COMPUTATIONAL FLUID DYNAMICS BASED INVESTIGATION ON MUDFLOW AROUND PDC BIT

By

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Dissertation submitted in partial fulfillment

of the requirements for the

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Universiti Teknologi PETRONAS

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Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been done by unspecified sources or persons.

Ahmad Faiz Najmuddin bin Harun

ABSTRACT

Drilling operations have a significant effect in oil and gas exploration and production due to its economic reason. Less drilling time can directly lower the overall cost of exploration and production in oil and gas. This project focuses on the hydrodynamics study of a Polycrystalline Diamond Compact (PDC) drill bit design particularly on nozzle inclination and how it affects the bit hydraulics characteristics of the drilling fluid in the bore hole and around the PDC bit. Optimizing the hydraulics while drilling is well-known and acknowledged to have significant effect on the overall drilling performance, where good hydraulics provide essential job of removing of drill cuttings to avoid unnecessary mechanical energy loss due to re-work on the produced drill cuttings, cooling of the diamond cutters to prolong the bit life and reduce the potential of bit balling. These factors assist in achieving high ROPs which in turn reduces drilling time thus effectively lowering the cost of a drilling operation. Different types of drilling fluids are also considered in this study as it is also known to have an effect on the drilling hydraulics characteristics. Drilling fluid systems have been continuously modified to aid in bit and drilling performance as well as functioning to maintain the well integrity with its role to provide hydrostatic pressure in the well to prevent collapsing of the well. The main objective of the study is to develop a CFD model in ANSYS Fluent for investigating PDC bit hydrodynamics. Other objectives include investigating the effects of nozzle inclination angle on the drilling fluid flow characteristics around the PDC bit and how different types of drilling fluid influences the PDC bit hydraulics. Drilling simulations models are created using the computer software ANSYS Fluent. Simulations are run using realizable k-epsilon model to correctly simulate the turbulence effect undergone by the fluids around the PDC bit during drilling operations. Several simulations are run with different nozzle inclination angle and types of drilling fluid which have been proven to have significant effect on the flow characteristic around the PDC bit.

ACKNOWLEDGEMENT

First and foremost, the author would like to say thanks to the Almighty for His blessing and gift of knowledge, and through His mercy and grace I was able to complete this project. The author would also like to express his gratitude and appreciation towards Universiti Teknologi PETRONAS for providing the opportunity for the research project to be planned and conducted.

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And of course, the author would like to thank his parents, grandparents, brothers, sisters and friends for their undivided support and continuous encouragement without which this report would not be possible.

The author would like to dedicate this work to his late grandfather Hj Abas bin Abdullah, for all the love, guidance and support from him that has made it possible for the author to be where he is today.

Thank you.

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ABBREVIATIONS AND NOMENCLATURES

CFD *Computational Fluid Dynamics*

FYP *Final Year Project*

PDC *Polycrystalline Diamond Compact*

ROP *Rate of Penetration*

RPM *Rotation per Minute*

UTP *Universiti Teknologi Petronas*

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Drilling engineering is a demanding and challenging discipline in the petroleum industry. The technological developments have allowed the oil industry to successfully utilize oil and gas field which may have been economically or technologically possible before. The profits and accomplishments of drilling projects are predicted on the capability of the drilling engineer who truly understands the engineering aspects and equipment required to drill a usable hole at the lowest cost possible. Azar & Samuel [1]

Ever since the 1980's, the oil and gas industry has given priority to fluid flow in annular spaces in oil well drilling operations with cuttings transport by the drilling muds. Acknowledging constant concern of operational costs and the need for raising production capacity; higher flow rates frequently been used, which results in the hydrodynamic losses in the annular spaces started to require a high amount of energy thus making it a significant factor in drilling costs. [2]

In terms of drilling bits technology, Deen et al. [3] it is well-recognized that each generation of PDC bit have produced enhanced performance than its predecessors, with one author claiming 60% improvement in rate of penetration between the year 1989 and 1995. These amazing improvements have fuelled the growth of this particular technology. Nevertheless, this capability has in turn nurtures a demand for more complicated well programs which in turns requires continuation of improvements in bit performance. Warren and Amagost [4] stated in their study that PDC bits have gained increasing favour because of innovations in bit designs and also various advancements regarding materials used in the bit manufacturing. In this project, the author will focus on Polycrystalline Diamond Compact (PDC) bit.

1.2 Problem Statement

Previous field experience with PDC bits has shown that these bits have been used to drill many various types of formations. A major factor in their successful application is the correct hydraulic control for effective cooling and cleaning of the bit. The bit hydraulic and mechanical design and also the operating conditions play a major role for cooling and cleaning the bit.

The flow patterns around a PDC bit are very complicated. Bits typically have numerous high velocity jets that create complex inter-connected fluid courses. The flow from each nozzle on the PDC bit is deflected by the cutters, the curvature of the bottom hole pattern and the bit body. This means that the resulting flow is very difficult to predict due to its complexity. Therefore, each bit needs to be studied to achieve the optimum bit design.

Previous experiments have been conducted with different setups representing annulus flow in a limited number of hole size to investigate the contribution of several physical and operating conditions. Due to time and cost constraint involved to conduct these experimental studies, thus it is necessary to rely on Computational Fluid Dynamics (CFD) models.

In this project, the author will address the issues regarding mud flow around a PDC drill bit. The issues are:

i. How does the bit nozzle geometry specifically nozzle inclination angle affect the drilling fluid flow characteristics around the PDC bit?
ii. What is the effect of drilling fluid properties on the PDC bit hydraulic performance?

1.3 Objective

The objectives of this project are:

i. To develop a CFD model in ANSYS Fluent for investigating PDC bit hydrodynamics.
ii. To investigate the effect of nozzle inclination angle and type of drilling fluid on the hydraulic characteristic of PDC bit
iii. To investigate the effect of drilling fluid properties on PDC bit hydraulic properties.

1.4 Scope of Study

The scopes of study can be simplified as follows:

i. Identification of drilling fluid properties which covers the fluid weight (density), the fluid viscosity and also its rheological properties.
ii. Bit design characteristic focusing on nozzle geometry. The author have focus specifically on the nozzle inclination angle.
iii. Run parametric CFD simulation using ANSYS Fluent. Early consideration would be to run on steady state flow, using both Newtonian and non-Newtonian fluid and single phase flow with k-epsilon turbulence model.

1.5 The Relevancy of the Project

This project is especially relevant to Y-UTP team where they are currently working on a project entitled "Bit Wear and Vibration Study to Aid Drilling Optimization". The author's scope of study and findings might help the team to achieve further progress on the project they are working on.

Furthermore, the project is highly relevant to the author as it requires a detailed and comprehensive study on the theory and applications which comprises of general petroleum engineering and mechanical engineering knowledge which directly applies to the oil and gas business.

1.6 Feasibility of the Project within the Scope and Time Frame

The project conducted is within the capabilities of a final year engineering student to be completed with under direct supervision of an assigned lecturer providing guidance and assistance making it very possible to complete within the allocated time.

CHAPTER 2

LITERATURE REVIEW

2.1 PDC Drill Bit

Deen et al. [3] stated that since the first introduction of PDC bits into oil and gas drilling, the bit engineering challenges have continuously shifted back and forth between bit material development and advancing bit design revolving around the expanding material capabilities. They also mention that failure to address manufacturing challenges in PDC bits, or at best addressing them in isolation from materials and designs. The most common case is the preference of bit manufacturers towards bit bodies cast from brittle and expensive tungsten carbide “matrix” rather than bit machined from tougher steel material.

All through the past 20 years, the drilling industry has looked to new technological advancement to halt the exponentially increasing cost of drilling oil and gas wells. This includes constant improvements in bit design to increase overall drilling performance and reduce drilling costs [5]. They stated these advancement include the development of PDC bits, to drill long and continuous intervals of soft to medium-hard formations more economically. The cost advantage is the result of the longer bit life and higher ROP obtained with PDC bits. They described drilling rate and bit life are two factors that is highly significant affecting the drilling cost per foot which relates directly to the drilling cost per foot. These two factors are in turn dependent on the applied operating conditions on the bit (bit hydraulics, rotary speed and weight), properties of the drilled formation and drilling fluids used and of course bit design.

According to Kerr [6], the development of the PDC bit since its first introduction in 1973 has progressed that today huge amount of footage is drilled with PDC bits. Through this process, a number of design features that affect the bit performance have become clear. The effects of bit material, back rake, side rake, cutter placement and density, bit profile and hydraulic horsepower on application and performance have been delineated. The industry has seen the introduction of the steel-body, then the tungsten-carbide-matrix drill bit. Hydraulic layouts of PDC bit are now optimized with the aid of flow-visualization chamber.


(a) *(b)*

FIGURE 1: PDC Bit Design (a) Conventional Matrix Blade (b) New Steel Blade

Source from Deen et al (2014) “Aligned Materials and Design Development of High ROP Drill Bits”

Some investigators have reported that nozzle location on the bit face holds a major role in PDC bit cutter cooling, enhancing bottom hole cleaning and mitigation of cutter balling [5]. They concluded that nozzle placement has an important effect on bottom hole cleaning thus significantly affecting drilling rate.

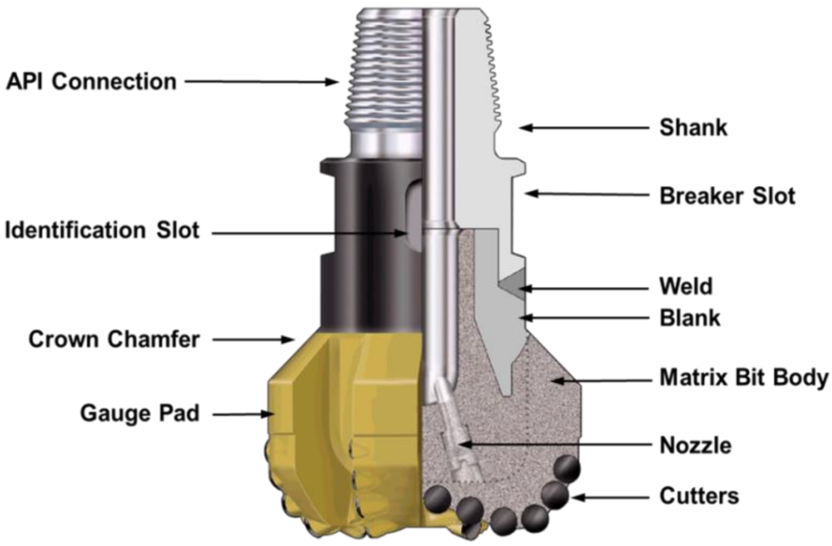

FIGURE 2: PDC drill bits components.

2.2 Bit Hydraulics

The optimum selection of independent variables to control bit hydraulics effectively requires a thorough and deep knowledge of fluid flow characteristics at the bottom of the well. This behaviour can be described by the fluid velocity profile or through observations of the pressure distributions underneath the drill bit [5]. According to them, the mechanisms by which hydraulics contribute to improve drill-bit performance have been well-established. These includes bottom hole and bit cleaning, bit cooling and decrease in chip-hold-down pressure. The contribution of these mechanisms to efficient drilling is highly related to the bottom hole fluid velocity profile, which depends on the initial hydraulic conditions and the characteristics of the cross flow field. They stated that flow rate and total flow area are responsible for the initial hydraulic conditions; nozzle configuration of the bit and the bit and cutter profile will establish the cross flow field profile shape.

Watson, Barton and Hargrave [7]stated whilst much attention is focused on the cutting structure and cutter technology, another aspect that makes a significant contribution to drill bit performance is hydraulics. They said that optimum performance can only be achieved by fully optimizing the available hydraulic energy which is especially relevant when drilling long or extended wells where system losses reduce both the mechanical and hydraulic energy present at the bit. With regards to bit cleaning, the ROP is greatly enhanced by the rapid removal of cuttings from the bit face to the annulus, increasing the mechanical efficiency of the bit by minimising the energy spent on cuttings reworking. Plus it is essential to maintain high velocity flow over the surface of the bit body because even a small fraction of cuttings are not expelled immediately from the bit face where in some formations these will adhere to the bit body in regions of slow flow and cause bit balling.

According to Watson et al. [7], an important factor affecting bit durability is the cutter density and its abrasion resistance. PDC bit rapidly degrades above 700^{o}C therefore it is highly essential to maintain the PDC cutters temperature as low as possible to prolong the bit life. This can be obtained by maintaining high fluid velocity over all the cutter and cutter substrates.

Although the specific requirements of each drill bit or application are different, they stated that the main objectives of hydraulic design are 1) to rapidly transport the cuttings into the annulus; 2) to keep the bit body clean and 3) to cool the cutters.

2.3 Drilling Fluid

Drill cuttings are removed from the wellbore by pumping the drilling fluid from the surface using mud pumps into the well through the drill pipe, the drilling fluid lubricating, cleaning and cooling the cut region and avoiding any requirements to increase because of the accumulation of particles. These particles are strongly related to the drilling mudflow velocity profiles in the annulus thus knowledge of "mud hydraulics" is directly related with an efficient drilling operation. [2]

They also said that drilling muds are generally suspensions non-Newtonian rheological behaviour, of which some are pseudoplastic and others are viscoplastic type. Viscoplastic suspensions are usually used in situations where cuttings sedimentations are required to be minimized in case it interferes with mud circulation.

According to King et al. [8], the function of drilling fluid is to provide cooling and cleaning of the PDC cutters. Otherwise a bad flow distribution could lead to a rise in the temperature and bit balling (cuttings created from the drilling operation are not removed from underneath the drill bit and the clog the bit) which will result in the reduction in the penetration rate, even the bits life-span and evidently increasing the drilling costs.

Kerr [6] mentioned in his article that the use of PDC bits in both water-based mud and oil-based mud have proven to be successful. He also stated that benefits of using oil-based mud with PDC bit operations have been accepted throughout the industry and well-documented. Mud properties is said to have an effect on PDC bit performance, consistent with results from conventional roller-cone bits.

2.4 Computational Fluid Dynamics

According to Pereira et al. [2] the physical aspect of any fluid flow adheres to three main principles: the conservation of energy, the conservation of mass and the second law of Newton. These principles are expressed in terms of mathematical equations, mostly leading to partial differential equations. The CFD techniques attempts to solve the equations that rule the fluids flow numerically, while the solution advances in time and space to achieve the complete numerical flow field description. They also stated that comparisons of the CFD results with data obtained from laboratory experiments has taken on a big role in validating and establishing limits of many approaches for the ruling equations.

CFD is a validated and well-established technique which is widely used to investigate and optimise fluid flows. CFD is often used as a additional evidence or as an alternative to experimental investigations. This is due to its capability to produce a large amount of information about a flow economically and in a short amount of time and is particularly appealing when conditions of the experiment are difficult to reproduce. A properly set up CFD simulation can accurately reproduce most turbulent and laminar flow. [7]

According to Watson et al. [7] CFD has been previously used to model PDC drill bits but only on a limited basis because it has demanded huge sums of investments in terms of expenses and time. The use of highly detailed PDC bit models have been precluded due to the highly complex drill bit design and the limitations of computing and meshing. They stated that in one study, individual cutters of a PDC bit were not modelled and significant simplifications to the design had to be made despite the use of a super-computer. However, continuous improvements in computer capabilities has increased the number of applications for CFD.

He also stated that the limitations of CFD are well known and have been understood but the significance of the errors in the simulations run are difficult to estimate without prior knowledge of a similar flow regime. Therefore, entirely new applications of the CFD simulations need to be validated before it can be accepted and used as part of any technical design procedure.

CHAPTER 3

METHODOLOGY

3.1 Project Flow Chart

This project is done step by step. Figure illustrates the flow chart diagram of this project.

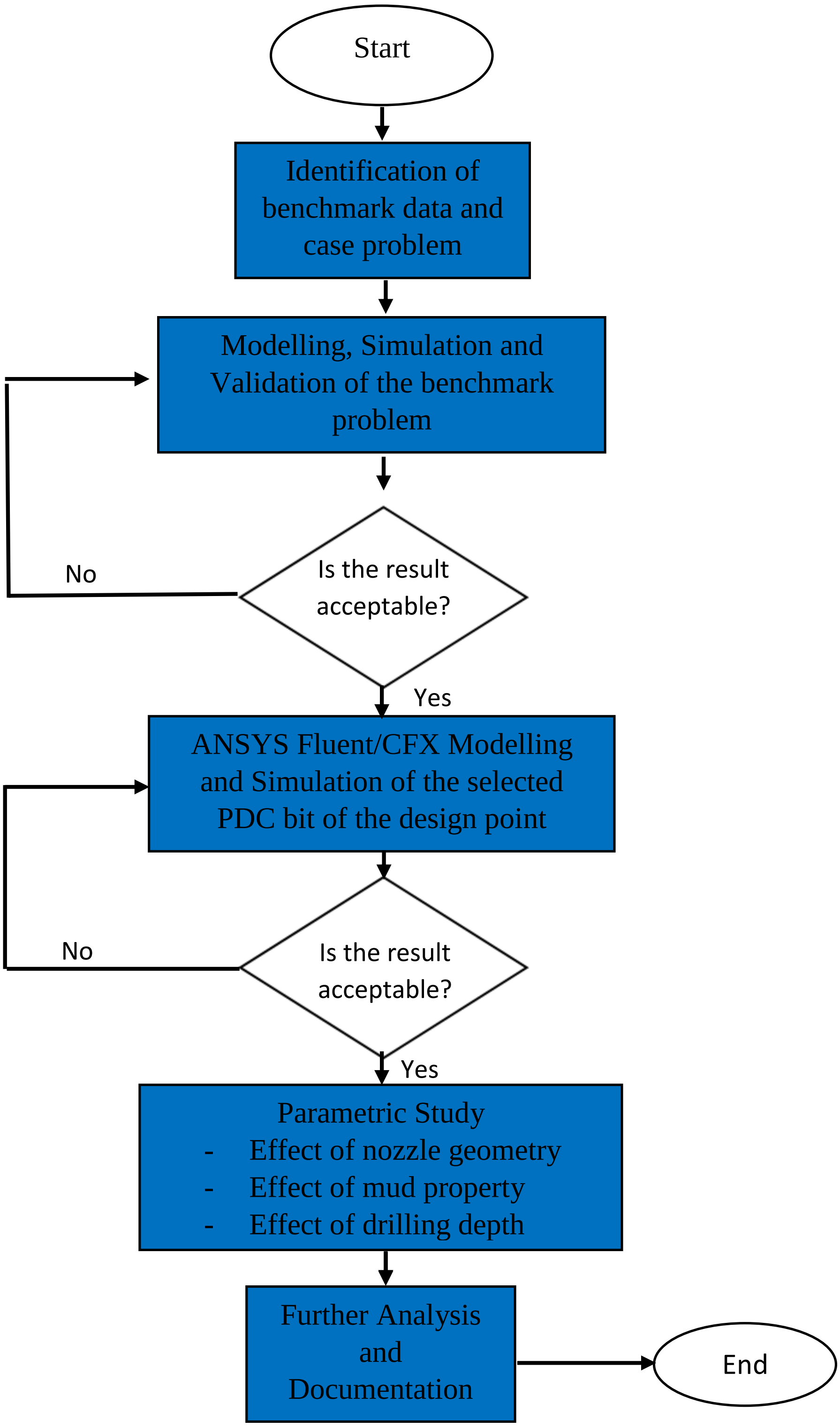

Figure 3: Project Flow Chart

3.2 PDC Bit Geometry

A total of six PDC bit geometry were provided by the supervisor, drawn in CATIA. Each bit with varying design regarding the bit profile, shape of the blades and junk-slots which can be observed in the figure below.

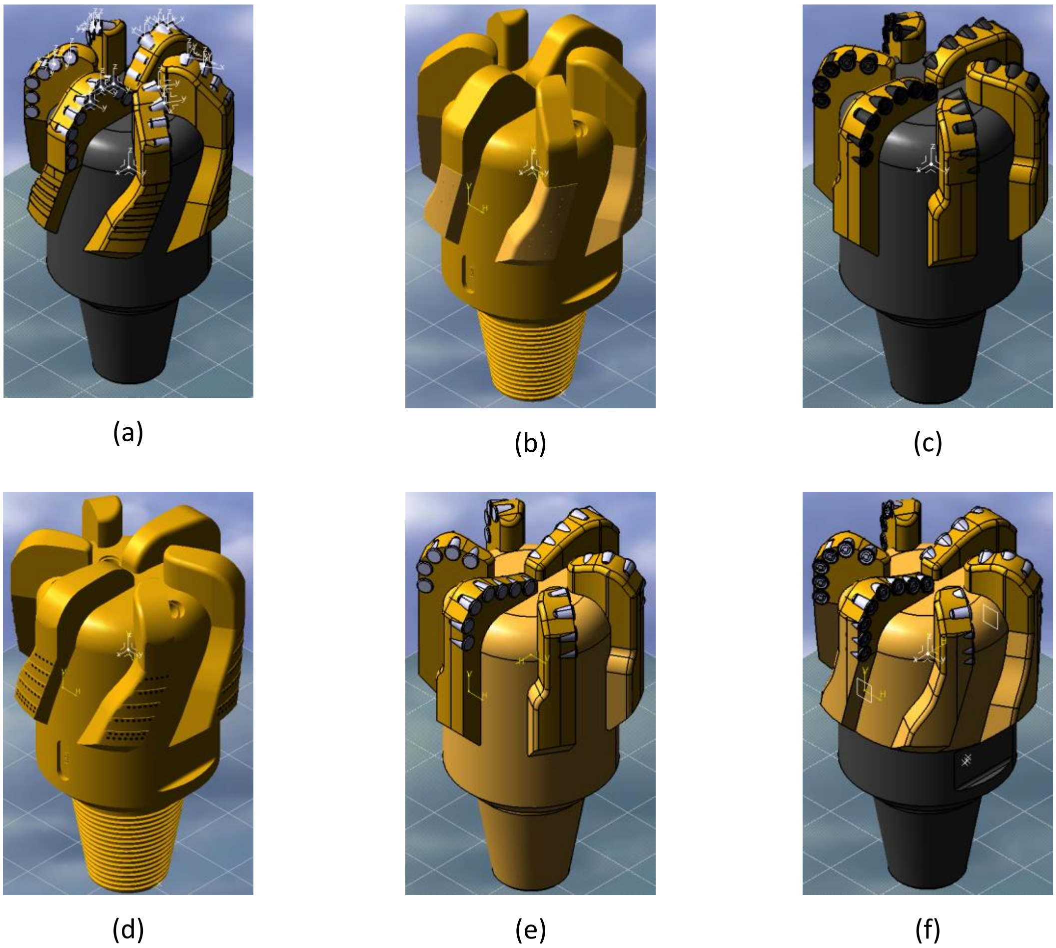

FIGURE 4: Different PDC Bit Geometries

The author has selected only one bit geometry to be run in the simulations and further analysed in the parametric study which is the bit labelled (c) in the figure above. The PDC bit is referred to as R1C1WOC. In conducting the simulation, the cutters are however removed to create a simplified bit model in the simulation for ease of meshing and calculation purposes. Specifications of R1C1WOC bit model are available in Table 1.

TABLE 1: Specifications of R1C1WOC Model

R1C1WOC PDC Bit Specifications	
No of Nozzle	8 (2 inner nozzle, 6 outer nozzle)
No of Blade	6
Crown Profile	Concave
Inclination Angle of Nozzles	Inner Nozzle: 20^o
	Outer Nozzle: 45^o

3.3 Types of Drilling Fluids

An assorted range of drilling fluid have been used in drilling operations with highly different characteristics and rheological properties selected to suit the conditions to achieve optimum drilling rate. The author have chosen two types of fluid which are water and Foam90 to represent both Newtonian fluid and non-Newtonian Power Law fluid. The details of the fluid are stated in the table below.

The density of the foam is calculated using the formula:

Foam Density = Foam Quality * Density of air + (1 – Foam Quality) * Density of Water

TABLE 2: Fluid Specifications

Fluid	**Values**	
Water	Density	998.2 kg/m^3
	Viscosity	0.001003 kg/m/s
Foam90	Quality	0.9
	K	3.73 $Pa.S^n$
	n	0.36
	Density	101.125 kg/m^3

3.4 Initial CFD Simulation

ANSYS Fluent software have a wide range of physical modelling capabilities needed to model fluid flows around complex geometry designs. Thousands of companies throughout the world have benefited from this software, using it as part of their design and optimization phase for product development. In order to study the complex fluid flow characteristics of drilling fluid around the PDC bit, the author decided the ANSYS Fluent software is most suitable for the desired application.

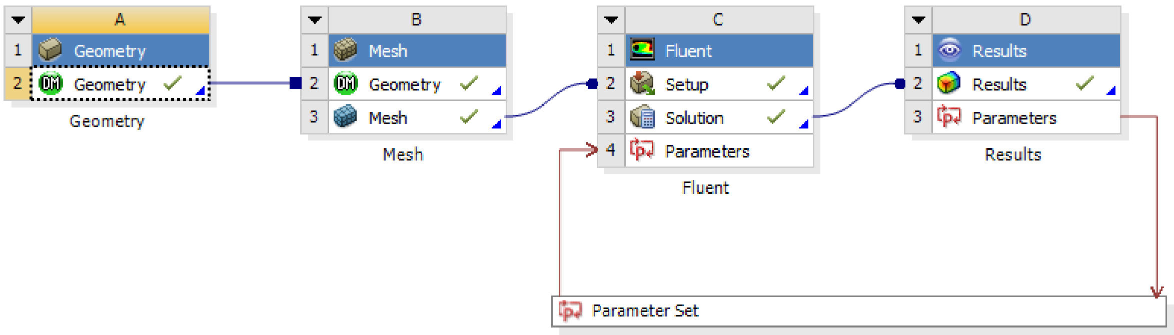

FIGURE 5: ANSYS Fluent Component Analysis

The simulation setup begins with selecting the pressure-based solver, absolute velocity formulation and conducted as steady-state. The realizable k-epsilon model is chosen with standard wall functions and curvature correction. The simulation is done first for water where it is readily available in the fluent database and another one is foam where the details stated previously are entered into fluent and selected as a non-Newtonian Power Law fluid. The cell zone conditions are set with water and foam respectively and the boundary conditions are the velocity-inlet which are selected directly at the nozzles of the bit to reduce the calculations required and improve the speed for the calculation to converge. The simulation is set to run for 2ft/s, 3ft/s, 4ft/s, 5ft/s, 6ft/s, 7ft/s and 8ft/s while the other boundary condition is the pressure-outlet which is initially set to zero. Bit rotation is considered to be zero.

For the spatial discretization section, the pressure is set to standard and first order upwind approximation for the rest. The scaled residuals together with the mass flow rate is monitored, with the absolute-error criterion of 0.001 was set to assess the convergence of the solution.

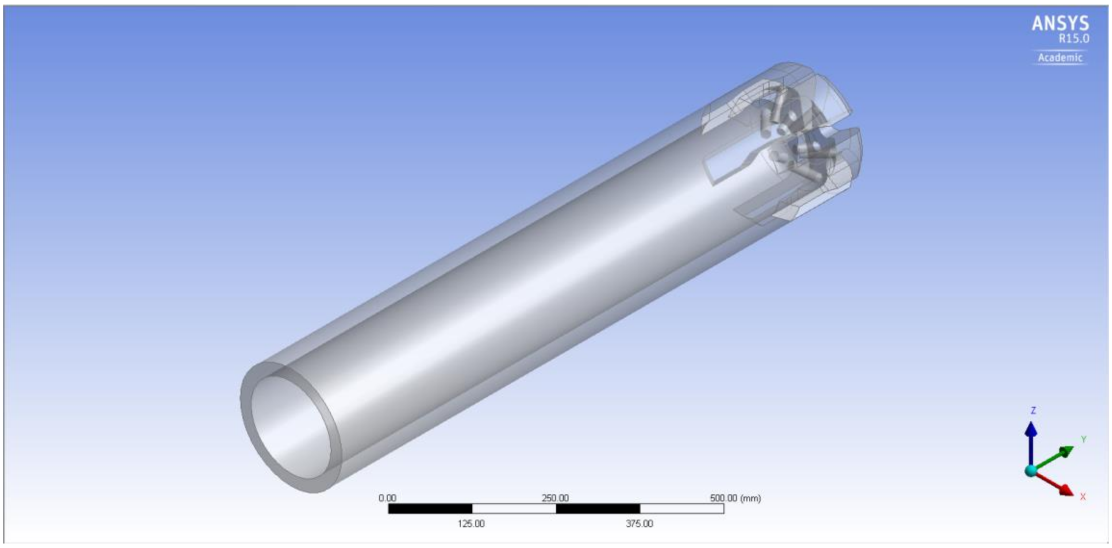

FIGURE 6: R1C1WOC Model in ANSYS

The model of the bit/formation engagement was done with an offset of 5mm to create a model imitating a realistic real-life drilling operation. The fluid volume was meshed using patch conforming algorithm with first aspect ratio as the inflation option resulting in a range of 1-1.6 million computational cells. The minimal and maximal size of element obtained was $5.7689e^{-4}$ and $5.7689e^{-2}$. The setup was done so that the mesh resolutions are finer near the walls and nozzles to generate a more accurate solution in these areas.

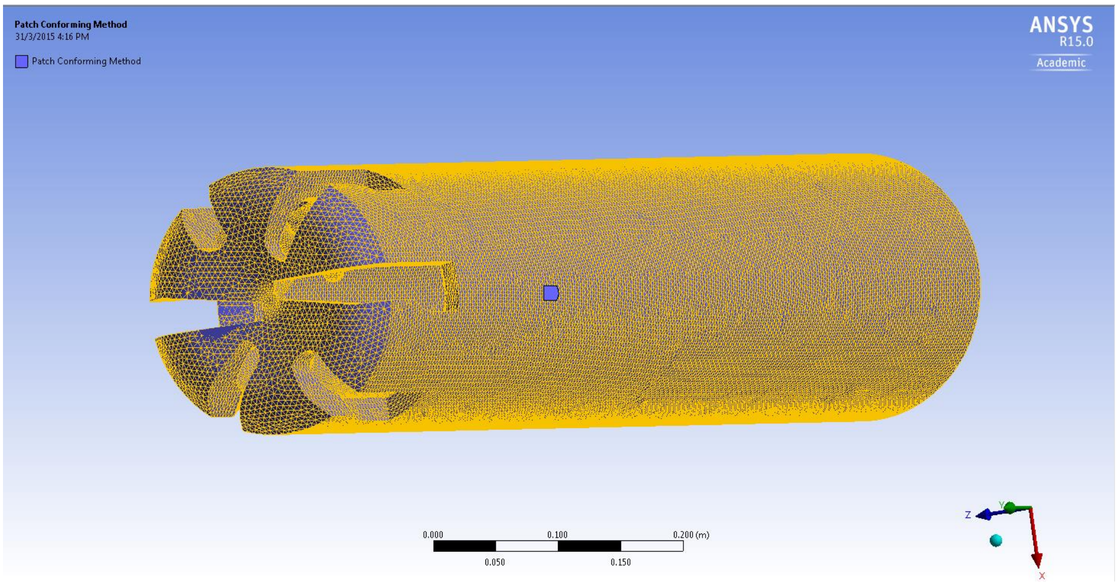

FIGURE 7: Generated Mesh of R1C1WOC Model

3.5 Parametric Study

After obtaining satisfactory results with the initial simulation, a parametric study was conducted on the R1C1WOC model, the author set six different number of inclination angle for the six outer nozzles, including the original inclination angle of the geometry.. The original inclination angle of 45^{o} was chosen as the base case for this parametric study. A total of six different nozzle inclination angle was set including the base case (35^{o}, 40^{o}, 45^{o}, 50^{o}, 55^{o}, 60^{o}) while the two inner nozzles inclination angle were maintained at 20^{o}. The simulation for the parametric study take into account the rotation of the bit, running the simulation with 10 RPM, 30 RPM, 50 RPM, 70 RPM and 110 RPM. The simulation was done for both water and foam and the inlet velocity was set at 5ft/s for all runs.

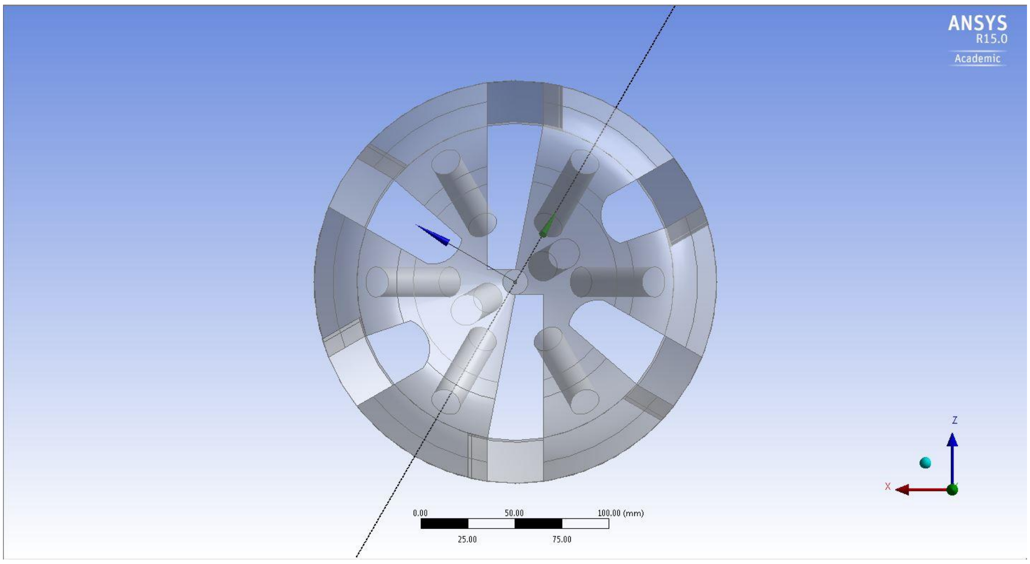

FIGURE 8: Top View of R1C1WOC with the Nozzles Visible

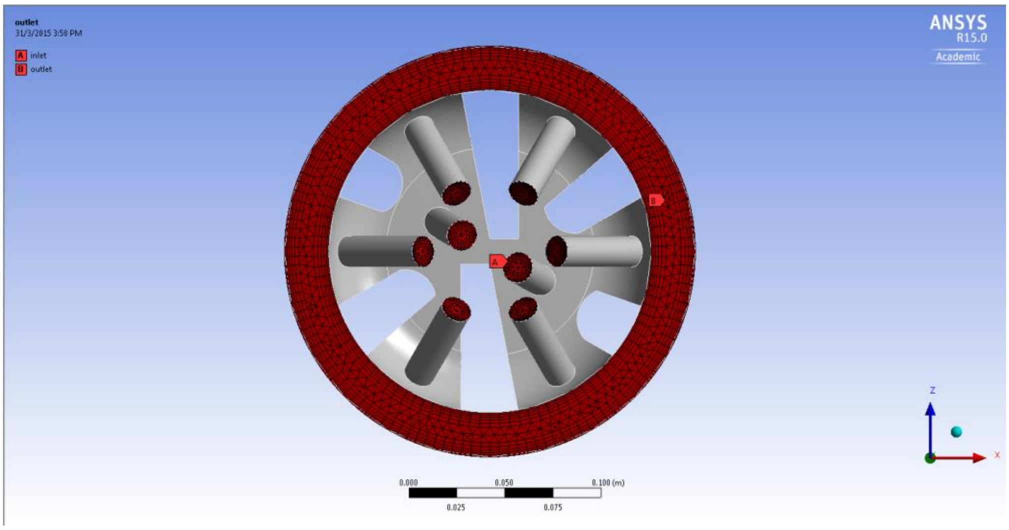

FIGURE 9: Bottom View of R1C1WOC with the Inlet & Outlet Highlighted

To include the rotation of the bit in the simulation, another boundary condition was set in the fluent setup recognizing the pipe connected to the bit as the rotating wall, and assigning the values of rotational speed as stated previously.

The meshing for the parametric study is also improved to generate higher quality mesh along the drill pipe and the wall of the annulus to obtain more accurate results of the effects of the pipe rotation on the drilling fluid flow characteristics.

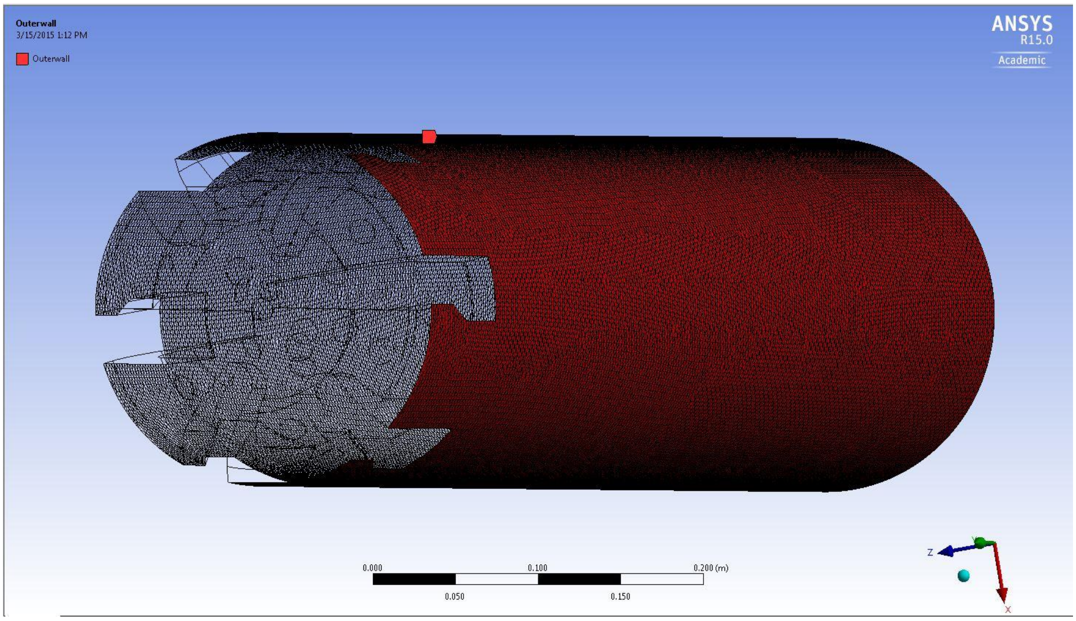

FIGURE 10: Generated Mesh of Annulus Wall

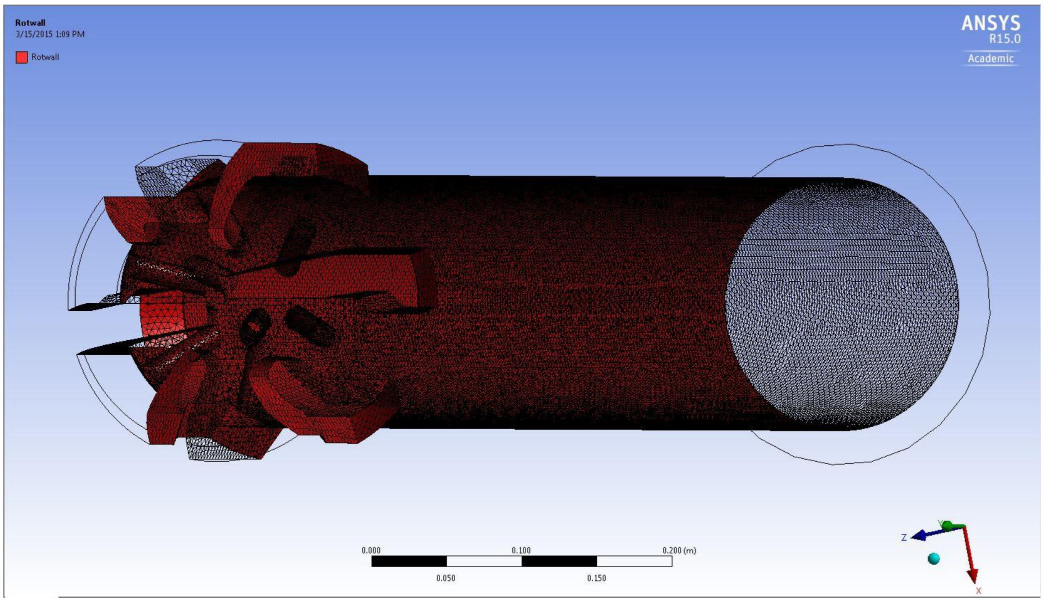

FIGURE 11: Generated Mesh of Rotating Pipe Wall

3.6 Tools and Equipment

Tools and equipment used in this project are CATIA software and ANSYS Fluent simulation software.

3.7 Gantt Chart and Project Milestone

Both Gantt chart for FYP1 and FYP2 and also the Project Milestones is located in the appendix as Appendix I and II.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results of Initial CFD Simulation

The output parameter of this project is the pressure drop across the bit. Furthermore, the drilling fluid flow characteristics around the PDC bit are observed and analysed through the velocity streamline and contour produced from the simulation. These data can help identify low and high fluid flow velocity zones where the possibility of cutting accumulation is high which could result in bit balling problems.

The results in TABLE 3 and FIGURE 12 are showing the values and the plot of pressure drop with increasing inlet velocity for both water and Foam90. Foam90 is showing significantly higher pressure drop values compared to when using water as the drilling fluid. But both fluids are showing a trend of increasing pressure drop with increasing inlet velocity. The difference in pressure drop values shows that different types of fluids or more accurately fluid characteristics would have a significant effect on the drilling process.

From the images shown in FIGURE 13 – FIGURE 16, the velocity streamline along the PDC bit and also the pressure contour cutting across one of the junk slot area produced from the simulation can be analysed and studied to investigate the characteristics of the fluid flow around the bit. It will help in determining possible low velocity or stagnation zones, cross flow area and re-circulation paths.

The results from using water as the drilling fluid is showing high velocity flows, with turbulence can be seen inside the junk slot area. Cross flows between inner nozzles and outer nozzles is preferable for bit cleaning as it produces high velocity zones across the bit face which will help to prevent any cuttings accumulations. Foam90 however is showing straight flow patterns, with clearly less turbulence comparing to water. The area across the bit face is also showing low velocity fluid flows.

Exact velocity values extracted from a straight line across the bit face can be seen in TABLE 4 and further analysis can be made from the plot in FIGURE 17, where similar trends can be seen but with water having significantly higher velocity compared to Foam90 all along the line, where it can be said overall that Foam90 produces lower velocity fluid flows compared to water with the same inlet velocities probably due to its different characteristics where the former is representing the Newtonian fluid and the latter set as Power Law fluid.

TABLE 3: Pressure Drop with different Inlet Velocities

Inlet Velocity (ft/s)	Pressure Drop (Pa)	
	Water	Foam90
2	92.472	1804
3	181.82	2104.7
4	299.54	2342.4
5	451.14	2548.7
6	636.44	2742.4
7	854.66	2932.8
8	1103.7	3115.4

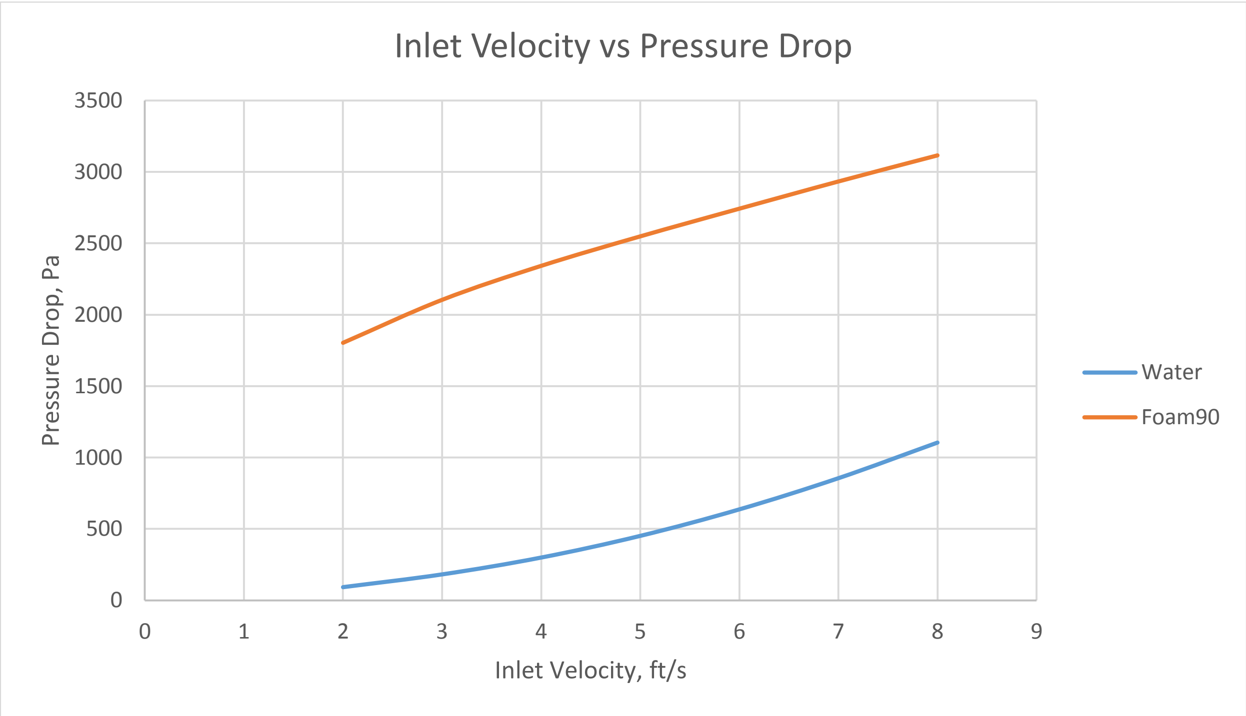

FIGURE 12: Pressure Drop vs Inlet Velocity Plot

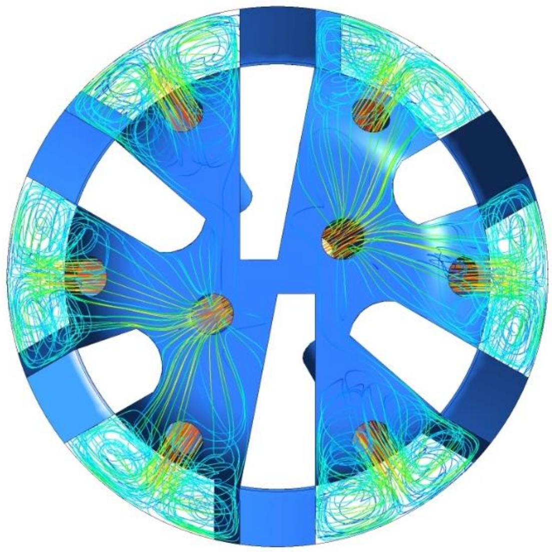

FIGURE 13: Velocity Streamline Topview (water)

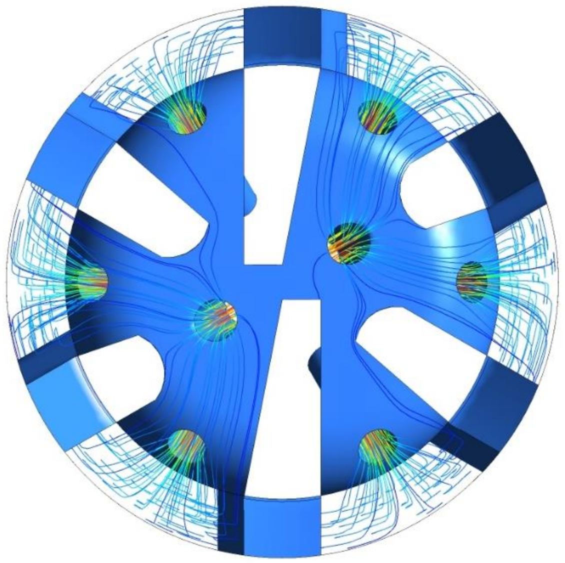

FIGURE 14: Velocity Streamline Topview (Foam90)

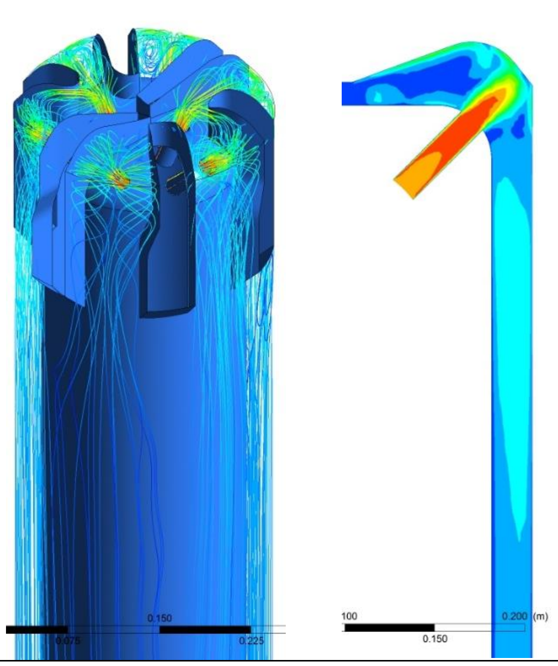

FIGURE 15: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot (water)

FIGURE 16: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot (Foam90)

TABLE 4: Fluid Velocity across Bit Face

Position (X-Axis), m	Fluid Velocity, m/s	
	Water	Foam90
-1.21E-04	2.00E-02	1.66E-05
1.17E-02	3.31E-02	6.21E-04
2.36E-02	1.33E-01	4.00E-02
3.54E-02	5.73E-02	3.55E-02
4.73E-02	5.96E-02	6.17E-02
5.91E-02	8.66E-02	6.45E-02
7.10E-02	5.89E-02	7.83E-02
8.29E-02	5.13E-01	1.27E-01
9.47E-02	5.08E-01	6.62E-02
1.07E-01	2.07E-01	1.59E-03

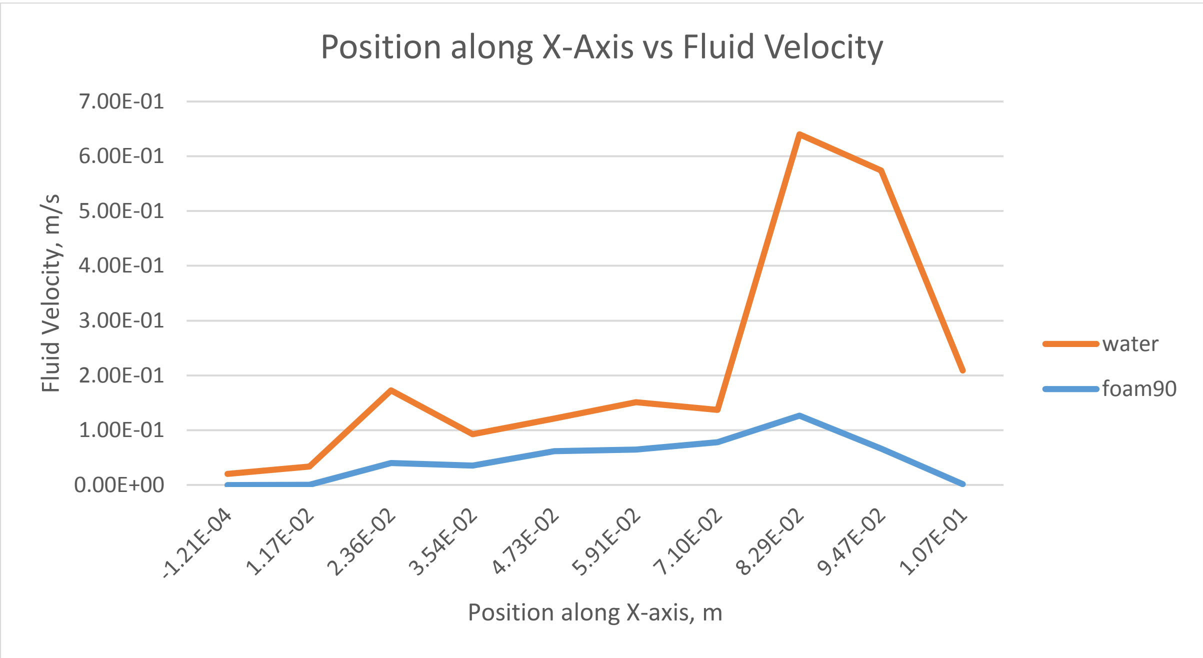

FIGURE 17: Fluid Velocity vs Position along X-Axis

4.2 Results of Parametric Study

Simulation Results for Water as Drilling Fluid

The values in TABLE 5 represents the pressure drop for each inclination angle with different RPM values. The highest pressure drop can be seen for the 50^o inclination angle with each single value of RPM set and the lowest pressure drop is obtained from the bit with nozzle inclination angle of 35^o.

From the trends observed in FIGURE 18, it is shown that the pressure drop value for each inclination angle set is increasing with increasing bit rotation speed (RPM). All of the simulated cases show similar the similar trend although the increasing pressure drop is seen as quite small. This increase in pressure loss can be explained due to resistance encountered by the fluids. The higher the RPM the higher the resistance created, causing turbulence in the fluid flow which leads to higher pressure loss.

The figures 19 – 30 shows the velocity streamline and velocity contours around the PDC bit face and along the junk slot. The velocity streamline for the 35^o inclination angle shows straight, less turbulence fluid flow. The is the result from the flow of the inner nozzles which is significantly close to the outer nozzles, producing high velocity flows directed straight and along the outer nozzle flowing along the junk slot and up the annulus. However low velocity flows can be seen across the bit face, particularly near to the middle. This can be identified as possible stagnation zone, where drill cutting would accumulate and thus lead to bit balling problems.

As for the 50^o angle, it shows a totally different flow profile where high turbulence and re-circulations can be seen in the junk slot area, where combined with the flow from the inner nozzles create cross flows produces higher velocity flow in the area across the bit face, which is essential for bit cleaning, preventing cuttings accumulations and possibility of bit balling. In TABLE 6 and FIGURE 31, the velocity values along the line are showing the same trend, where the highest values are in the area where the line is in front of the outer nozzle. For inclination of 50^o, 55^o and 60^o the peak highest velocity is not there because the angles are causing the nozzles to be pointing towards the side of the bit. This produces direct flow that hits the annulus wall where the flow is deflected towards the bit face resulting in cross flows with the flow from the inner nozzle, generating higher fluid flow velocity across the bit face.

TABLE 5: Pressure Drop with Different Rotational Speed

RPM	Pressure Drop (Pa)					
	Inclination Angle 35º	Inclination Angle 40º	Inclination Angle 45º	Inclination Angle 50º	Inclination Angle 55º	Inclination Angle 60º
10	130.92	291.77	413.5	429.11	394.26	332.08
30	132.29	293.24	413.69	430.67	396.28	332.44
50	134.1	295.67	416.55	432.45	398.99	334.37
70	137.78	299.78	420.79	434.46	402.59	337.96
90	142.11	304.83	425.66	437.79	406.76	342.78
110	147.19	311.16	431.18	443.99	414.31	349.67

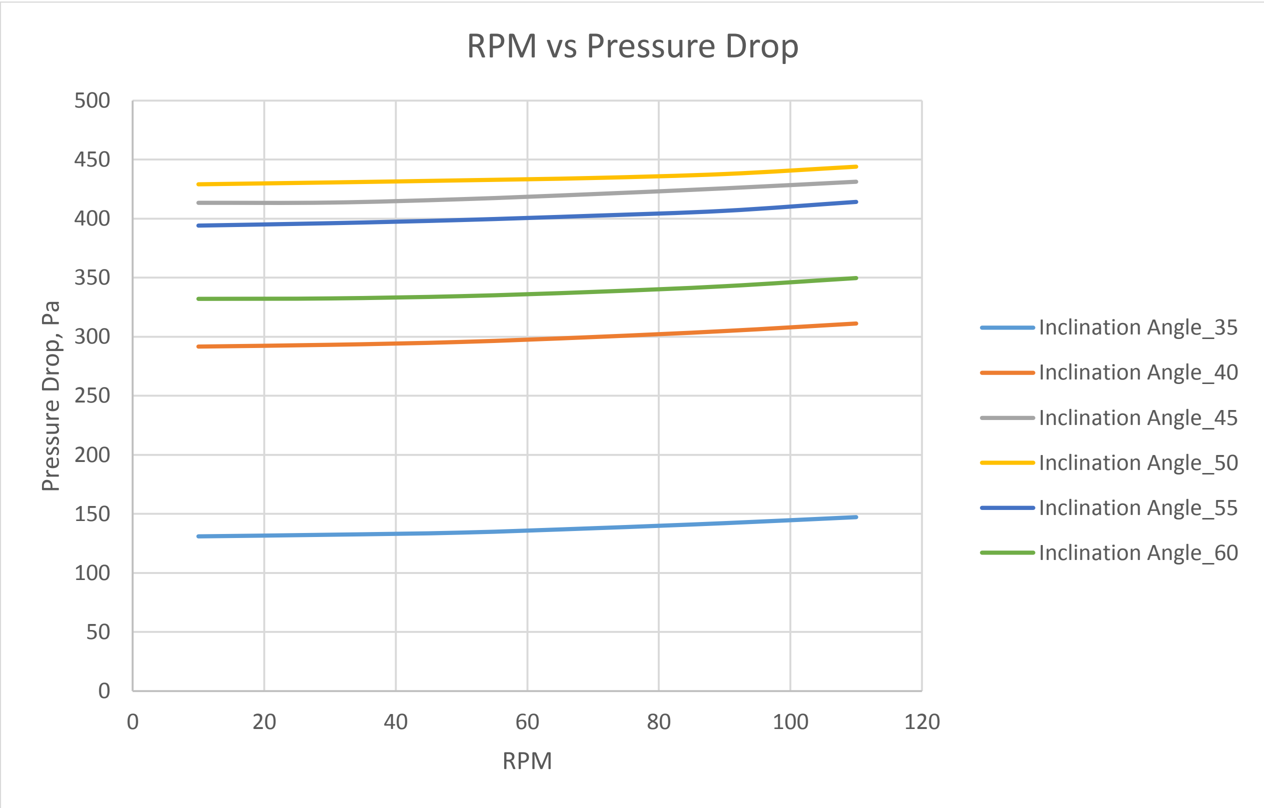

FIGURE 18: Pressure Drop vs Rotational Speed

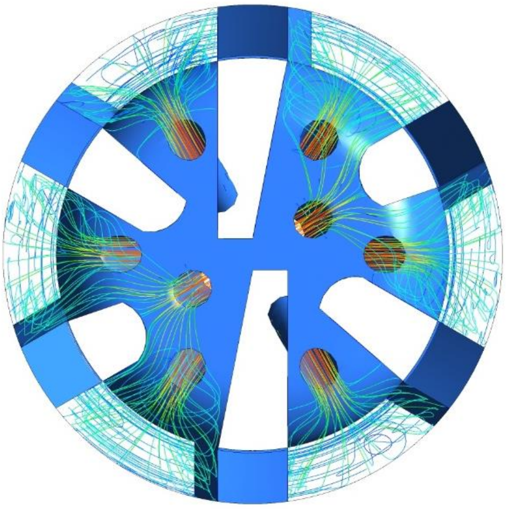

FIGURE 19: Velocity Streamline Topview (35º angle, water)

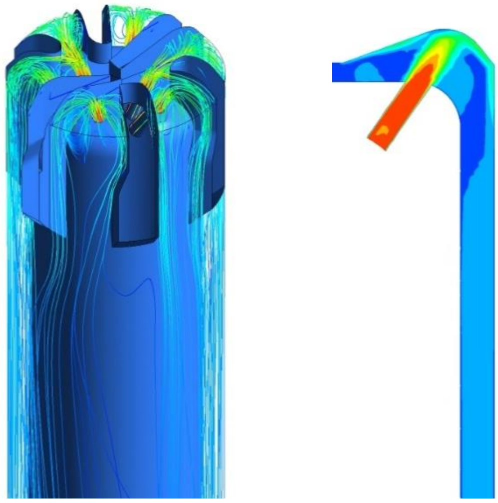

FIGURE 20: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(35º angle, water)

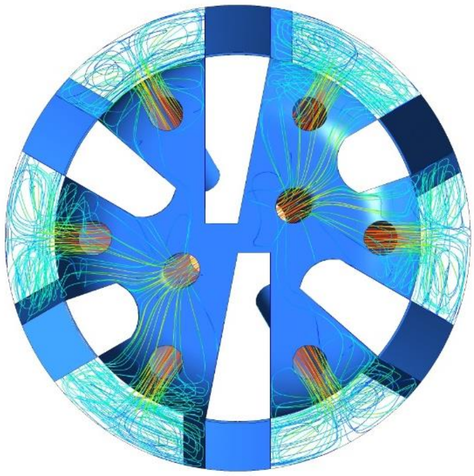

FIGURE 21: Velocity Streamline Topview (40º angle, water)

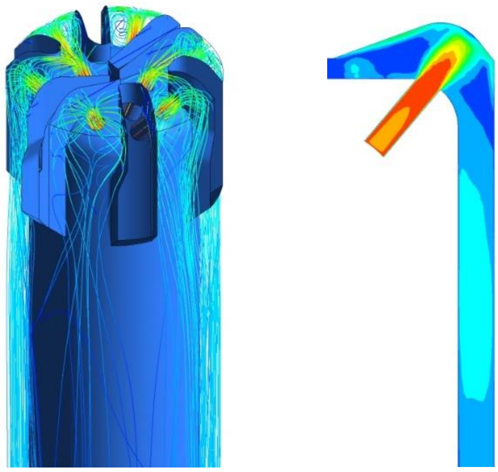

FIGURE 22: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(40º angle, water)

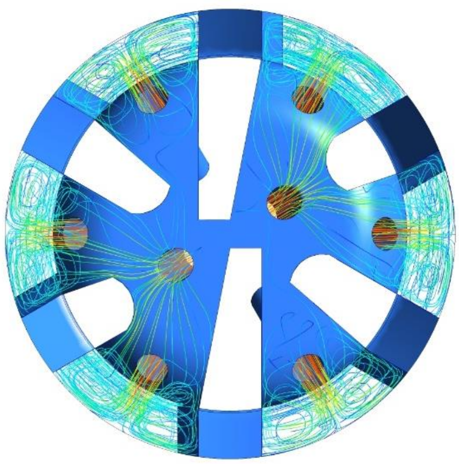

FIGURE 23: Velocity Streamline Topview (45º angle, water)

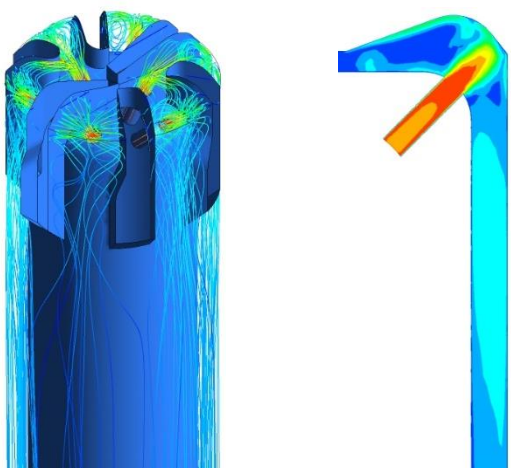

FIGURE 24: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(45º angle, water)

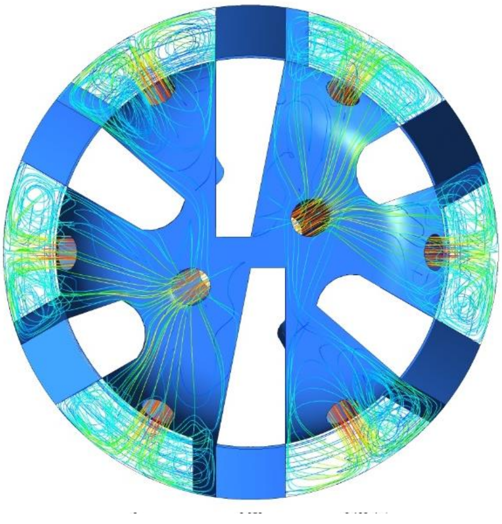	
FIGURE 25: Velocity Streamline Topview (50^o angle, water)	FIGURE 26: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(50^o angle, water)
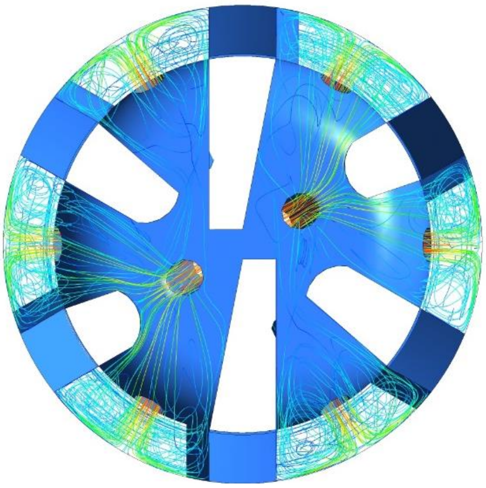	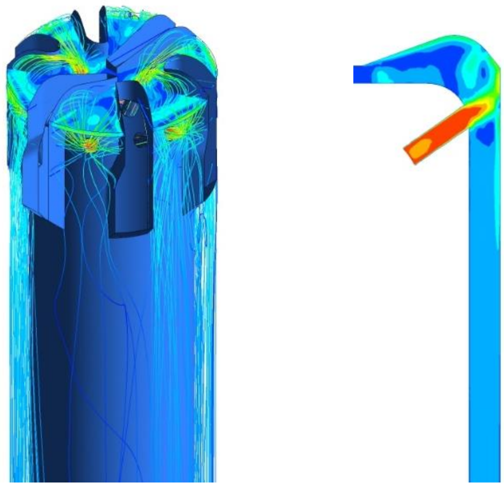
FIGURE 27: Velocity Streamline Topview (55^o angle, water)	FIGURE 28: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(55^o angle, water)
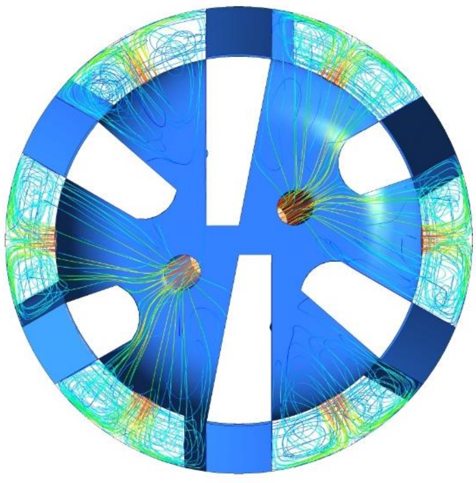	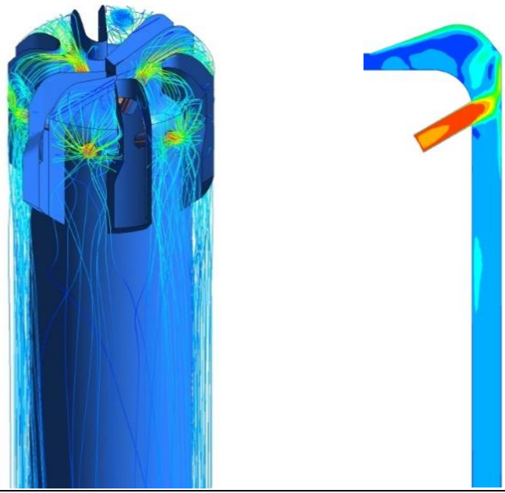
FIGURE 29: Velocity Streamline Topview (60^o angle, water)	FIGURE 30: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(60^o angle, water)

TABLE 6: Fluid Velocity across Bit Face with Different Inclination Angle

Position (X-Axis), m	Fluid Velocity, m/s					
	Inclination Angle 35 º	Inclination Angle 40 º	Inclination Angle 45 º	Inclination Angle 50 º	Inclination Angle 55 º	Inclination Angle 60 º
-1.21E-04	6.82E-02	8.89E-02	5.23E-02	4.99E-02	9.36E-02	1.15E-01
1.17E-02	1.15E-01	1.11E-01	1.19E-01	9.75E-02	1.06E-01	1.78E-01
2.36E-02	2.83E-01	3.12E-01	3.32E-01	4.04E-01	3.52E-01	2.65E-01
3.54E-02	8.39E-02	1.13E-01	1.29E-01	1.71E-01	1.66E-01	1.24E-01
4.73E-02	1.11E-01	9.32E-02	1.27E-01	2.03E-01	2.19E-01	2.52E-01
5.91E-02	1.45E+00	1.42E-01	1.74E-01	2.60E-01	2.14E-01	2.54E-01
7.10E-02	8.08E-01	1.56E+00	1.03E-01	1.39E-01	1.19E-01	1.82E-01
8.29E-02	2.17E-01	1.13E+00	1.23E+00	3.99E-01	4.72E-01	3.19E-01
9.47E-02	1.12E-01	2.83E-01	1.22E+00	4.86E-01	8.74E-02	4.33E-01
1.07E-01	2.57E-01	2.72E-01	2.37E-01	6.39E-01	8.14E-01	5.11E-01

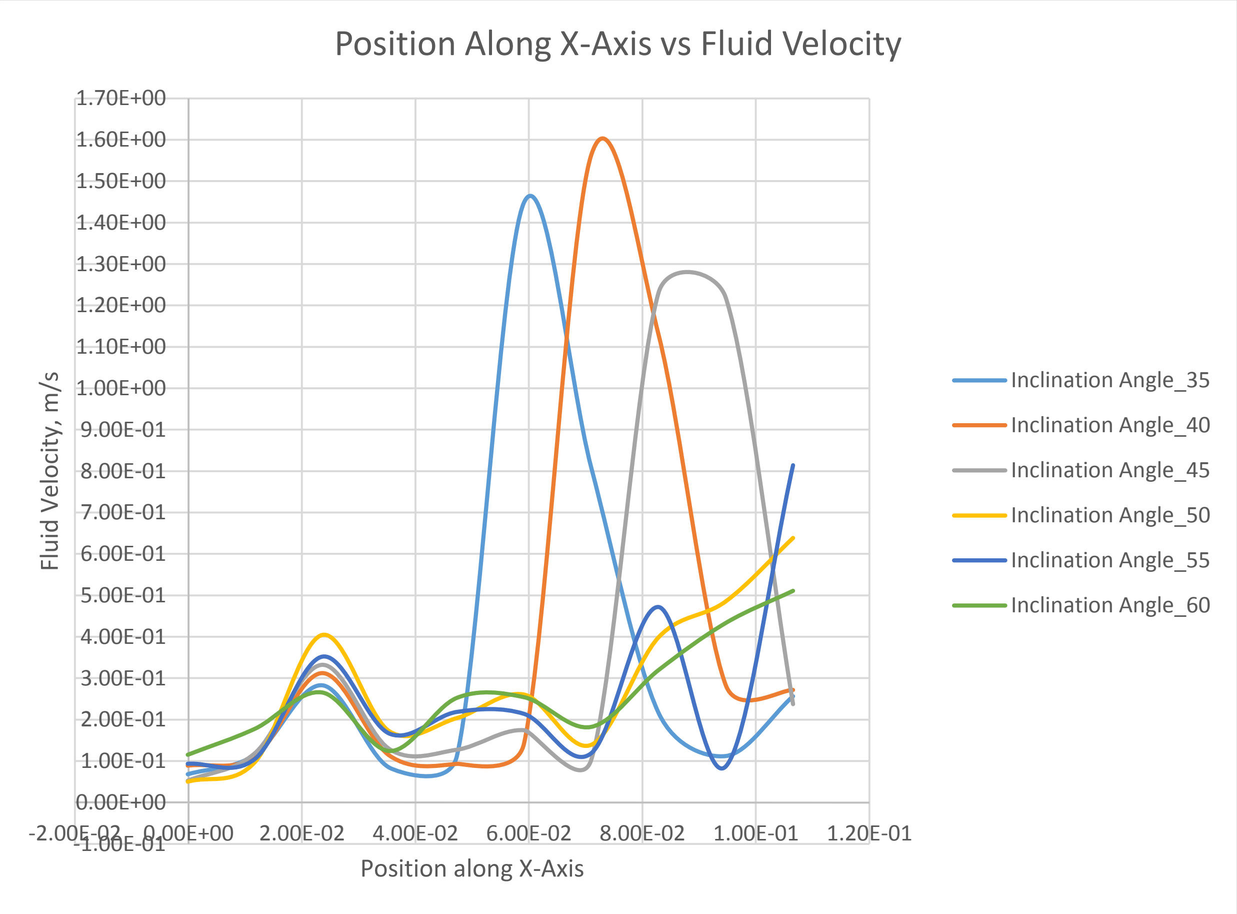

FIGURE 31: Fluid Velocity vs Position along X-Axis

Simulation Results for Foam90 as Drilling Fluid

Based on the results in TABLE 7, the highest pressure drop is now shown by the 35^o inclination angle while the lowest pressure drop values are shown by the 55^o. The difference in pressure drop values are observed to be very small between the varying nozzle inclination angles, with each angle showing similar trends of decreasing pressure drop with increasing bit rotation speed. This shows the opposite trend when compared to the simulation run with water as the drilling fluid. This can be explained based on the characteristics of the Foam90 fluid.

The fluid is determined to be a non-Newtonian Power Law fluid during the setup of the simulation where the n value, which is the flow behaviour index is 0.36. The trend in the pressure drop can be explained as the Foam90 fluid is actually portraying a pseudoplastic fluid characteristics, where the fluid is showing lower apparent viscosity with increasing shear rate. The shear force described is produced by the rotation of the bit, causing shearing and agitation which in turns reveals the behaviour of the fluid.

In terms of the velocity streamline and contours from FIGURE 33-44, all nozzle angles are showing low velocity fluid flow where the flow characteristics is showing straight and steady flow from the bit face moving out of the annulus through the junk slot with almost no turbulence or re-circulation patterns seen, which results in no cross flow to produce higher fluid flow velocities across the bit face.

As the numbers show in TABLE 8 and the plot in FIGURE 45, there is particularly low fluid flow velocity across the bit face with the peak of the highest velocity values are just in the area of the nozzle outlet. Since the parametric study includes the rotation of the bit, slight difference can be seen for the flow characteristics around the drill pipe, where it is seen to help increase the velocity of the fluid in the annulus thus assisting in improving the transport of the drill cuttings.

TABLE 7: Pressure Drop with Different Rotational Speed

RPM	Pressure Drop (Pa)					
	Inclination Angle 35 º	Inclination Angle 40 º	Inclination Angle 45 º	Inclination Angle 50 º	Inclination Angle 55 º	Inclination Angle 60 º
10	2515.8	2567.5	2565.4	2517.8	2467.3	2429.8
30	2405.7	2464	2474.4	2415.6	2359.8	2326.1
50	2287.6	2350	2362.1	2301.3	2242.4	2214.3
70	2184	2249	2262.4	2198.2	2143.4	2115.3
90	2093.4	2162.1	2176.7	2115	2056.6	2029.7
110	2014.2	2086.8	2101.3	2039	1981.4	1955.4

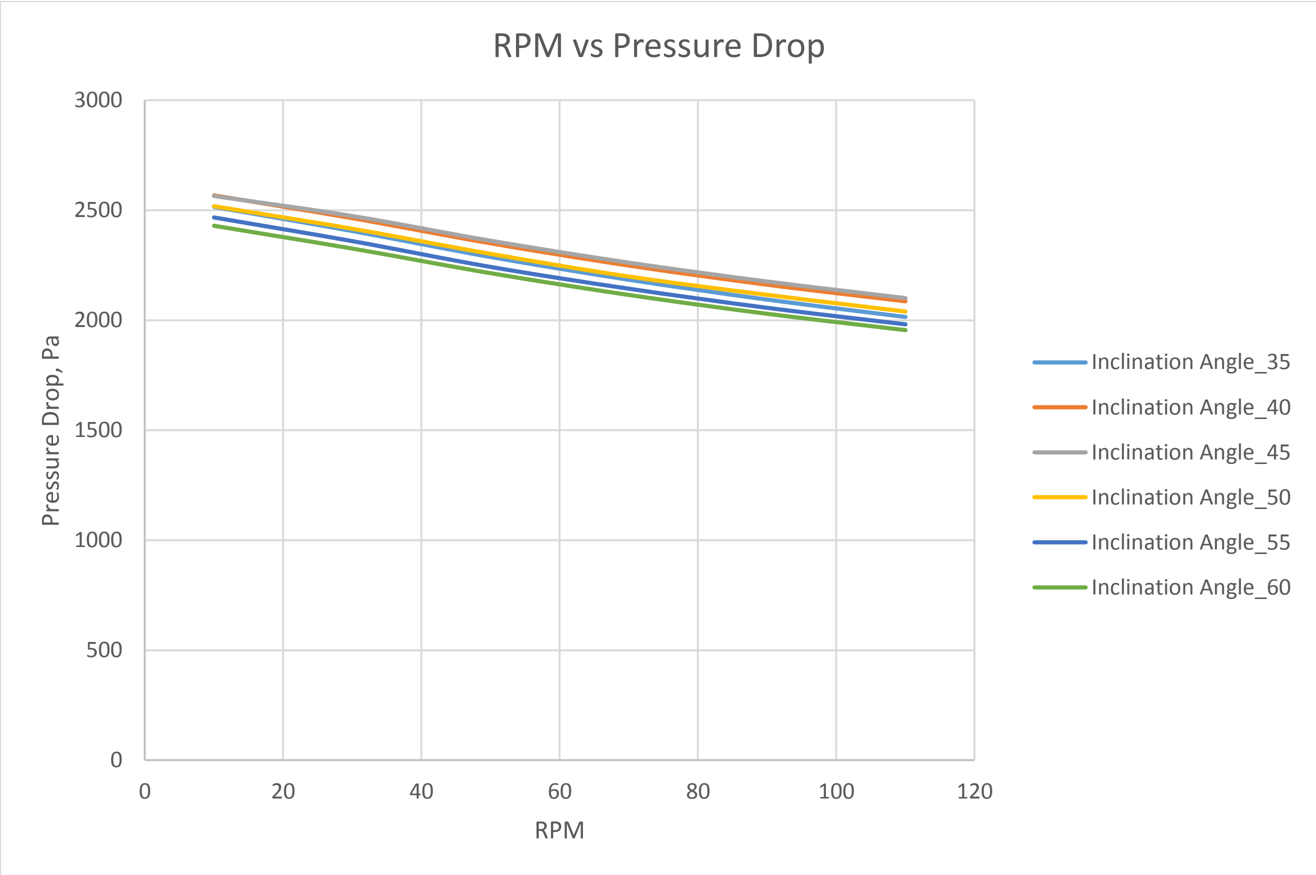

FIGURE 32: Pressure Drop vs Rotational Speed

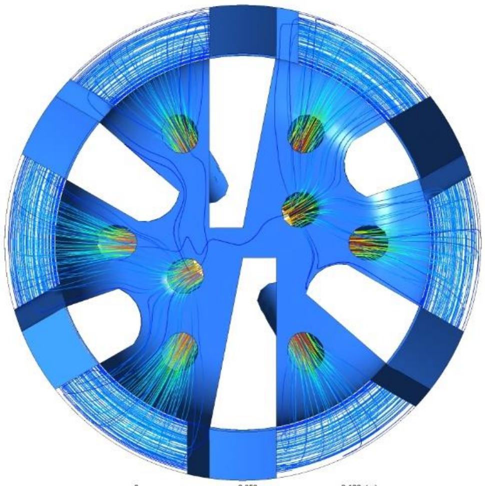	
FIGURE 33: Velocity Streamline Topview (35º angle, Foam90)	FIGURE 34: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(35º angle, water)
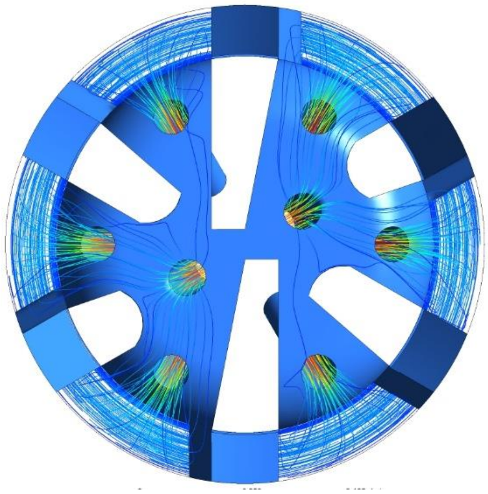	
FIGURE 35: Velocity Streamline Topview (40º angle, Foam90)	FIGURE 36: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(40º angle, water)
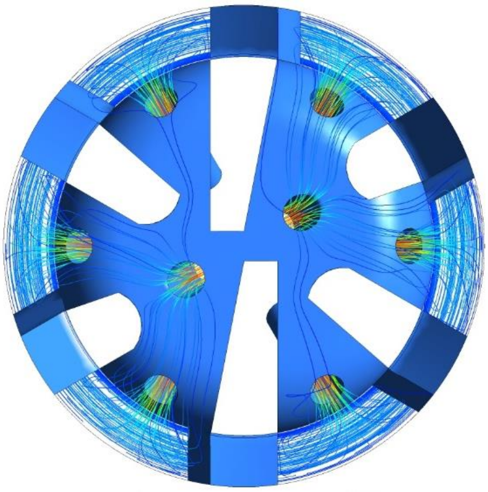	
FIGURE 37: Velocity Streamline Topview (45º angle, Foam90)	FIGURE 38: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(35º angle, water)

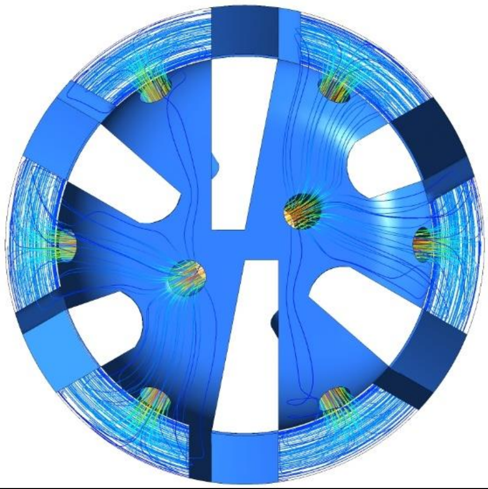	
FIGURE 39: Velocity Streamline Topview (50º angle, Foam90)	FIGURE 40: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(50º angle, water)
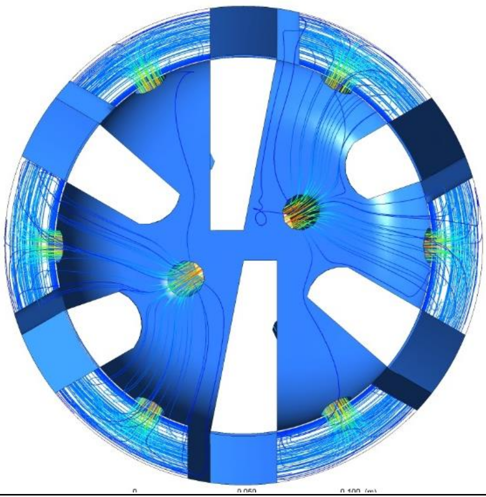	
FIGURE 41: Velocity Streamline Topview (55º angle, Foam90)	FIGURE 42: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(55º angle, water)
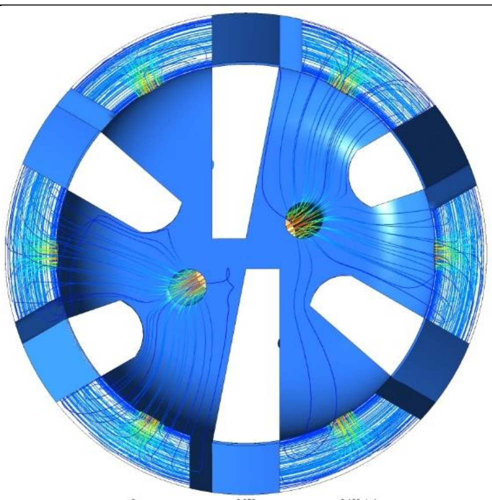	
FIGURE 43: Velocity Streamline Topview (60º angle, Foam90)	FIGURE 44: Isometric View of Velocity Streamline and Velocity Contour along Junk Slot(60º angle, water)

TABLE 8: Fluid Velocity across Bit Face with Different Inclination Angle

Position (X-Axis), m	Fluid Velocity, m/s					
	Inclination Angle 35 º	Inclination Angle 40 º	Inclination Angle 45 º	Inclination Angle 50 º	Inclination Angle 55 º	Inclination Angle 60 º
-1.21E-04	3.48E-03	3.47E-03	3.28E-03	2.74E-03	2.76E-03	3.28E-03
1.17E-02	6.64E-03	6.75E-03	6.13E-03	6.23E-03	6.15E-03	6.28E-03
2.36E-02	6.40E-02	7.61E-02	7.79E-02	6.93E-02	6.96E-02	7.40E-02
3.54E-02	5.00E-02	5.04E-02	5.19E-02	4.54E-02	4.24E-02	4.56E-02
4.73E-02	1.32E-01	1.44E-01	1.22E-01	1.16E-01	1.06E-01	1.20E-01
5.91E-02	1.42E+00	2.05E-01	1.71E-01	1.49E-01	1.37E-01	1.42E-01
7.10E-02	7.74E-01	1.25E+00	1.72E-01	1.60E-01	1.39E-01	1.40E-01
8.29E-02	4.32E-01	7.94E-01	5.11E-01	1.13E-01	1.19E-01	1.30E-01
9.47E-02	2.98E-01	3.58E-01	2.87E-01	5.98E-02	5.11E-02	7.70E-02
1.07E-01	1.02E-02	1.27E-02	4.42E-03	1.43E-03	6.55E-04	2.17E-03

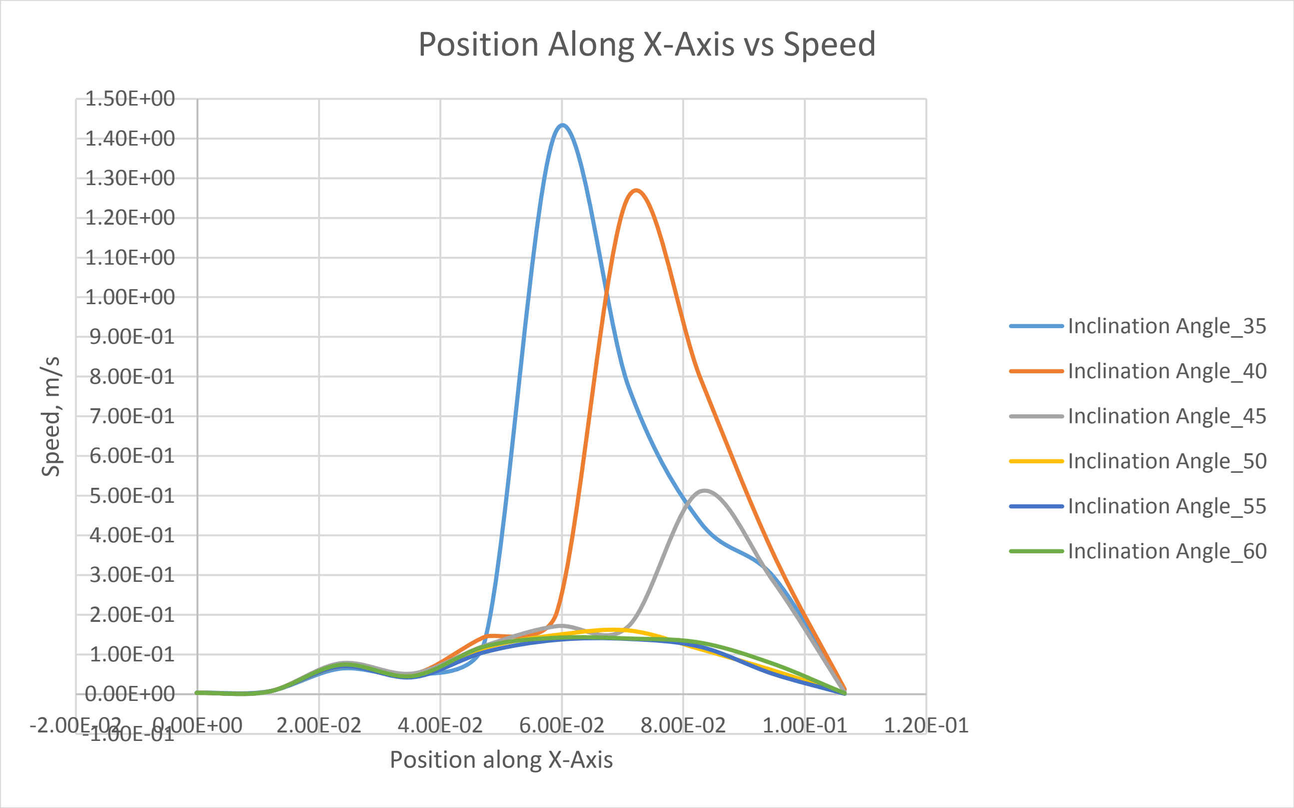

FIGURE 45: Fluid Velocity vs Position along X-Axis

CHAPTER 5

5.1 CONCLUSION

This project has provided a review of the literature associated with effect of nozzle geometry specifically nozzle inclination angle on the hydraulics characteristics of PDC bit and how drilling fluids affect bit hydraulics performance. A number of important conclusion can be stated as follows:

1. Nozzle inclination angle have a significant effect on the fluid flow around the PDC bit however an optimum angle depends on the overall design of the bit.
2. An increase in pipe rotation speed (RPM) makes it necessary to increase the inlet velocity to ensure high fluid velocity across the bit face and along the annulus.
3. Different type of drilling fluid requires different drilling conditions in order to optimize its function of transporting cuttings out of the wellbore.
4. The inner nozzle on the PDC bit plays a major role in providing high velocity fluid flow across the bit face to produce good bit cleaning condition while drilling.

5.2 RECOMMENDATION

The author would like to state several recommendation to further improve the study that have been conducted. Some of the recommendations are:-

- Changing the nozzle inclination angle of the inner nozzles of the bit.
- Use of a different type of drilling fluid such as the modified Herschel-Bulkley model.
- Investigating effect of a curved PDC bit blade design.
- Run the simulation using different PDC bit geometries available.
- Consider the effect of temperature on the flow characteristics and drilling fluid behaviour.

I

REFERENCES

[1] Azar, J. J., & Samuel, G. R. (2007). *Drilling Engineering*: PennWell Books.

[2] Pereira, F., Barrozo, M., & Ataíde, C. (2007). CFD predictions of drilling fluid velocity and pressure profiles in laminar helical flow. *Brazilian Journal of Chemical Engineering, 24*(4), 587-595.

[3] Deen, C. A., Kitagawa, C., Schneider, B., & King, G. (2014). *Aligned Materials and Design Development of High ROP Drill Bits.* Paper presented at the IADC/SPE Asia Pacific Drilling Technology Conference.

[4] Warren, T., & Armagost, W. (1988). Laboratory drilling performance of PDC bits. *SPE drilling engineering, 3*(02), 125-135.

[5] Garcia-Gavito, D., & Azar, J. (1994). Proper Nozzle Location Bit Profile and Cutter Arrangement Affect PDC-Bit Performance Significantly. *SPE drilling & completion, 9*(03), 167-175.

[6] Kerr, C. J. (1988). PDC drill bit design and field application evolution. *Journal of petroleum technology, 40*(03), 327-332.

[7] Watson, G., Barton, N., & Hargrave, G. (1997). *Using new computational fluid dynamics techniques to improve PDC bit performance.* Paper presented at the SPE/IADC Drilling Conference.

[8] King, I., Bratu, C., Delbast, B., Besson, A., & Chabard, J. (1990). *Hydraulic Optimization of PDC bits.* Paper presented at the European Petroleum Conference.

[9] Bilgesu, H., Ali, M., Aminian, K., & Ameri, S. (2002). *Computational Fluid Dynamics(CFD) as a tool to study cutting transport in wellbores.* Paper presented at the SPE Eastern Regional Meeting.

[10] Crouse, R., & Chia, R. (1985). Optimization of PDC bit hydraulics by fluid simulation. *SPE, 14221*, 1-10.

[11] Glowka, D. (1983). Optimization of bit hydraulic configurations. *Soc. Petrol. Engrs J, 23,* 21-32

[12] Moslemi, A., & Ahmadi, G. (2014). Study of the Hydraulic Performance of Drill Bits Using a Computational Particle-Tracking Method. *SPE Drilling & Completion, 29*(01), 28-35.

[13] Sivagnanam, M. (2014). *PDC Drill Bit Redesign and Simulation for Optimized Performance.*

[14] Taylor, M., Murdock, A., & Evans, S. (1999). High penetration rates and extended bit life through revolutionary hydraulic and mechanical design in PDC drill bit development. *SPE drilling & completion, 14*(01), 34-41.

[15] Wells, M., Marvel, T., & Beuershausen, C. (2008). *Bit Balling Mitigation in PDC Bit Design.* Paper presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition.

[16] Yan, L., Shan, X., Seng, Y. S., Suresh, K., Ningbo, W., Jianping, W., ... & Lu, Z. (2014, March). *Innovative Bit Design Coupled with New Cutter Technology Improves PDC Bit Performance in Challenging Changbei Gas Field Application*. In *Offshore Technology Conference-Asia*. Offshore Technology Conference.

APPENDIX

APPENDIX I: Gantt Chart for FYP-1 and FYP-2

No.	Activities	Weeks in FYP-1													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature review														
2	Non-Newtonian Fluid models														
3	Selection of benchmark problem											M1			
4	CAD model and meshing of benchmark problem														
5	Modeling and Simulation of the benchmark problem														
6	Validation of the benchmark problem														M2
7	Standard PDC bit modeling														
8	Simulation of standard PDC bit														
9	Investigation of the effect of mud properties														
10	Investigation of the effect of bit geometry														
11	Investigation of the effect of drilling depth														
12	Further Analysis														
13	Documentation														

No.	Activities	Weeks in FYP-2													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature review														
2	Non-Newtonian Fluid models														
3	Selection of benchmark problem														
4	CAD model and meshing of benchmark problem														
5	Modeling and Simulation of the benchmark problem														
6	Validation of the benchmark problem														
7	Standard PDC bit modeling														
8	Simulation of standard PDC bit					M3									
9	Investigation of the effect of mud properties														
10	Investigation of the effect of bit geometry														
11	Investigation of the effect of drilling depth											M4			
12	Further Analysis														
13	Documentation													M5	

APPENDIX II: Project Milestones

Milestones		Date
M1	Finalized selection of Benchmark Problem	5/12/2014
M2	Completed Simulation & Validation of Benchmark Problem	24/12/2014
M3	Completed Modeling & Simulation of Case Study	13/2/2015
M4	Completed Parametric Study	27/3/2015
M5	Further Analysis & Documentation	10/4/2015