00E-03 for all the geometries and the following table shows an approximate number of elements for each model and these values were used throughout the whole project.

TABLE 4. Mesh Summary

Geometry	No of elements
R1C1	1.34 million
R1C2	1.42 million
R2C1	1.34 million
R2C2	1.42 million
R3C1	1.41 million
R3C2	1.44 million

4.4 PDC Bit Preliminary Simulation Results

Preliminary simulation results shows the velocity, Figure 16 shows an isometric view of velocity streamline of the drill bit and where it is observable how the velocity decreases from the inlet of the nozzles all the way to the annulus and to the outlet when simulating for non-Newtonian fluid (Water) as the drilling fluid for the base case with R1C1 geometry.

Base Case Details:

Fluid: Water Inlet Velocity: 5 ft. /sec Outlet Pressure: 0 Pa

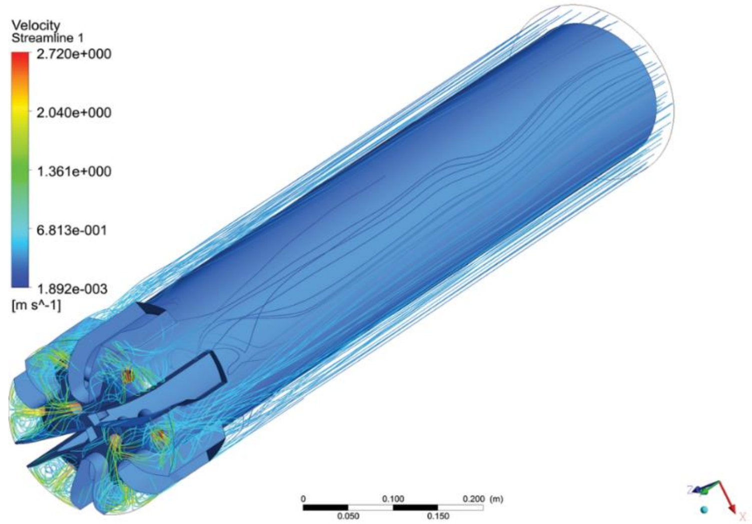


FIGURE 16. Velocity Streamline into PDC bit (Water, 5 [ft. /sec])

The following streamline represents the drilling mud streams through the nozzle and around the bit body which is the most critical place. That is the velocity streamlines when the material used is water. However when using other fluid properties the values will change and that will be shown for other rheological models and geometric models.

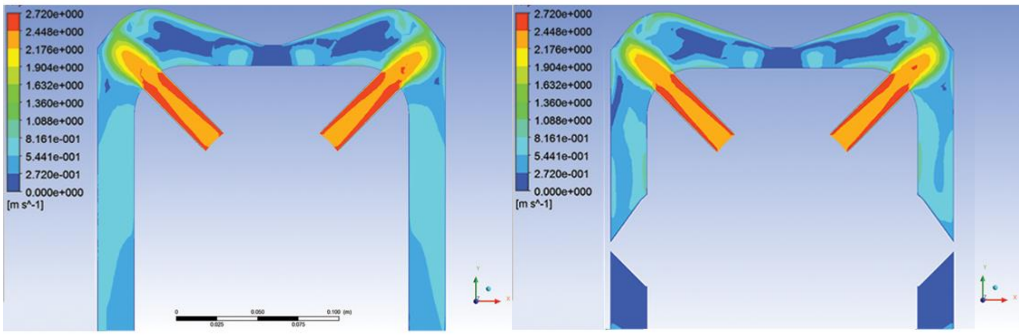


FIGURE 17. Velocity contours into Concave PDC bit geometries with Straight/Spiral gauge (Water, 5ft. /sec)

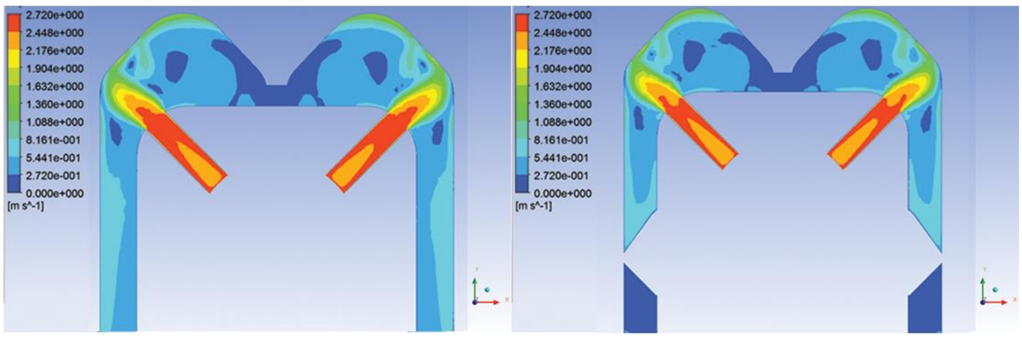


FIGURE 18. Velocity contour into double cone PDC bit geometries with Straight/Spiral gauge (Water, 5ft. /sec)

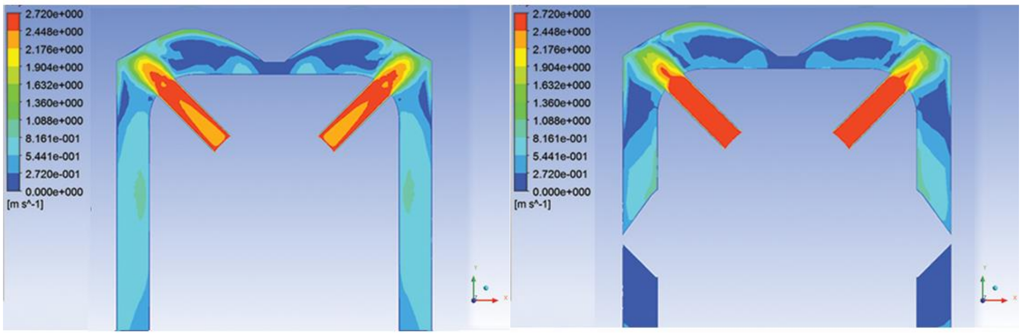


FIGURE 19. Velocity contour into Parabolic PDC bit geometries with Straight/Spiral gauge (Water, 5ft. /sec)

The result showed different velocity trends with changing the geometry which could be seen in Concave, Double Cone, and Parabolic geometries for both straight and spiral profiles.

4.5 Geometry change effect on the pressure drop

For the current time being, the pressure drop across the drill bit was measured with response to the changes in PDC Bit geometry. After running simulation for different inlet velocities and different rheological models such as water, foam, and Herschel Bulkly models. Different behaviors were observed in terms of pressure drop .The results extracted are shown in the following tables:

4.5.1 Water pressure drop in the different geometries

From the obtained results in the case of water which behaves like a Newtonian fluid, it could be observed that by gradually increasing the inlet velocity from 2 ft. /sec until reaching 8 ft. / sec will increase pressure drop specially in the double cone geometries (R2C1, R2C2) followed by the concave geometries that have a less steep curves. For Parabolic geometries (R3C2, R3C1), they seem to steadily increase pressure drop with increasing inlet velocity. However, they are not dramatically significant as other geometries.

In terms of drill gauge orientation, pressure drop tends to increase when changing the geometry of the gauge from straight to spiral in Concave and Double Cone geometries meanwhile it shows the opposite for the parabolic geometry as the pressure drop tend to decrease when changing from straight gauge to spiral gauge.

TABLE 5. Pressure drop for water as a function inlet velocity and type of geometry

Inlet velocity, [ft./sec	**Pressure Drop, [Pa]**					
	R1C1	*R1C2*	*R2C1*	*R2C2*	*R3C1*	*R3C2*
2	16.2227	18.6163	20.444	24.084	10.278	7.053
3	34.6189	40.2017	44.14	51.961	20.354	14.445
4	57.7855	68.0591	74.321	88.186	31.534	23.145
5	85.2293	100.196	109.798	131.75	42.813	31.876
6	116.415	129.283	149.7	182.01	53.934	39.555
7	150.876	165.154	193.74	238.37	64.174	45.256
8	186.47	203.894	241.67	300.78	72.682	48.3601

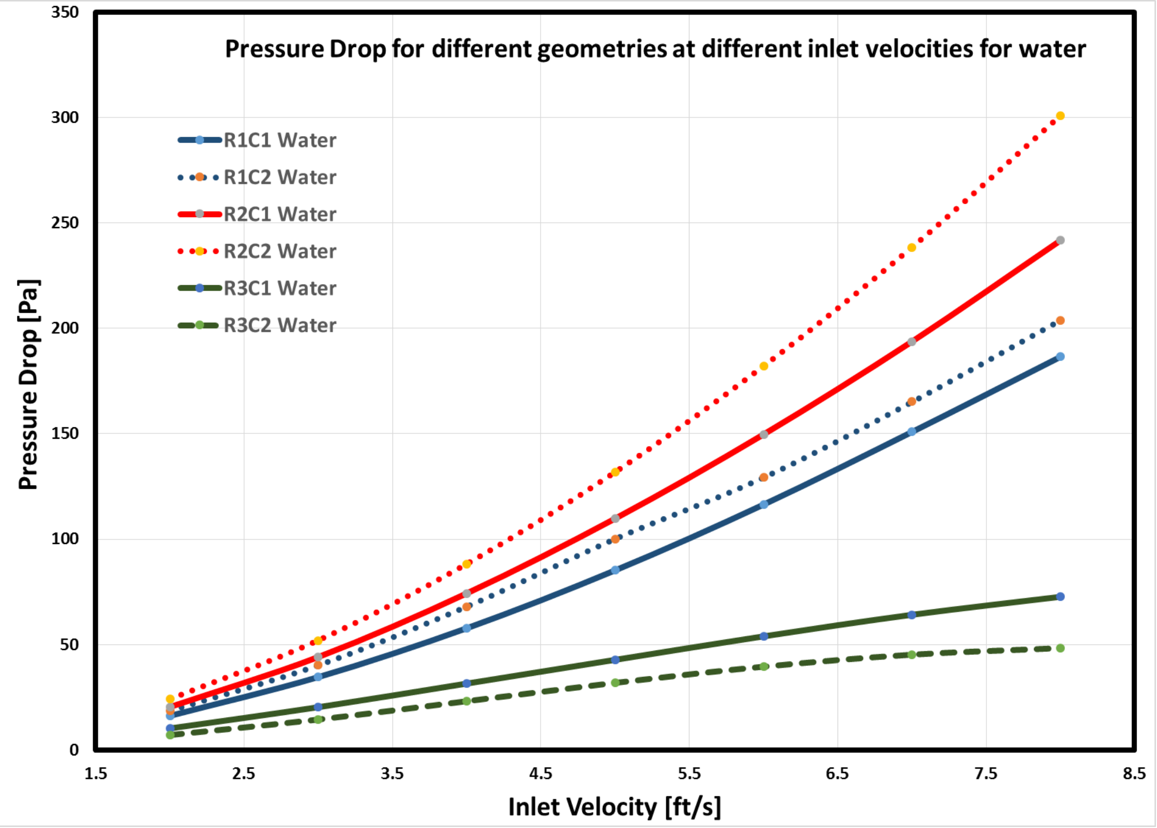


FIGURE 20. pressure Drop change with geometric changes (Water)

4.5.2 **Foam 90% pressure drop in the different geometries**

When changing the fluid to Foam 90% quality, the behavior of the pressure drop across all geometries is changing from the previously observed Newtonian fluid. However, the similarity with previous observation is increased pressure drop with increasing inlet velocity.

For foam when gradually increasing the inlet velocity from 2 ft. /sec until reaching 8 ft. / sec will increase pressure drop especially in all the geometries either they are concave, double cone or parabolic where the change is steady.

In terms of drill gauge orientation when running for foam, pressure drop tends to increase when changing the geometry of the gauge from straight to spiral in Concave and Double Cone geometries. Meanwhile for parabolic geometries, at low inlet velocities (2 to 5 ft. /sec) the pressure drop is higher for the straight gauge than the spiral gauge.

TABLE 6. Pressure drop for foam as a function inlet velocity and type of geometry

Inlet velocity, [ft./sec]	**Pressure Drop, [Pa]**					
	R1C1	*R1C2*	*R2C1*	*R2C2*	*R3C1*	*R3C2*
2	1268.91	1324.16	1348.6	1392	1287.9	1249.3
3	1481.84	1538.31	1571.4	1620.3	1500.9	1469.2
4	1638.87	1700.96	1721.1	1791.6	1666.7	1649.8
5	1753.24	1816.66	1858.5	1920.3	1790	1797.1
6	1837.35	1902.7	1933.6	2013.7	1881.8	1919.7
7	1888.76	1956.54	1992.3	2075.3	1939.6	2022.3
8	1912.84	1985.59	2030	2107.1	1970.6	2099.3

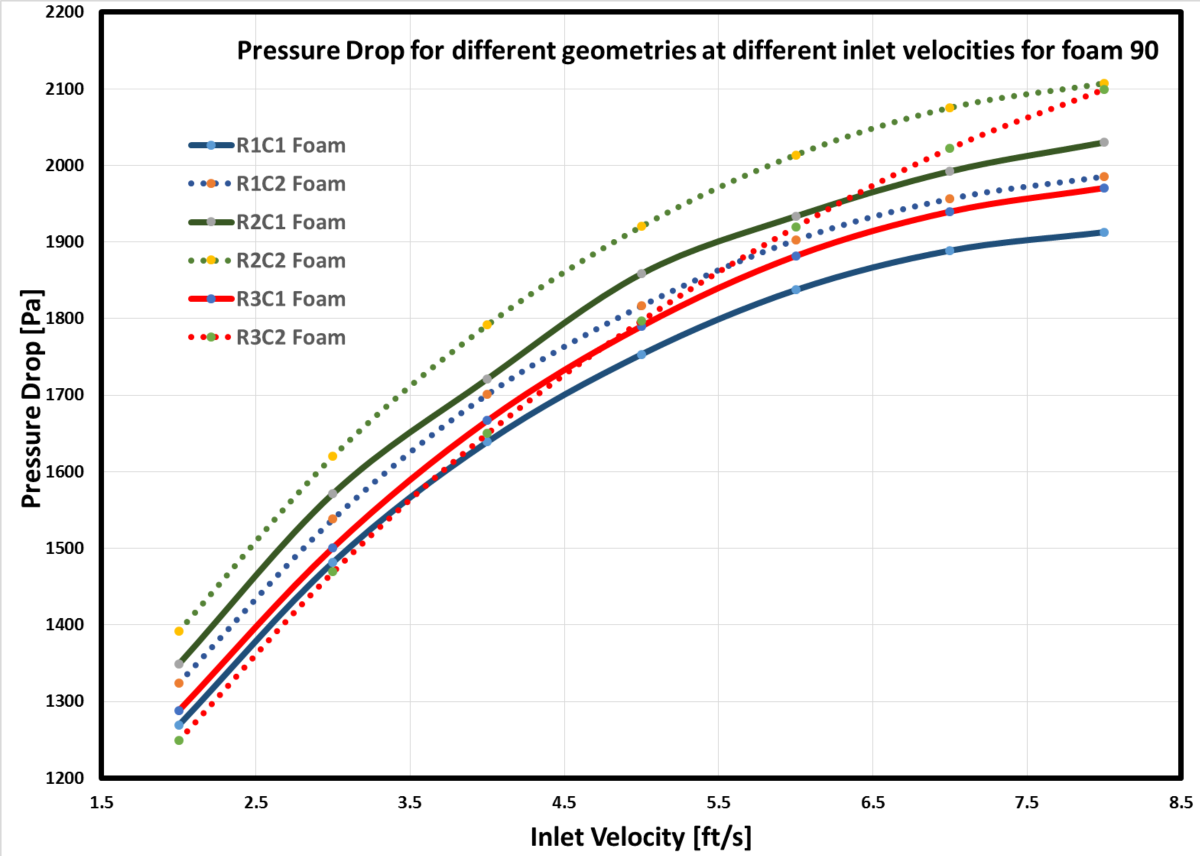


FIGURE 21. Pressure Drop change with geometric changes (Foam)

4.5.3 Generalized Herschel-Bulkley pressure drop in the different geometries

Generalized Herschel-Bulkley fluid shows irregular trend from the previous foam and water materials as the pressure drop tend to increase with the increased inlet velocity until medium speeds and then the pressure drop decreases after exceed medium inlet velocities.

In terms of drill gauge orientation when running for Herschel Bulkley, pressure drop tends to increase when changing the geometry of the gauge from straight to spiral in Concave and Double Cone geometries. Meanwhile for parabolic geometries, at low inlet velocities (2 to 5 ft. /sec) the pressure drop is higher for the straight gauge than the spiral gauge.

TABLE 7. Pressure drop for Generalized Herschel-Bulkley model as a function inlet velocity and type of geometry

Inlet velocity, [ft./sec]	Pressure Drop, [Pa]					
	R1C1	*R1C2*	*R2C1*	*R2C2*	*R3C1*	*R3C2*
2	3176.15	3341.74	3250.47	3263.6	3228.7	3263.6
3	3345.29	3548.04	3410.52	3582.2	3440.7	3582.2
4	3274.67	3476.79	3360.11	3711.1	3402.4	3711
5	3034.12	3212.66	3115.66	3650.6	3128.2	3685.5
6	2700.86	2738.81	2638.81	3491.2	2662.2	3504.9
7	2241.23	2239.95	2130.13	3150.5	2161.2	3254.2
8	2171.45	2197.8	2090.1	3045	2045.4	3045.4

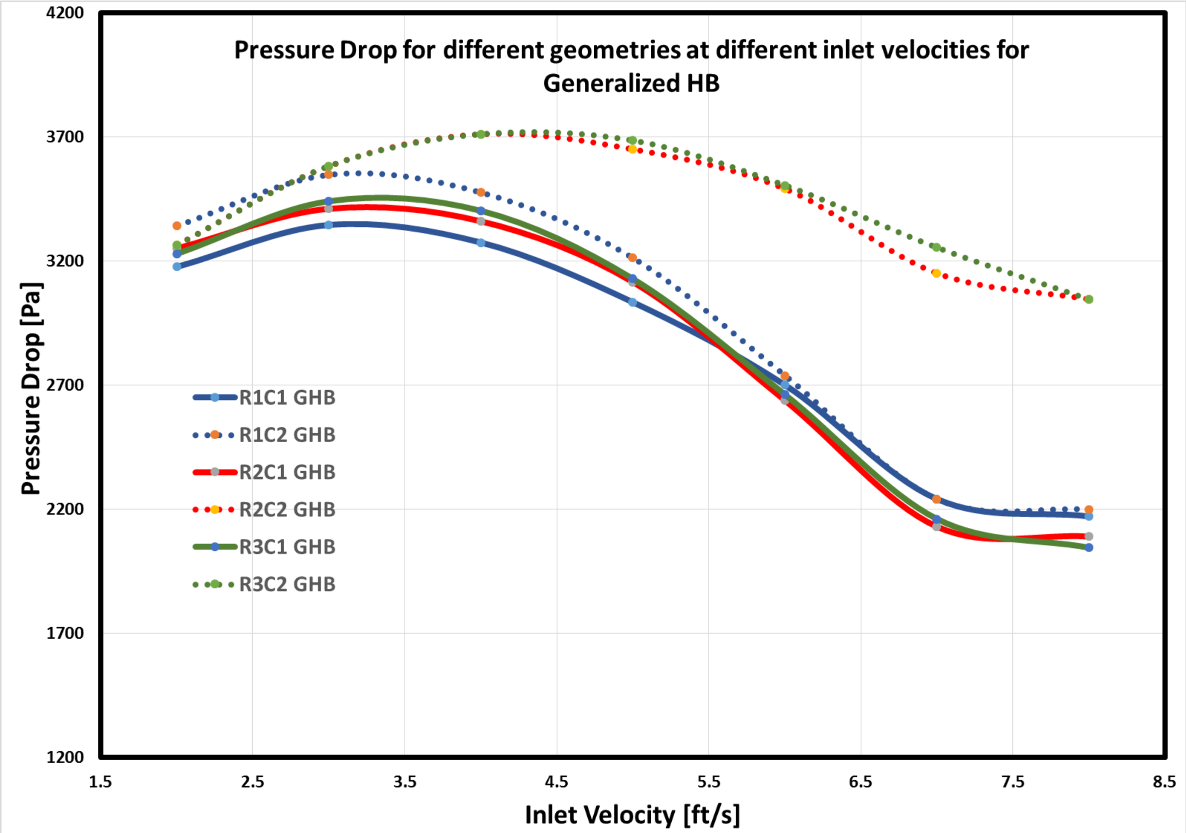


FIGURE 22. Pressure Drop change with geometric changes (Foam)

4.6 Bit rotational movement effect on pressure drop

Bit rotation has a very big impact on the pressure drop since higher RPM will always result in higher resistance on the bit body. The results shows that with increasing the rotational speed the pressure drop will increase and it's also proportional to the inlet velocity. 3 different inlet velocities were used to represent small, moderate, and high inlet speeds (2 ft. /sec, 5 ft. /sec, 8 ft. /sec). It is noticed also bit rotation has a strong effect on the pressure drop specially at high values of RPM (RPM>50)

TABLE 8. Effect of the rotary speed change on the pressure drop

Inlet velocity, ft./sec	Rotation, rpm						
	0	**10**	**30**	**50**	**70**	**90**	**110**
2	16.223	19.311	33.328	51.159	69.752	89.096	112.78
5	85.229	88.81	104.18	125.231	156.75	191.88	228.96
8	186.47	189.94	200.51	224.33	249.17	288.79	333.99

A 3d representation of the 3 properties together for R1C1 geometry is shown in **FIGURE 23.**

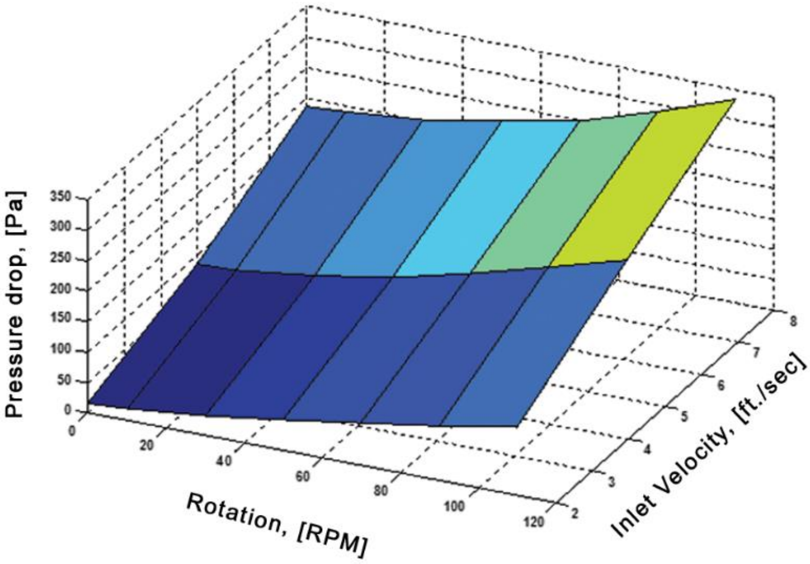


FIGURE 23. 3D plot of RPM, Inlet Velocity and Pressure Drop

4.7 Velocity profiles at different locations (R1C1 Geometry)

The velocity profile was investigated at different heights of R1C1 Model and the locations are as follows with reference to the inlet of the nozzle as shown in Figure 24 and detailed in **TABLE 9.**

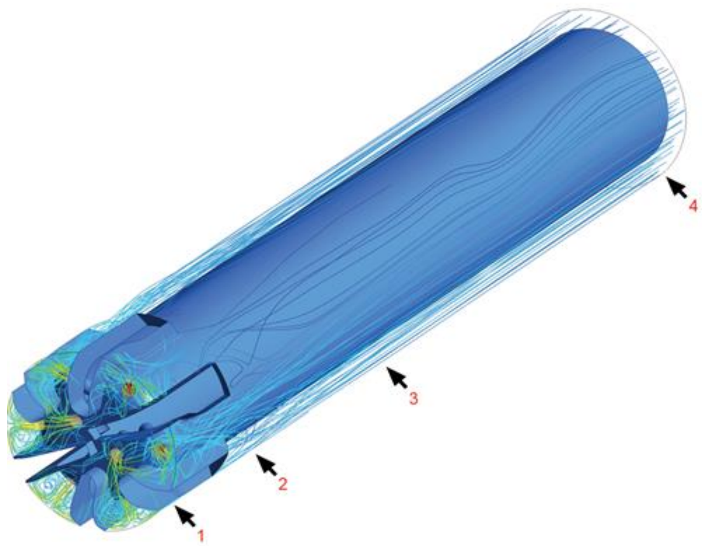


FIGURE 24. Locations at where the velocity profile was measured

4.7.1 Water velocity profile in the R1C1 Geometry

The velocity profile was investigated at different locations (heights) to see the how the velocity changes all the way until the outlet from the bit wall to the outer wall For water at Location 1 since it's close to the nozzle outlet, the velocity profile seems to be lifted towards the outer wall but by moving further from the nozzle outlet, the velocity starts to develop until its fully developed towards the outlet (Location 4).

TABLE 9. Different heights were the velocity was calculated

Different Locations	Height (with reference to nozzle inlet)
Location 1	+ 0.05 m
Location 2	- 0.050 m
Location 3	- 0.200 m
Location 4 (Outlet)	- 1.000 m

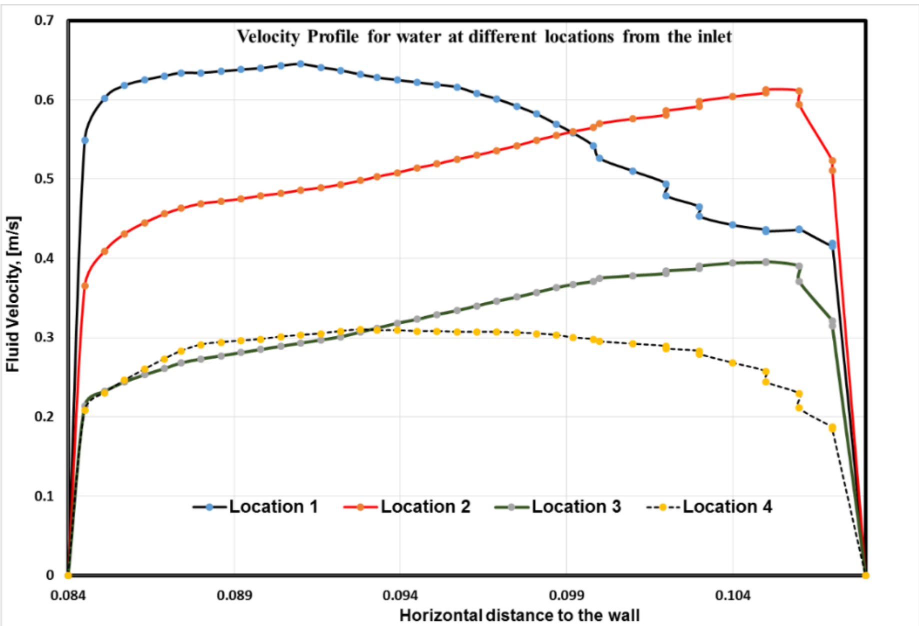


FIGURE 25. Velocity profile for water: R1C1 geometry

4.7.2 Foam velocity profile in the R1C1 Geometry

For foam, the velocity profile looked quite similar at all location but with difference in the which reduces to 0.3 m/s at locations 3 and 4 while it is also lifted towards the walls near to the nozzle outlet before the flow regulates

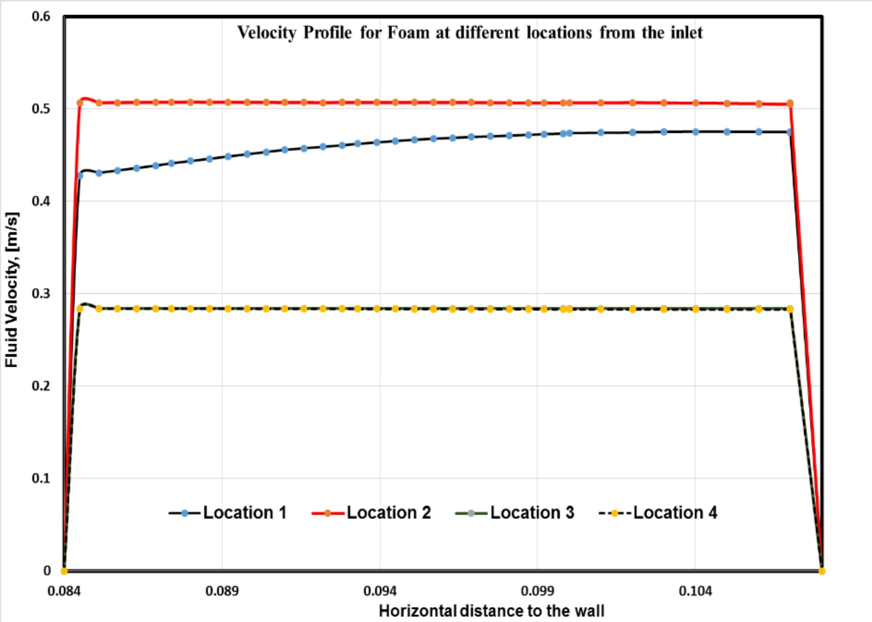


FIGURE 26. Velocity profile for foam: R1C1 geometry

4.7.3 Herschel-Bulkley velocity profile in the R1C1 Geometry

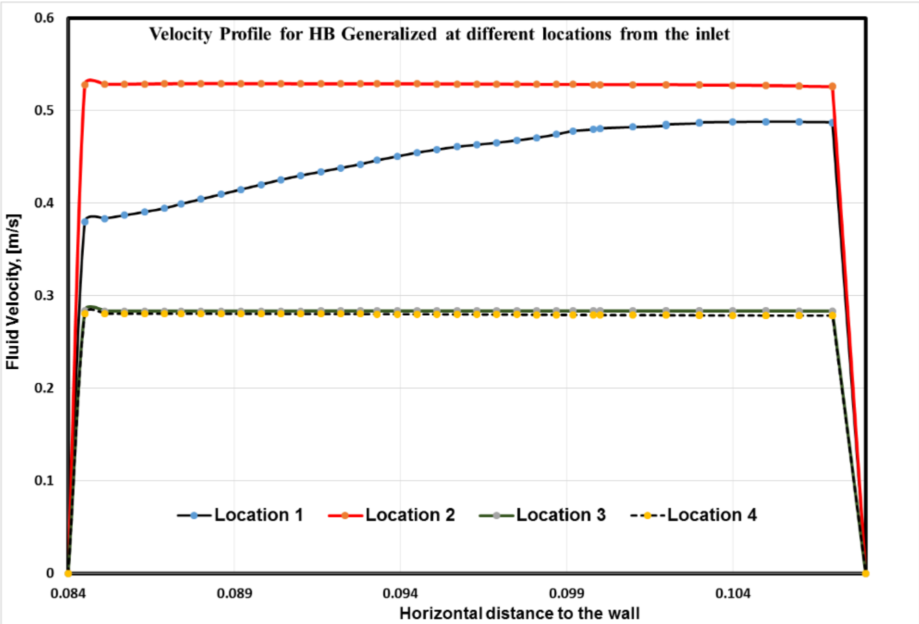


FIGURE 27. Velocity profile for Herschel Bulkley Generalized: R1C1 geometry

Since Herschel-Bulkely and Foam are non-Newtonian fluids, their behavior is quite similar although there is a big difference in their densities as velocity also reduces to 0.3 m/s at locations 3 and 4 while it is also lifted towards the walls near to the nozzle outlet before the flow regulates

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The purpose of this project has been to investigate the effect of bit geometry and drill string rotation on mud flow behavior in terms of pressure drop and velocity profile. Accordingly, six models of PDC bits were created, meshed and simulated fluid flow of different rheological models. The drill string movement and geometry effect on the mud behavior was found as that:

- Geometry of PDC bit has a very significant effect on the pressure drop in the system and a unique change in the geometry can achieve lower pressure drop such as R3C2 geometry
- An increase in RPM will lead to an increased pressure drop regardless of the geometry.
- Increasing the inlet velocity will increase the pressure loss in the system which was proved by different geometries.
- Rheological properties have very strong impact on the velocity profiles as well as pressure drop and hydrodynamic properties which are associated with the success of the drilling job.

5.2 Recommendations

The presented work didn't include changing the number of nozzles or geometry of well and cutting transport. In general we recommend the following to be considered as an extension of the current work:

i) Varying the number, geometry, and location of nozzles and studying the effect on the mud flow behavior.

ii) Considering high pressure and high temperature condition for the simulation. Real drilling environment involves such conditions.

iii) Adding the cutters to the blades of PDC bit created geometries to be more relevant to the real PDC bits and studying the effect and change.

iv) Considering more rheological models specially the ones with similar properties like the real drilling fluids.

REFERENCE

[1] Yan, L., Shan, X., Seng, Y. S., Suresh, K., Ningbo, W., Jianping, W., … Lu, Z. (2014, March 25). Innovative Bit Design Coupled with New Cutter Technology Improves PDC Bit Performance in Challenging Changbei Gas Field Application. Offshore Technology Conference. doi:10.2118/24943-MS

[2] Watson, G. R., Barton, N. A., & Hargrave, G. K. (1997, January 1). Using New Computational Fluid Dynamics Techniques to Improve PDC Bit Performance. Society of Petroleum Engineers. doi:10.2118/37580-MS

[3] Moslemi, A., & Ahmadi, G. (2014, January 1). Study of the Hydraulic Performance of Drill Bits Using a Computational Particle-Tracking Method. Society of Petroleum Engineers. doi:10.2118/169812-PA

[4] Devereux, Steve. Drilling Technology in Nontechnical Language, 2d Ed. PennWell, 2012.

[5] Bourgoyne, A.T. Jr., Chenevert, M.E., Millheim, K.K., Young, F.S. Jr.: Applied Drilling Engineering, SPE Textbook Series Vol. 2, Richardson, TX, (1991)

[6] Ernst, S., Pastusek, P. E., & Lutes, P. J. (2007, January 1). Effects of RPM and ROP on PDC Bit Steerability. Society of Petroleum Engineers. doi:10.2118/105594-MS

[7] Wells, M., Marvel, T., & Beuershausen, C. (2008, January 1). Bit Balling Mitigation in PDC Bit Design. Society of Petroleum Engineers. doi:10.2118/114673-MS

[8] King, I., Bratu, C., Delbast, B., Besson, A., & Chabard, J. P. (1990, January 1). Hydraulic Optimization of PDC Bits. Society of Petroleum Engineers. doi:10.2118/20928-MS

[9] Ryen Caenn, H.C.H. Darley and George R. Gray, Chapter 5 - The Rheology of Drilling Fluids, In Composition and Properties of Drilling and Completion Fluids (Sixth Deen, C. A., Kitagawa, C., Schneider, B., & King, G. (2014, August 25). Aligned Materials and Design Development of High ROP Drill Bits. Society of Petroleum Engineers. doi:10.2118/170494-MS

[10] Wang Zhenquan, Su Dongyu, Optimal Design of the Flow Field of Bi-center Bit, Procedia Engineering, Volume 73, 2014, Pages 345-351, ISSN 1877-7058, http://dx.doi.org/10.1016/j.proeng.2014.06.208.

[11] M. Eesa, M. Barigou, CFD analysis of viscous non-Newtonian flow under the influence of a superimposed rotational vibration, Computers & Fluids, Volume 37, Issue 1, January 2008, Pages 24-34, ISSN 0045-7930, http://dx.doi.org/10.1016/j.compfluid.2007.03.015.

[12] Bilgesu, H. I., Ali, M. W., Aminian, K., & Ameri, S. (2002, January 1). Computational Fluid Dynamics (CFD) as a Tool to Study Cutting Transport in Wellbores. Society of Petroleum Engineers. doi:10.2118/78716-MS

[13] Meyers, M. H., & Funk, J. E. (1967, December 1). Fluid Dynamics in a Diamond Drill Bit. Society of Petroleum Engineers. doi:10.2118/1696-PA

[14] Menand, S., Sellami, H., & Simon, C. (2004, March 1). PDC Bit Classification According to Steerability. Society of Petroleum Engineers. doi:10.2118/87837-PA

[15] Edition), edited by Ryen Caenn, H.C.H. Darley and George R. Gray, Gulf Professional Publishing, Boston, 2011, Pages 179-269

[16] Zaeem, M. A., Lapin S., Matveev K. The effect of vibration on flow rate of non-Newtonian fluid roceedings of 2009 SIAM Conference Mathematics for Industry, 137-142

[17] H. I. Bilgesu, M. W. Ali, K. Aminian, and S. Ameri, "Computational Fluid Dynamics (CFD) as a Tool to Study Cutting Transport in Wellbores.", paper SPE 78716 presented at the SPE Eastern Regional Meeting, Lexington, Kentucky, USA (Oct 23-25 2002).

[18] Dagrain, F., Detournay, E., & Richard, T. (2001, January 1). Influence of Cutter Geometry In Rock Cutting. American Rock Mechanics Association.

[19] Alessandro De Rosis, Harmonic oscillations of laminae in non-Newtonian fluids: A lattice Boltzmann-Immersed Boundary approach, Advances in Water Resources, Volume 73, November 2014

APPENDIX

Appendix 1: Literature review summary

Researcher (year)	Research	Approach	Parameters	Points to be taken	Remark
(G. R. Watson, 1997)	Using New CFD Techniques to Improve PDC Bit Performance	. CFD Simulation . Experimental (Flow-Visualization Rig) . Field Application (Armada Field around 2700 ft of drilling operation) 8.5 inch Section	. Nozzle Alignment . No. Nozzles Lab parameters WOB= 20 Klbs	. CFD shows a close correlations with the experimental flow patterns which shows the validity of it to some extent depending on the accuracy of the simulation. . CFD simulation along with flow visualization rigs (experimental) suggested 4 versions of PDC bit design including the standard bit by realigning the existing bits or adding more bits . Only 2 versions were taken to the field application for Armada field (Version 2 showed 10% increase for modified 4 nozzles, Version 4 showed improvements in ROP 29% for cross flow design)	Version 3 Failure: Addition of 3 more nozzles to the original design caused internal congestion that placed severe restriction on the orientation of the extra 3 nozzles. This version was neglected in the field application.
(Yan, Keshan & Seng, 2014)	Innovative Bit Design Coupled with New Cutter Technology Improves PDC Bit Performance in Challenging Changbei Gas Field Application	After optimizing the drill bit it was used to drill real 12.25 Section of the Changbei field	. blade count .abrasion resistance . layout	. Studying the formation compressive strength measurements and dull grade analysis helped to drill the section with less number of bits	Bits taken from wells 22 and 23 showed medium wear where it was pulled out in a very poor condition
Moslemi & Ahmadi, 2014	Study of the Hydraulic Performance of Drill Bits Using a Computational Particle-Tracking Method	Simulating the mud cutting by modelling the cutting evacuation, spherical particles with diameters ranging from 0.1 to 10 mm to simulate real cuttings condition	.cutting transport ratio .drag coefficient . fluid velocity	. particle size and nozzle size has a very big effect on the cutting transport ratio . effect of the waterway profile has an effect on the cutting transport ratio too	This study considered water to be the drilling fluid and it neglected the interaction between the cutting particles

Appendix 2: Gantt Chart

The project Gantt Chart is as follows:

No.	Activities	Weeks in FYP-1														Weeks in FYP-2													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature review																												
2	Identification of the fundamental equations																												
3	Identification of benchmark problem											M1																	
4	Preparation of CFD model for the benchmark problem																												
5	Simulation and validation of benchmark problem														M2														
6	Preparation of CFD model for the PDC bit flow																												
7	Design point simulation of PDC bit flow model																												
8	Studying the effect of mud properties																												
9	Studying the geometri changes																												
10	Studying the effect of drillstring/ PDC bit movement																					M3							
11	Further analysis of the result																												
12	Report writing																											M4	

Appendix 3: Milestones

Several milestones were set for this study as follows:

No.	Milestone	Date
M1	Completion of identification of fundamental equations and benchmark model	5-December 2014
M2	Completion of modeling and simulation of the benchmark problem	26-December 2014
M3	Completion of the design point simulation and parametric study	27-February 2014
M4	Completion of further analysis and final report	10-April 2014