EFFECT OF PDC BIT DESIGN AND DRILLING FLUID ON RATE OF PENETRATION FOR MULTI-LAYER FORMATION

by

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Dissertation submitted in partial fulfillment

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Universiti Teknologi PETRONAS

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31750 Tronoh

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 undertaken or done by unspecified sources or persons.

Nurfatin Adibah Binti Mohd Habib

Abstract

The project focuses on the optimization of Polycrystalline Diamond Compact (*PDC*) drill bit design features for improvement in rate of penetration *(ROP)* for multi-layer formation. Case history shows that conventional *PDC* drill bit failed to complete the section that provides troublesome multi-layer formation. The *PDC* drill bit's performance dropped and affects the rate of penetration. Therefore, an intensive study in *PDC* drill bit design features would help complete the section with high *ROP* if the design features of *PDC* drill bit can be optimized. The enhancement of *ROP* will result in the reduction of the well costs. Other than bit design, drilling fluid also plays a vital role in the drilling process especially in sticky or soft formations. Improper bottomhole cleaning was resulted from a poor drilling fluid circulation which may results in accumulation of cuttings on the bit face that reduces the *ROP*. The project started with getting the *3D CAD* model of conventional *PDC* drill bits by using reverse engineering approach. In this process, *3D* scanner was used to scan the dull *PDC* drill bit and converted the cloud model into a *3D CAD* model. From there, the design features of the model can be improved. Relatively deepened analysis was carried out and come out with four important design parameters that can help in improving the *ROP*. They are bit body material, size of cutter, shape of cutter and row of cutter. The design of drilling simulation experiments are set up using Taguchi method. Nine 3D models of *PDC* bit were selected and drawn in CATIA software. Each 3D model was tested in simulation software to analyze the rate of penetration. The drilling mud simulations were done using the same software to analyze the effect of ROP on the properties of the drilling fluid.

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Abbreviations and Nomenclatures

3D *Three Dimensional*
CAD *Computer Aided Design*
FYP *Final Year Project*
PDC *Polycrystalline Diamond Compact*
ROP *Rate of Penetration*
UCS *Unconsolidated Compressive Strength*
UTP *Universiti Teknologi Petronas*

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Drilling engineering is a challenging discipline in the petroleum industry. The technological developments in the past two decades have been very significant. These developments have allowed the oil industry worldwide to economically and successfully utilize oil and gas field that may have not been possible before. The profits and successes of drilling projects are predicted on the capability of the drilling engineer who fully understands all the engineering aspects and equipment required to drill a usable hole at the lowest costs. (J. J. Azar & Samuel, 2007)

There are many types of drill bit used to drill whether in soft, medium or hard formation. The most challenging part is when the formation is interbedded with hard stringers. The formation usually consists of sedimentary rocks where the majority of petroleum was found in this rock. 98% of hydrocarbon production in sedimentary rocks comes from sandstone and limestones. Bowers, Heavysege, Hamzah, and Passey (2004) stated in the *Formation Evaluation School Book*, sedimentary rocks are formed through physical, chemical or biological processes and is classified under clastics and carbonate. Clastics rocks are defined as those created by physical sedimentation which include conglomerates, sandstones, siltstones, claystones and shale. Clastics are classed by grain size, from conglomerates to sandstones to siltstones to claystones (in order of decreasing grain size). Shale are non-reservoir rocks, fine-grained and composed of clay minerals. Shale provides seals that prevent the migration of hydrocarbon and generate traps.

Even though the overall benefit of a drilling operation is when the cost per foot is reduced, drill bit performance is related to rate of penetration, life and directional response. While more attention is focused on the cutter technology and cutting structure, a further aspect that makes a huge contribution to drill bit performance is drilling fluids. The best possible use of the available hydraulic energy will produce an optimum performance. This is applicable when drilling long or extended wells where both mechanical and hydraulic energy experiences system losses at the bit. (Watson, Barton, & Hargrave, 1997).

In general, drill bit selection is a complicated process but when performed properly, can give a major impact on the total well cost. There are two types of drill bit which are roller cone bit and fixed cutter bit. A roller cone bit comprise one, two or three cones having teeth sticking out of them while a fixed cutter bit has no moving part and can drill a very long hole sections when a proper drilling conditions are given. In this project, the design features that will be optimized by the author is the Polycrystalline Diamond Compact (*PDC*) which is a fixed cutter bit.

1.2 Problem Statement

One of the greatest challenges that any *PDC* bit manufacturer faces today is the extension of *PDC* bit application into hard rock drilling (Clayton, Chen, & Lefort, 2005). Different formations have different strength types and *UCS* value. However, to economically complete the section, multi-layer formation creates a big problem. This is because hard stringers need a bit features that differ with those needed for softer homogenous formations. Case history shows that conventional *PDC* bit failed to complete the section that provides troublesome multi-layer formation. Bit inspection shows intensive chipping of shoulder cutter which is the result from frequent change of rocks hardness. The bit was graded as poor dull condition and not re-runnable. As a result, operators need to consume more money in order to complete drilling in multi-layer formation.

The criteria for an effective cleaning under the bit, which is that the cuttings are removed as fast as they are generated, are based upon the maximized bit horsepower or nozzle-jet impact force. Unfortunately, the design criteria for optimal drilling fluids are not fully understood. There are still many unanswered questions with regards to the effect of bit geometry, nozzle orientation, number of nozzles, layout and blade height on bit-hydraulics performance. (Moslemi & Ahmadi, 2014)

In this project, the author will address issues on the effect of drilling fluid on *ROP* of *PDC* drill bit. The issues are:

1. How to maximize *ROP* of a *PDC* bit when drilled in multi-layer formations?
2. What are the relationship between ROP and properties of the drilling fluid?

1.3 Objective

The objectives of this project are:

1. To investigate the effect of mechanical characteristics of the bit to different rock materials.
2. To reverse engineered the dull *PDC* bit into *3D CAD* model design.
3. To find optimal design features to maximize the *ROP*.
4. To analyze the effect of rate of penetration on the properties of drilling fluid

1.4 Scope of Study

The scopes of study based on the objectives can be simplified as follows:

1. Mechanical characteristics of the bit such as cutting angle, material type and hardness on cutting efficiency and their effect to the behavior of different rock materials.
2. Non-contact method of reverse engineering using *3D* scanner.
3. *CAD* drawing, Catia V5.
4. Drilling simulation software, Ansys Explicit Dynamic and Fluent.
5. Fabrication of the prototype using *3D* printer.

1.5 The Relevancy of the Project

The present project is relevant especially to *Y-UTP* team. This *Y-UTP* team is currently working on a project entitled "Bit Wear and Vibration Study to Aid Drilling Optimization". This team consists of two academic staffs from *UTP*, two research collaborators from *UniKL* and three final year students. The author's effort on completing this project might help *Y-UTP* team to achieve certain limit.

The project is also relevant to the author since it's involves a very comprehensive study on theory and the application. The theory and calculations used comprises of general petroleum and mechanical knowledge which can be applied in the oil and gas industry.

1.6 Feasibility of the Project within the Scope and Time Frame

The project is within the capability of a final year student to be executed with the help and guidance from the supervisor and the lab instructor. Drilling Engineering course is one of the compulsory subjects for a Petroleum Engineering student. Therefore, the author has the knowledge that can be useful for this project. The time frame is also feasible and the project can be completed within the time allocated.

CHAPTER 2

LITERATURE REVIEW

2.1 PDC Drill Bit

The polycrystalline diamond compact *(PDC)* consists of a layer of bonded diamond particles backed up by a thicker layer of a tungsten carbide (Gouda et al., 2011). The use of the *PDC* bits has come to a direct influence factor for economical drilling challenges in offshore. Therefore, the highest benefits could be obtained by using the *PDC* bit when keeping the *PDC* cutter in good conditions.

The introduction of polycrystalline diamond compact *(PDC)* cutter in 1973 has facilitated the maturation of the first drill bit that used synthetic diamonds as cutting elements. The evolution process has progressed so that today a large amount of footage is drilled with *PDC* bits. Through this process, several design features that affect bit performance have become clear. Kerr (1988) mentioned that some of the technological advancement that have been tested are the *PDC* cutter. According to him, a large diameter of *PDC* cutter can provide an increase in exposure which features a higher point loading.

Currently, the *PDC* bits are still evolving. They perform best in soft, firm and medium-hard non-abrasive formation (Bourgoyne, Millheim, Chenevert, & Young, 1986). Good results of these bits have been accomplished in sandstone, siltstone and shale although bit balling is a serious problem in soft formations. Rapid cutter abrasion and breakage are a serious problem in hard abrasive formations.

Figure 1 *Several types of PDC bits that is available.*

2.2 Design Features

For effective drilling, different technological parameters can be applied for different rock types. According to Taylor, Besson, Minto, and Mampuk (1998), to minimize the cutter damage when entering and leaving hard stringers, the shape of the *PDC* bit profile can be redesigned. Bit shape and crown profile are an important design feature of *PDC* bit. The crown shape of bit should be designed within a similar plane or concave conical. Zhu et al. (2012) mentioned that under certain circumstance, the lateral side of bit is very sharp, which is advantageous to deflect without affecting the axial cutting. The crown shape can't be designed to the convex conical, because the lateral cut capacity is very low and it will disturb the lateral cutting rock.

Other important design features of *PDC* bit include the size, shape and number of cutters used and the angle of attack between the cutter and the surface of the exposed formations. Cutter orientation is defined in terms of back rake angle, side rake angle and cutter exposure. Cutter orientation must be properly matched to the hardness of the formation being drilled.

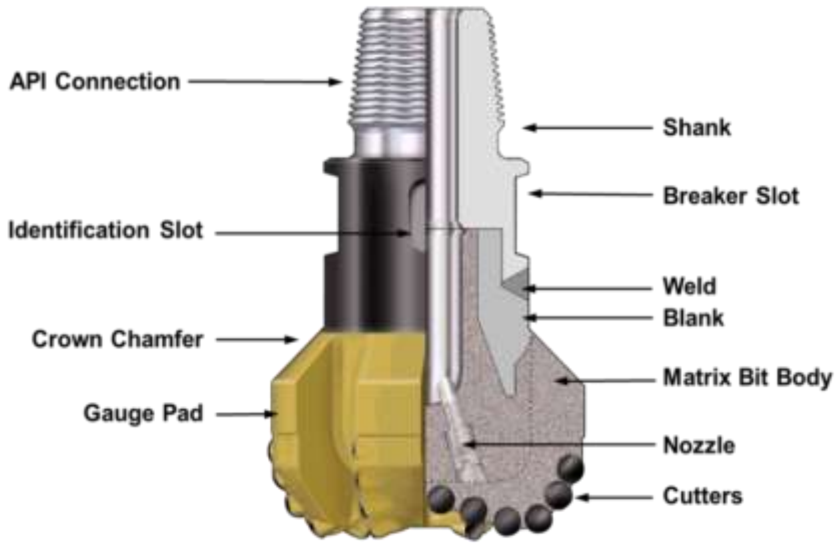


Figure 2 *Component of PDC drill bits.*

Due to the important role that the cutting elements play in the application of the bit, the *PDC* cutters are treated as a unique entity. Each of the major parts of the bit has a number of features. For effective drilling, different technological parameters shall be applied for different rock types.

According to Kerr (1988), the two current PDC bit-body material that are being used are tungsten-carbide matrix and steel. There have not been any definite answer to which of the design is more efficient, but a few characteristics of each have become apparent. Among the differences are those matrixes bits are resistant to wear than steel. However structurally, steel bits are more resilient than matrix bits. An internal steel structure support is required for matrix bits.

Figure 3 *Steel-Body Bit* ***Figure 4*** *Matrix-Body Bit*

Source from Halliburton Drill Bits and Services

Now, steel and matrix are continuously progressing and their restrictions are regularly diminished. Steel bits are greatly being protected with materials that are more resistant to abrasion and erosion than matrix. Concurrently, the structural and wear resisting properties of matrix are swiftly improving. The importance of steel bits is growing relative to matrix bits but both types have their place (M. Azar et al., 2002).

The challenge when drilling any section is to remain on the well profile at the highest penetration rate possible without causing hole problems (Taylor et al., 1998). A high average rate of penetration is required in an interbedded formation so that the total time for a section can be reduced. Larger cutters usually produce larger cuttings that improve cleaning in soft formation. Larger cutters have a high amount of usable diamond volume compared to smaller cutters, thus increase the bit's durability (Taylor et al., 1998). Case history shows that certain formations are believed to respond more positively to width of cut than depth of cut. For that case, larger cutters that cover a wider sideways area will be efficient. On the other hand, smaller cutter provides long bit life in medium-soft to medium hardness formations. Middle-range cutters respond to a midpoint between the softest and the hardest formations.

Figure 5 *PDC Cutters. Source from Kerr (1988) "PDC Drill Bit Design and Field Application Evolution*

Multiple rows of cutter can drill through a variety of lithology without having to sacrifice its performances. Multiple cutters provide a stable, low vibration bit for a tool face control. Less energy is required thus optimizing the efficiency and stability even at a low rate of penetration. For drilling in harder formations, the multiple cutters are used to increase the amount of diamond available to drill without reducing the open face volume of the bit.

Figure 6 *PDC Multiple Row of Cutters. Source from Beaton, Krooshoop, and Herman (2008) "Multi-Row Steel PDC Drill Bit Technology Redefines Performance Standard in Hard, Interbedded and Abrasive Application*

2.3 Drilling Challenges

Among things a drilling engineer need to do is bit selection. Usually, they are not an expert on the bit design. Therefore, they need to depend on the suggestions from the bit manufacturer specialists. According to Nygaard and Hareland (2007) the selection of bit design criteria is commonly indefinite. To justify the basis of the bit selection is sometimes hard for the drilling engineer. One of the greatest challenges that any *PDC* bit manufacturer faces today is the extension of *PDC* bit application into hard rock drilling, where impact damage, heat damage and abrasive wear of *PDC* cutters limits performance (Clayton et al., 2005).

There are many factors and applications that need to be considered in order to do a bit selection or designing a new bit. One of the important factors that can affect the bit performance is the formation being drilled. Different formations have different strength types and *UCS* value. Kamatov (2013) in his article mentioned that special attention is required in multi-layer formations that are highly different in mechanical properties, in particularly strength and abrasivity. Multi-layer formation can be defined as a formations interbedded with another types of formation. The problem becomes more serious when the soft formations interbedded with hard stringers. Zhu et al. (2012) in their research found that there are many interbedded stratums in Western South China Sea oilfields. They are mudstone interbedded with shale and sandstone with the *UCS* of 50 to 120 MPa. Selecting a suitable bit has become difficult especially when the hard stringer are unpredictably scattered throughout the section. Catastrophic failure of *PDC* bit might occur if unsuitable bit are used to drill hard stringer.

Beaton et al. (2008) stated that multi-layer formation often include several trips in order to remove the bit from the hole and change to another bit in an attempt to maximize drilling performance. Selecting the suitable bit becomes increasingly difficult when the hard stringer are unpredictably scattered throughout the section (Taylor et al., 1998).

Figure 7 *Bit condition after drilled in multi-layer formation. Source from Kamatov (2013), Hybrid Drill Bit For Horizontal Drilling In Highly Interbedded Formations Of Timano-Pechora Arctic Fields*

2.4 Optimizing Drilling Performance

Optimizing drilling performance is frequently interpreted as maximizing penetration rate. However, this is not always the case as in some applications drilling performance will be optimized by maximizing run length and reducing the number of trips. In these applications, an example of which is interbedded formations, the goal is to protect the cutting structure so it may be necessary to compromise penetration rate for run length.

2.5 Drilling Fluid

The development of oil and gas industry has driven the exploration and production sector to search for new resources in unexplored areas and in deeper formation. Deeper formation has a higher temperature and pressure. Therefore, in order to drill a deeper formation, the selection of drilling fluids that can withstand high temperature and high pressure are important. High Pressure and High Temperature (HPHT) wells have a bottom hole pressure of 10,000 psi and bottom hole temperature of 150°C or higher. (Amani, Al-Jubouri, & Shadravan, 2012)

Water-Based mud (WBM) and Oil-Based mud are most commonly used drilling fluids and they have some similar characteristics that meet the requirements to drill a HPHT wells. The most common problem affecting drilling fluids in HPHT wells, is the possibility of the mud destruction under such high temperature and pressure. Hence, it has to have a proper mud balance in order to avoid formation damage, oil and gas surge, kicks, and other drilling hazards related with HPHT wells.

Generally, drilling fluid properties can significantly affect the rate of penetration. One of the functions of drilling fluid is for cooling purposes. Very essential to the life of PDC cutter is the temperature it reaches while drilling. Heat is generated at the interface between the cutter and the rock due to the friction against the rock (Crouse & Chia, 1985). The removal of the heat is by convective cooling of the mud flowing past the cutter. To keep the temperature of the cutter as lows as possible, but still has a high ROP, the cooling of each of the cutter must be maximized. The cooling rate is dependent on the mud properties and the velocity and direction of the mud flow around the cutter. Since the bit designer does not have control over the mud properties, he can shape the bit to optimize the mud flow around each cutter.

2.6 Finite Element Analysis (Explicit Dynamics)

Finite Element Analysis (FEA) is a computer model of a material or design that is analyzed to get specific results. It is used in existing or new product refinement. A company can verify a proposed design to meet client's specifications subject to manufacturing or construction. Modifying an existing product or structure is utilized to improve or qualify the product for a new service condition. If the model fails, FEA is very useful to help designer to modify back the design to meet the targeted condition. FEA help analyst to predict failure due to unknown stresses by showing problem areas on an object and giving chances for designers to see all of the theoretical stresses within. This method can help to reduce manufacturing costs and time rather than making and testing the real component(Szabo, 1991). Explicit Dynamics is one of the features in Finite Element Analysis. The ANSYS explicit dynamics product suite helps user to gain insight into the physics of short-duration events for products that undergo highly nonlinear, transient dynamic events. These specialized, accurate and easy-to-use tools have been designed to maximize productivity. With the ANSYS explicit dynamics products, the author can study how a structure responds when subjected to severe loadings. Algorithms based on first principles accurately predict responses, such as large material deformations and failure, and interactions between bodies and fluids with rapidly changing surfaces.

2.7 Computational Fluid Dynamic (Fluent)

One of the biggest providers of commercial computational fluid dynamics (CFD) software and services is Fluent. Fluent provide general-purpose CFD software for a wide range of industrial applications, together with highly automated, packages. ANSYS Fluent software contains the broad physical modeling capabilities needed to model flow, turbulence, heat transfer, and reactions for industrial application ranging from air glow over and aircraft wing to combustion in a furnace and from bubble columns to oil platform.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Project Flow Chart

Figure 4 below illustrate the flow chart diagram for this project.

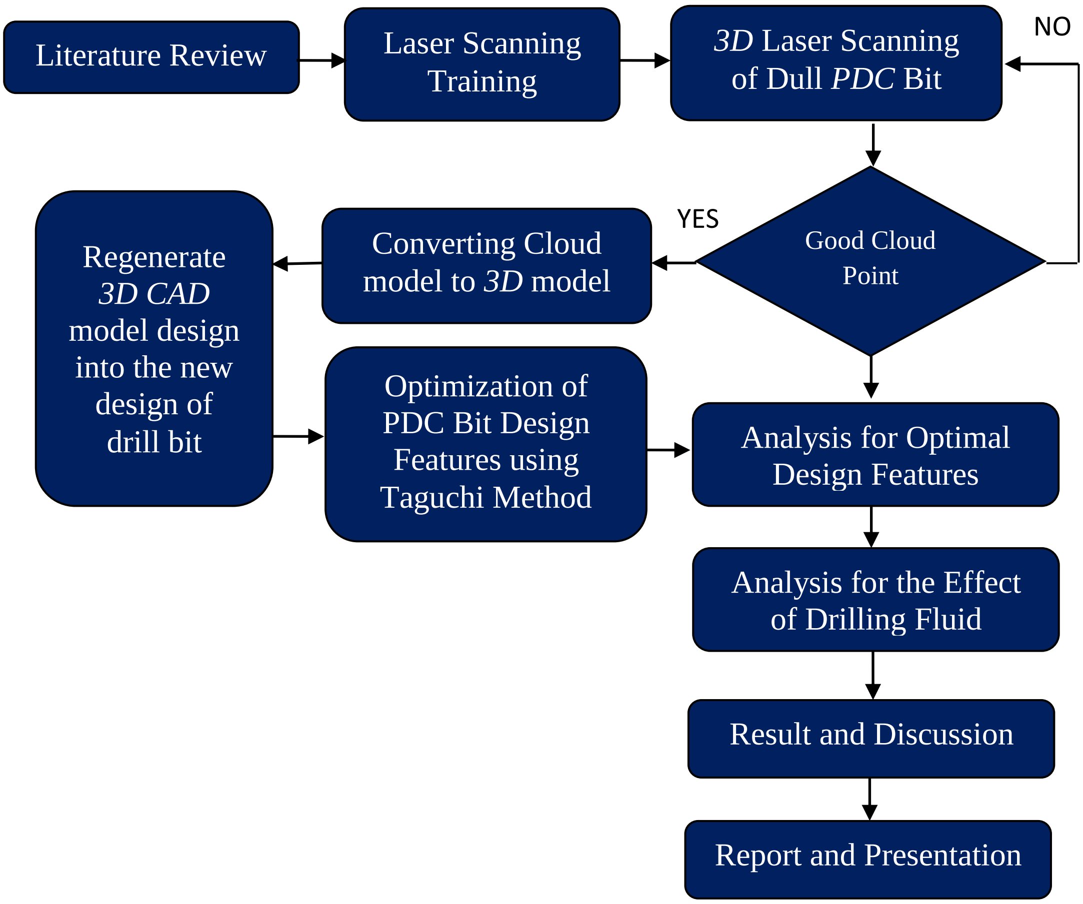


***Figure 8** Project Flow Chart*

The project started with the preliminary research on existing studies on the topic from various articles. At this stage, the author study the effect of mechanical characteristics of the bit cutters, the profile of the *PDC* drill bit and the case history on *PDC* drill bit's performance. The author undergoes one day training on laser scanning in order to apply reverse engineering approach on this project. In reverse engineering, a dull *PDC* drill bit was used for scanning purpose. Scanning process was repeated until a good point of cloud generated. After that, the complete cloud model was converted into *3D CAD* model and ready to be redesign in *CAD* drawing software, CATIA. The optimized 3D CAD model of PDC bit is then run in drilling simulation software to generate result of bit's performance.

3.2 Reverse Engineering

In this project, reverse engineering method has been used in getting the *3D CAD* model of conventional *PDC* drill bit. The reason why the author chooses reverse engineering method is because of time limit. The author only has 8 weeks to generate the *3D CAD* model of conventional *PDC* drill bit. Reverse engineering help minimize time consumptions in generating *3D CAD* model of *PDC* drill bit. According to Y. Zhang (2003), the difficulties of creating a *CAD* model of an existing product that has a free-form surface or a sculptured surface in engineering area such as aerospace, automotive, shipbuilding and medicine can be solved by using reverse engineering approach. In this project, the author gain benefits from the application of reverse engineering as the *CAD* model of *PDC* drill bit has been generated in just 1 week time. This project used dull *PDC* drill bit borrowed from Petroleum Department of Universiti Teknologi Petronas in order to generate the *CAD* model. The details of the dull *PDC* drill bit are shown below.

Table 1 *Product specifications*

Product Specifications			
Nomenclature	M50BPX	No. of Blades	6
Size	6 inches	Cutter Quantity	34
Manufactured by	SMITH Bits	No. of Nozzles	3
Condition	Used/Not Rerunable	Connection	3 ½ API REG

Figure 9 Dull PDC drill bit

3.3 Scanning Dull PDC Drill Bit

The dull *PDC* drill bit was scanned by using *3D* VIUscan scanner. VIUscan scanner captured every detail and deliver hyper realistic results. The scanning process setup is shown in figure below.

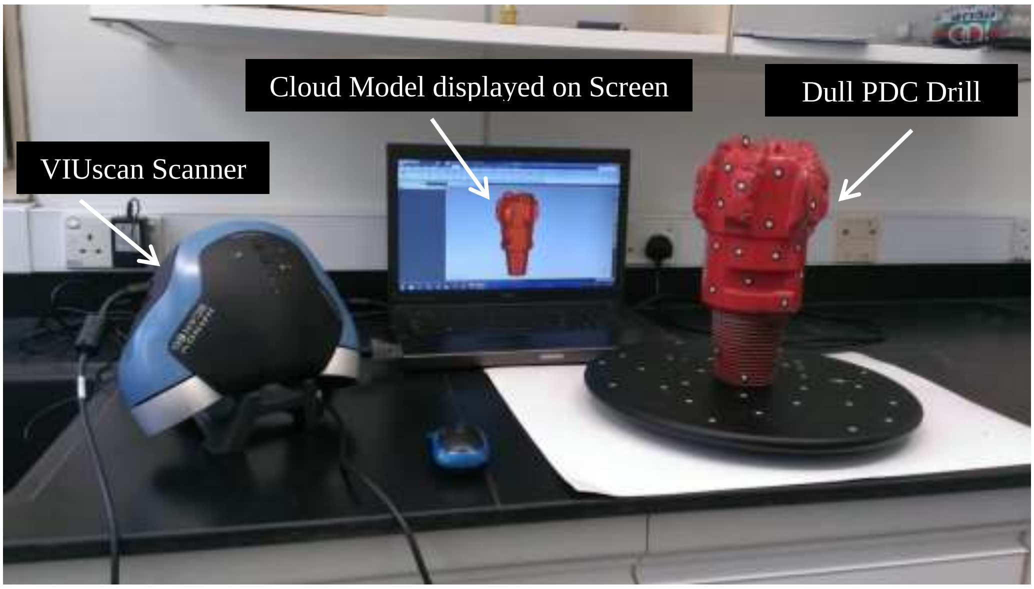


Figure 10 *Scanning Set-Up*

From the scanning process, the cloud model of dull *PDC* drill bit has been obtained. However, the cloud obtained was not perfect as a lot of noise produced. This is caused by the small particles in the air surround the dull *PDC* drill bit.

Figure 11 *Scanning Process* ***Figure 12*** *Initial Cloud Model of Dull PDC Bit*

After the scanning process completed, the VXelement software was used to remove the noise and facets surround the *3D* cloud model.

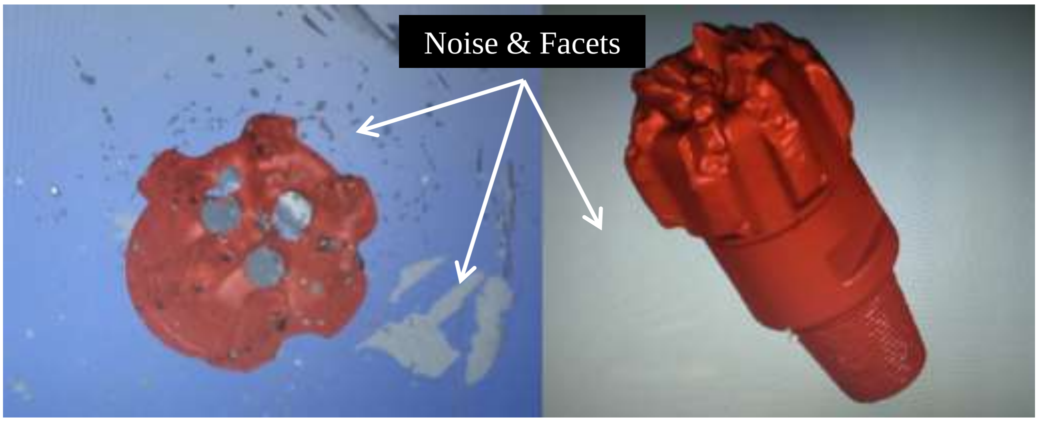


Figure 13 *Process of Removing Noise and Facets in VXelement Software*

3.4 Converting Cloud Model into *3D CAD*

The cloud model obtained from the *3D* scanning process is then used in GeoMagic12 software to generate the *3D CAD*. The *3D CAD* model is ready to redesign or regenerate in any designing software.

Figure 14 *3D CAD Model of PDC Drill Bit*

3.5 Design Features

Drill bit design features are one of the important factors affecting the drill bit's performance. In this project, we can say that design features are the input parameters and bit's performance is the output considerations. The author had find out the possible input and output parameters and listed in table 5 below.

Table 2 *List of Input and Output Considerations*

No.	Input (Design Features)	Output
1	Bit body *a. Material (Matrix/Steel)* *b. Profile (Short/Medium/Long)*	Rate of Penetration (ROP) *a. Meterage/Interval/Footage* *b. Drilling hours*
2	Cutter *a. Size of cutter* *b. Type of cutter* *c. Interface* *d. Shape of cutter* *e. Backup cutters* *f. Cutter edge geometry* *g. Diamond carbide Interface* *h. Back Rake*	Dull Grading *a. Inner area* *b. Outer area* *c. Dull characteristics* *d. Gage condition (undergauge/ingauge)* *e. Reason pulled*
3	Blade *a. No. of blade* *b. Style of the blade (Spiral/Straight)*	Properties of the drilling fluid *a. Velocity of the drilling fluid* *b. Heat transfer coefficient*
4	Junk Slot Area/Face volume	
5	Nozzle *a. Nozzles orientation* *b. No of Nozzles* *c. Size of the nozzles*	
6	Gauge *a. Gauge design* *b. Gauge length* *c. Gauge cutters* *d. In-gauge cutters* *e. Gauge pads*	
7	Hardfacing	
8	Bit Stability Features	
9	Updrill Option/Backreaming	

Due to time constraint, the author only choose the important design features (input) in *PDC* drill bit for this project. They are bit body material and cutter design which plays an important role in the effect of rate of penetration on drilling fluid for multi-layer formation. The author believe these two design features contribute the most in *PDC* bit's performance based on the articles reviewed.

Table 3 *Tools parameter*

No.	Parameter	Constant
1	Formation	Interbedded soft to medium hard formation
2	Bit Size	8.5"
3	Bit Material	Tungsten Carbide
5	Material of Cutter	Carbide
6	No. of Blade	6

Table 4 *Operating parameter*

No.	Parameter	Constant Value
1	Weight on Bit (WOB)	300k lb
2	Rotation per minute (RPM)	300 rpm

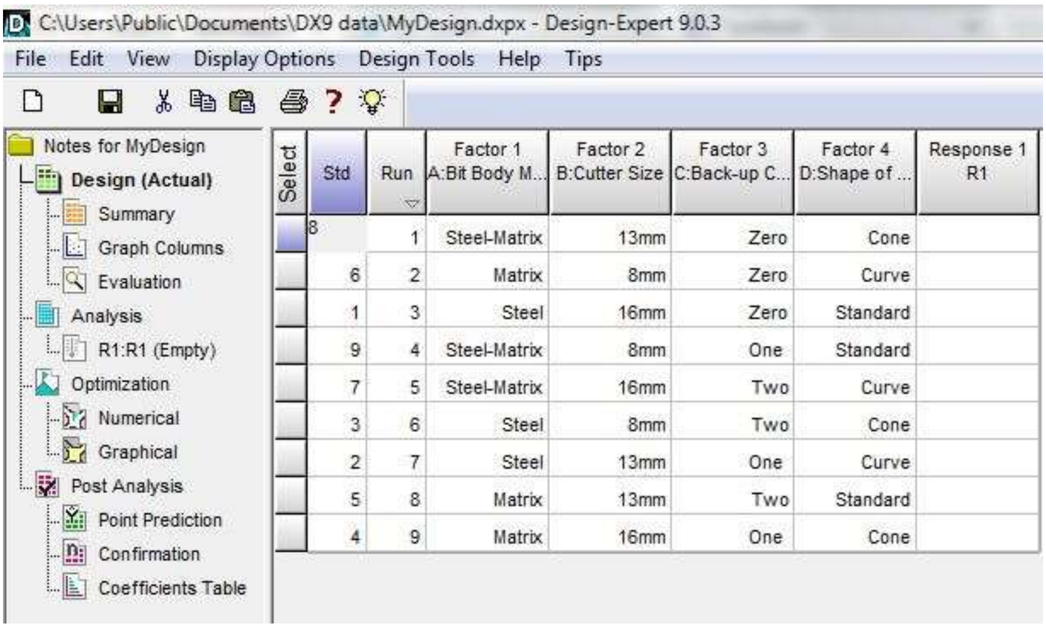
The value chosen for the parameters above are based on the data from case history drilled on 8.5" hole, multi-layer formation in a well in Malaysia.

3.6 PDC Bit Optimization

After deciding the value and type of each parameter, the author combines each parameter by using Taguchi method in order to optimize PDC bit. Below are the parameter and level chosen by the author.

Table 5 *Parameter and Level Chosen*

Parameter	Bit Body Material	Size of Cutter	Back-Up Cutter	Shape of Cutter
Level 1	Steel	16 mm	Zero	Standard
Level 2	Matrix	13 mm	One	Curve
Level 3	Steel-Matrix	8 mm	Two	Cone



Std	Run	Factor 1 A:Bit Body M...	Factor 2 B:Cutter Size	Factor 3 C:Back-up C...	Factor 4 D:Shape of ...	Response 1 R1
8	1	Steel-Matrix	13mm	Zero	Cone	
6	2	Matrix	8mm	Zero	Curve	
1	3	Steel	16mm	Zero	Standard	
9	4	Steel-Matrix	8mm	One	Standard	
7	5	Steel-Matrix	16mm	Two	Curve	
3	6	Steel	8mm	Two	Cone	
2	7	Steel	13mm	One	Curve	
5	8	Matrix	13mm	Two	Standard	
4	9	Matrix	16mm	One	Cone	

Figure 15 *Results from Taguchi Method using Design Expert Software*

Taguchi through Design Expert software suggests nine runs to be simulated. Each of the run contains different level from every parameter. In order to get response for each run, the author need to draw nine different design of PDC bit based on the results shown in Figure 19.

3.7 3D Drawing

3D model of optimized PDC bit are drawn using CATIA software. The author re-scales the diameter of the 3D CAD model of worn PDC bit generated by using reverse engineering method from 6 inch to 8.5 inch.

3.7.1 3D Model of Bit Body

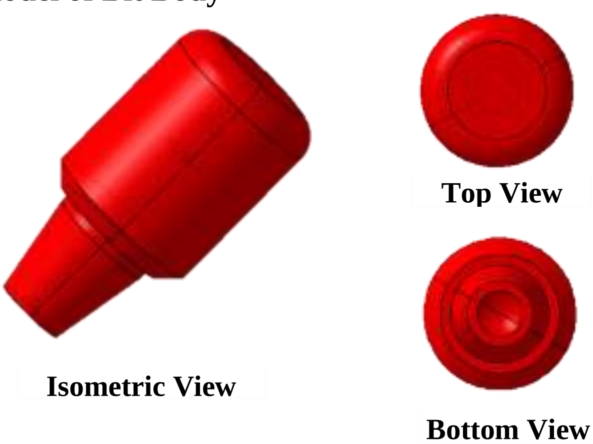
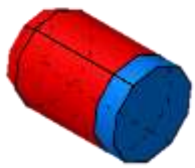
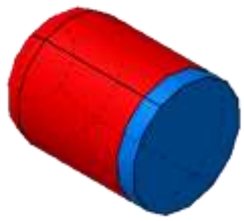
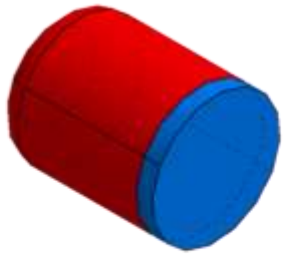


Figure 16 *3D Model of Bit Body: Isometric, Top and Bottom View*

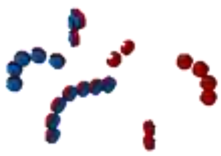
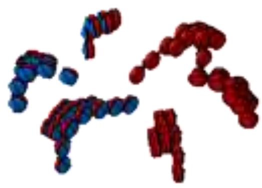
3.7.2 3D Model for Size of Cutter

Table 6 *3D Model for Size of Cutter*

View/Level	8 mm	13 mm	16 mm
Isometric			

3.7.3 3D Model for Back-Up Cutter

Table 7 *3D Model for Back-Up Cutter*

View/Level	Zero	One	Two
Isometric			

3.7.4 3D Model for Shape of Cutter

Table 8 *3D Model for Shape of Cutter*

View/Level	Standard	Curve	Cone
Isometric			

The author draws each level in every parameter separately in CATIA mechanical part design. To generate one 3D model of PDC bit, mechanical assembly design was used to import each level in every parameter. This method minimizes the time consumption as the author will not have to redraw the same level for the next 3D model of PDC bit.

3.7.5 3D Model of Rock Formation

Figure 17 *3D Model of rock formation*

Each level in every parameter was drawn separately by the author in CATIA mechanical part design. Mechanical assembly design was used to import each level in every parameter to generate one 3D model of PDC bit. This step is less time consuming as the author will do not have to redraw the same level for the next 3D model of PDC bit. Figure 20 shows one of the optimized PDC bit with the rock formation in mechanical assembly design drawn in CATIA software. It is for run number 1, the combination of steel-matrix body material, 13mm cutter, zero back-up cutter and coned cutter. The 3D model in figure 25 is then saved to .stp file type for future use in ANSYS for drilling simulation.

Figure 18 *3D Model of PDC bit in assembly design*

3.8 Drilling Simulation

3.8.1 Structural Simulation

The design of products that need to survive impacts or short-duration high-pressure loadings can be greatly improved with the use of ANSYS explicit dynamics solutions. These specialized problems require advanced analysis tools to accurately predict the effect of design considerations on product response to severe loadings. Understanding such complex phenomena is especially important when it is too expensive or impossible to perform physical testing. Typical applications used in explicit dynamics are drop tests, impact and penetration. In this project, the author would like to study on the penetration rate of the *PDC* bit. Thus, ANSYS explicit dynamics is the most suitable analysis for this project. Figure below shows the optimized PDC bit with the rock formation in ANSYS explicit dynamic.

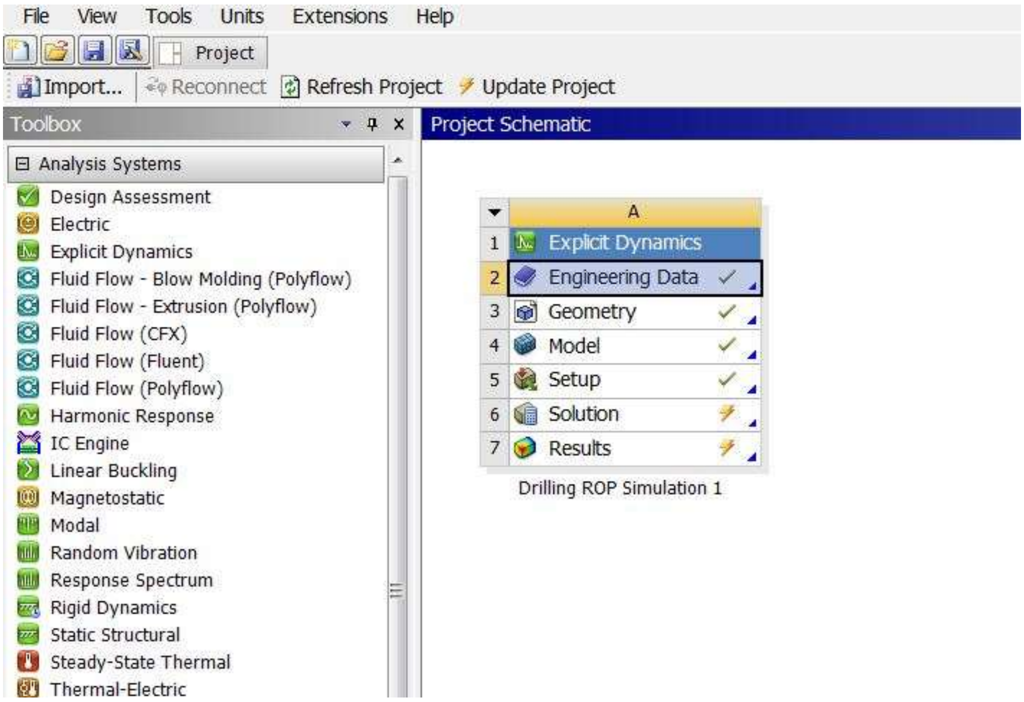


Figure 19 *Explicit dynamic component analysis*

Engineering Data

The properties and material for the component will be used in the analysis is defined in engineering data. Table below shows the material and properties used for the analysis.

Table 9 *Engineering data: Material properties*

	Material	Properties
Cutter	Polycrystalline Diamond Compact	Density: 3250 kg m^-3 Young's Modulus: 1.5231E+08 Poisson's Ratio: 0.38462 Bulk Modulus: 2.2E+08 Shear Modulus: 5.5E+08
Bit body	Tungsten Carbide	Density: 19300 kg m^-3 Young's Modulus: 3.968E+11 Poisson's Ratio: 0.24 Bulk Modulus: 2.5436E+11 Shear Modulus: 1.6E+11
Rock formation 1	Limestone	Density: 1580kg m^-3 Young's Modulus: 3.2034E+09 Poisson's Ratio: 0.14407 Bulk Modulus: 1.5E+09 Shear Modulus: 1.4E+09
Rock formation 2	Sandstone	Density: 2650kg m^-3 Young's Modulus: 1.8456E+08 Poisson's Ratio: 0.2 Bulk Modulus: 1.0253E+08 Shear Modulus: 7.69E+07
Rock formation 3	Coal	Density: 2650 kg m^-3 Young's Modulus: 9.5756E+10 Poisson's Ratio: 0.063953 Bulk Modulus: 3.66E+10 Shear Modulus: 4.5E+10
Rock formation 4	Dolomite	Density: 2872 kg m^-3 Young's Modulus: 1.1657E+11 Poisson's Ratio: 0.29527 Bulk Modulus: 9.49E+10 Shear Modulus: 4.5E+10

Geometry

The 3D model of PDC bit and multi-layered rock formation in .stp format are imported into ANSYS Geometry and open in Workbench Mechanical for analysis setting.

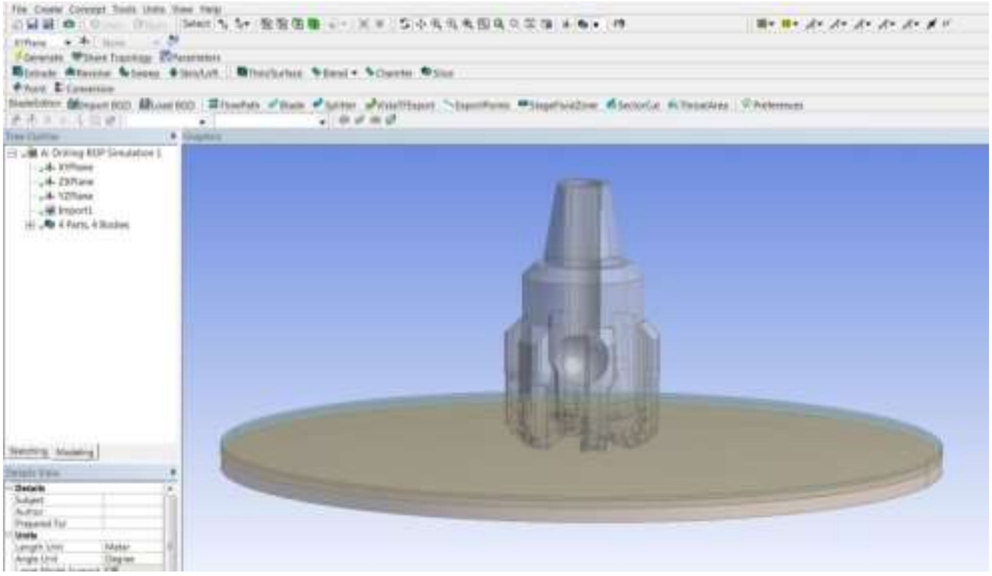


Figure 20 *Workbench Mechanical interfaces*

Material of the geometry, coordinate systems, connection, meshing properties, initial condition and analysis setting are defined in ANSYS Workbench Mechanical.

Coordinate Systems

In ANSYS Mechanical, coordinate systems reside in the Model Tree between Geometry and Connections. In this project, three coordinates was set-up under coordinate systems. There are global coordinate system, coordinate system 1 and coordinate system 2.

Global coordinate system has an ID of 0, and sits at 0,0,0. The value cannot be changed. Coordinate system 1 is used for the rotation of PDC bit. The direction of Y axis rotate clockwise while X and Z axis is the same as global coordinate system. The third coordinate system is used for constant load on top of the bit. Figure below shows the three coordinate systems used for the analysis.

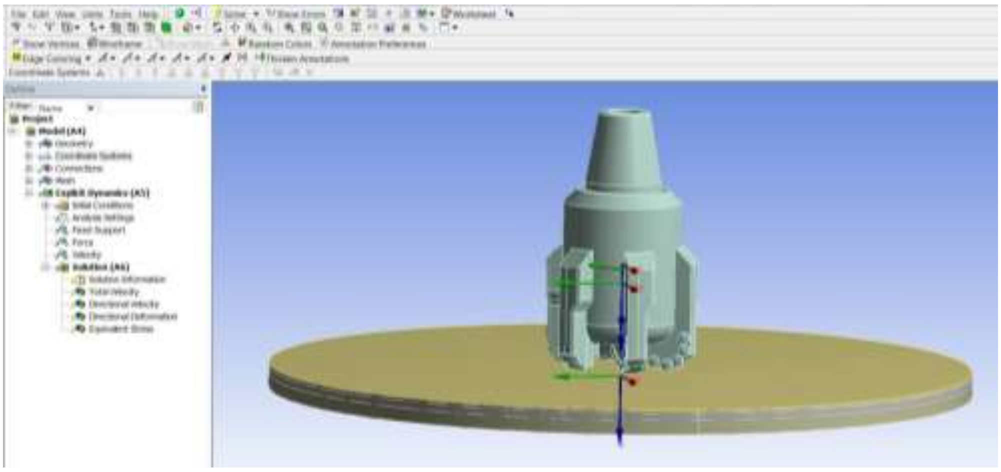


Figure 21 *Coordinate systems*

Meshing

Meshing is one of the important aspects in engineering simulation. Meshing is an integral part of the computer-aided engineering simulation process. The mesh influences the accuracy, convergence and speed of the solution. The meshing setting and pattern for this project was set as shown in figure below.

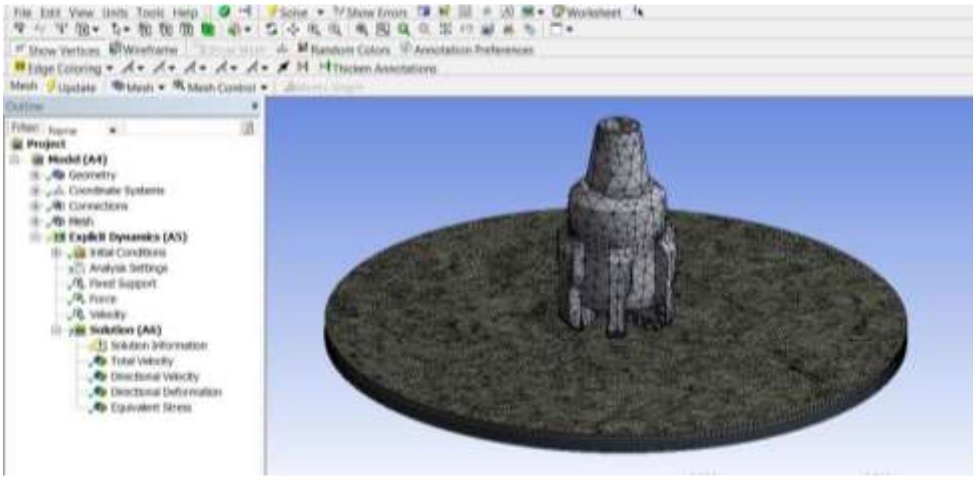


Figure 22 *Meshing setting and pattern*

Explicit Dynamics

For an Explicit Dynamics system, the Initial Conditions folder includes a Pre-Stress object to control the transfer of data from an implicit static or transient structural analysis to the explicit dynamics analysis. Transferable data include the displacements or the more complete Material State (displacements, velocities, stresses, strains, and temperature) while the Analysis Settings include erosion, boundary condition and body interaction are defined under explicit dynamics. Angular velocity of 300 rpm is defined as initial condition. Other parameters such as force on top of the PDC bit, the constant angular velocity of PDC bit and fixed support of rock formation are inserted under analysis settings as shown in figure below.

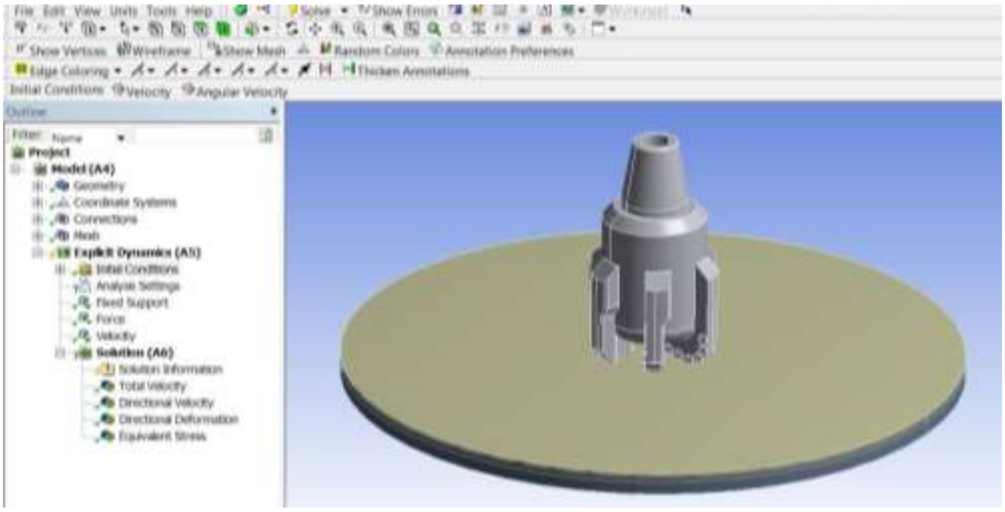


Figure 23 *Explicit Dynamic*

In the real drilling situation, weight on bit (WOB) is the weight of the drill pipe up to the surface. This weight acting as a force to push the PDC bit into the rock formation. In this drilling simulation, the author defined the value of WOB as 100 000 Newton. Fixed support for the outer diameter of rock formation is defined in order to prevent it from moving due to impact from PDC bit.

After all the settings are defined, the analysis now can be solved. For this project, the type of solution used is “Total Velocity” to analyze the rate of penetration of PDC bit in meter per seconds. The target solver for this analysis is AUTODYN.

3.8.2 Drilling Fluid Simulation

ANSYS Fluent is a superior in multiphase modeling technology. Engineers manage to gain insight into equipment that is often difficult to probe due to its diverse capabilities. ANSYS Fluent complete suite of models allows it to apprehend the interplay between multiple phases like gases and liquids, dispersed particles and droplets, and free surfaces. In this project, the author would like to study the efficiency of the drilling mud flowing through the nozzle of the *PDC* bit. Thus, ANSYS Fluent is the suitable for the desired application.

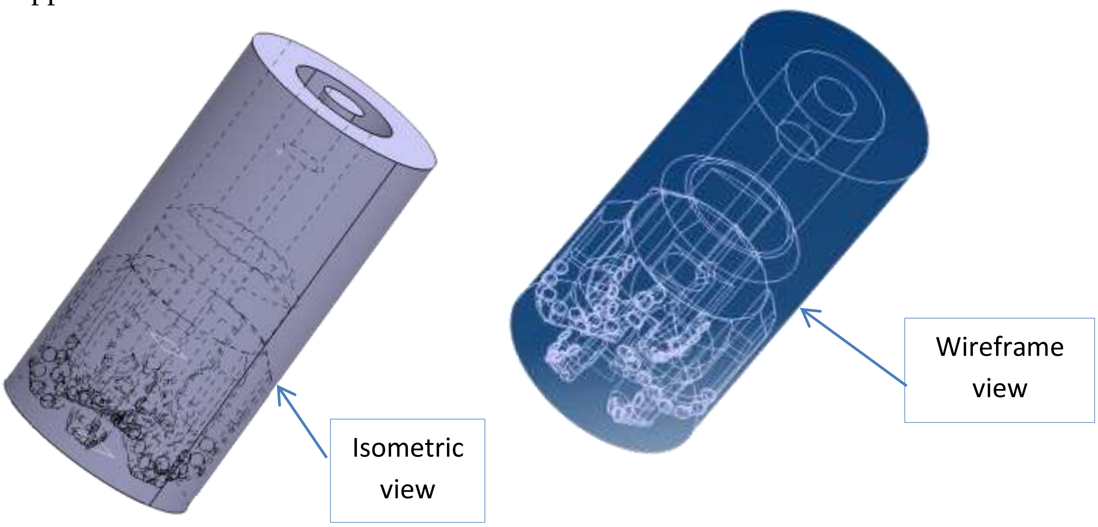


Figure 24 *3D Model of reversed PDC bit*

The hydraulic simulation is done by using ANSYS Fluent. Boolean operation is used to reverse the geometry of the PDC bit. The reversed geometry of PDC bit is then used as drilling mud for hydraulic simulation in ANSYS Fluent. Drilling fluid is injected through the nozzles and flow out through the annulus.

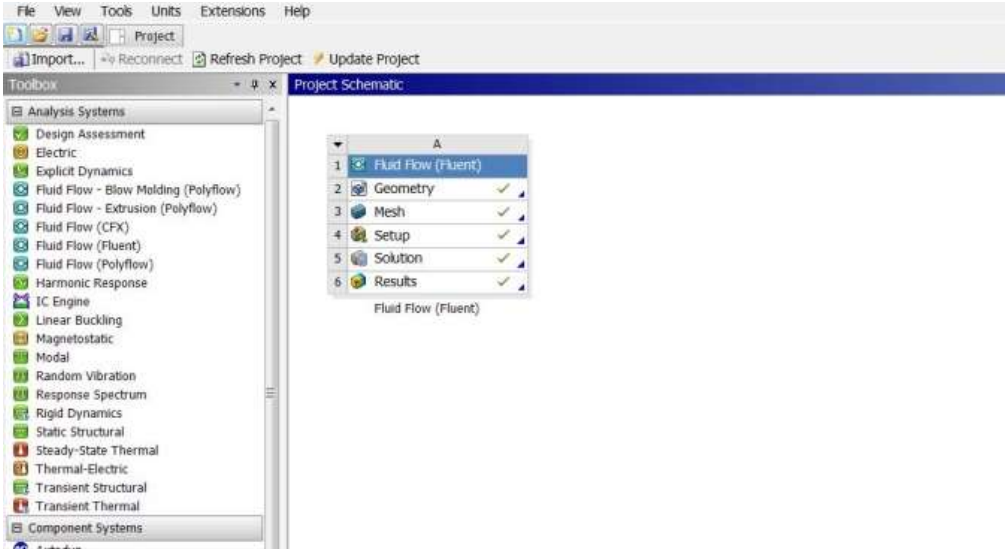


Figure 25 Fluent component analysis

Geometry

The reversed 3D model of PDC bit in .stp format are imported into ANSYS Geometry and open in Fluent for analysis setting.

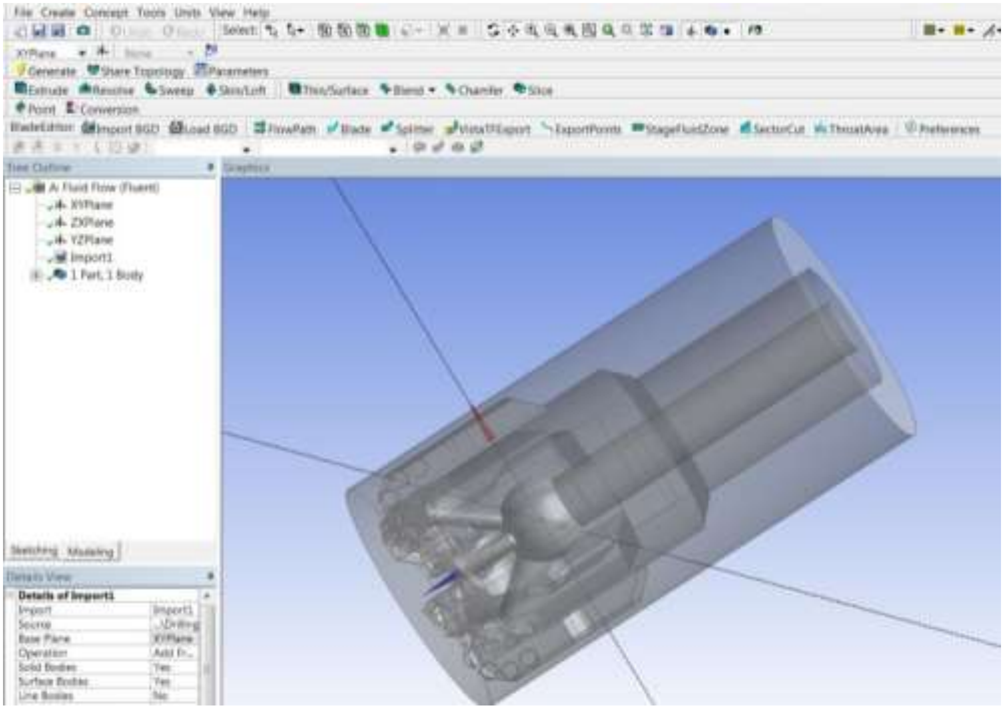


Figure 26 Fluent Geometry interface

The selections of the geometry, coordinate systems, meshing properties are defined in Fluent Meshing.

Meshing

Meshing is one of the important aspects in engineering simulation. Meshing is an integral part of the computer-aided engineering simulation process. The mesh influences the accuracy, convergence and speed of the solution. The meshing setting and pattern for this project was set as shown in figure below.

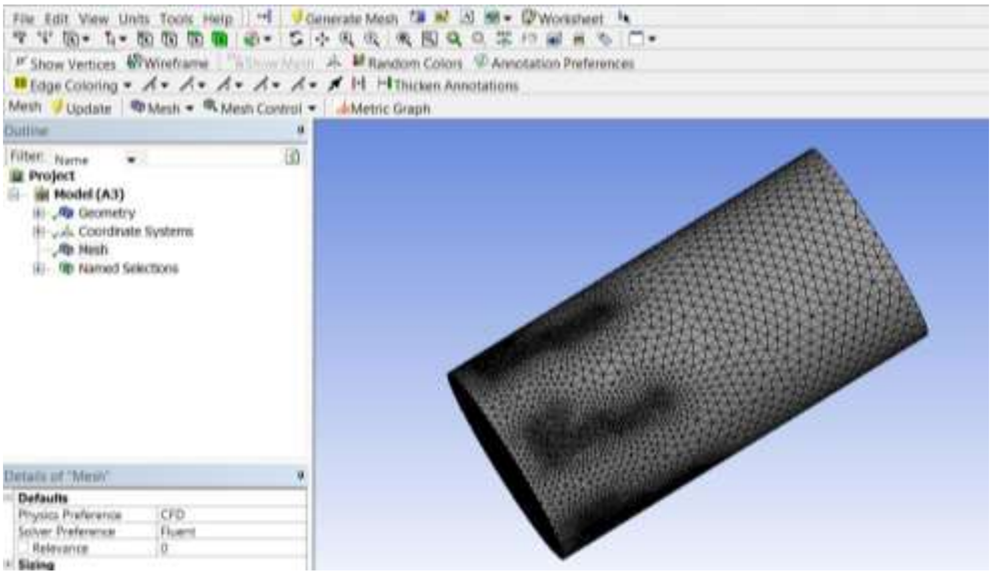


***Figure 27** Meshing setting and pattern*

Fluent

For drilling fluid simulation, in order to get the velocity of the drilling fluid, the author relates velocity with heat transfer coefficient. In order for the Fluent to show the heat transfer coefficient, the Energy in the Models section has to be turned on. Also, the author input drilling fluid properties at the Materials section. For the purpose of simplifying the simulation, the author has set the fluid behavior to be Power Law. The results of the simulations are the velocity and the heat transfer coefficient.

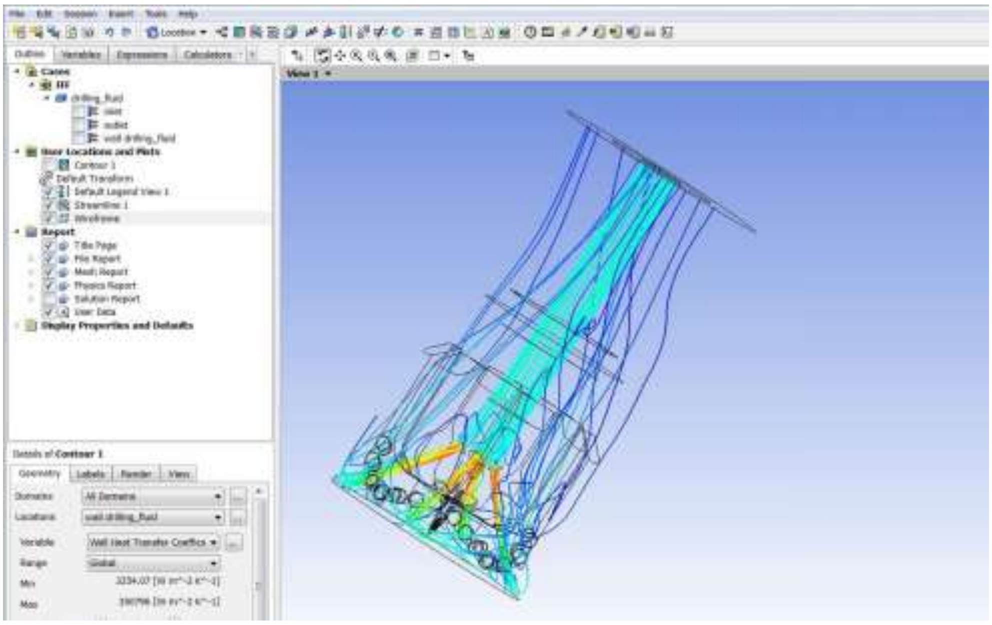


Figure 28 *Flowline representing velocity*

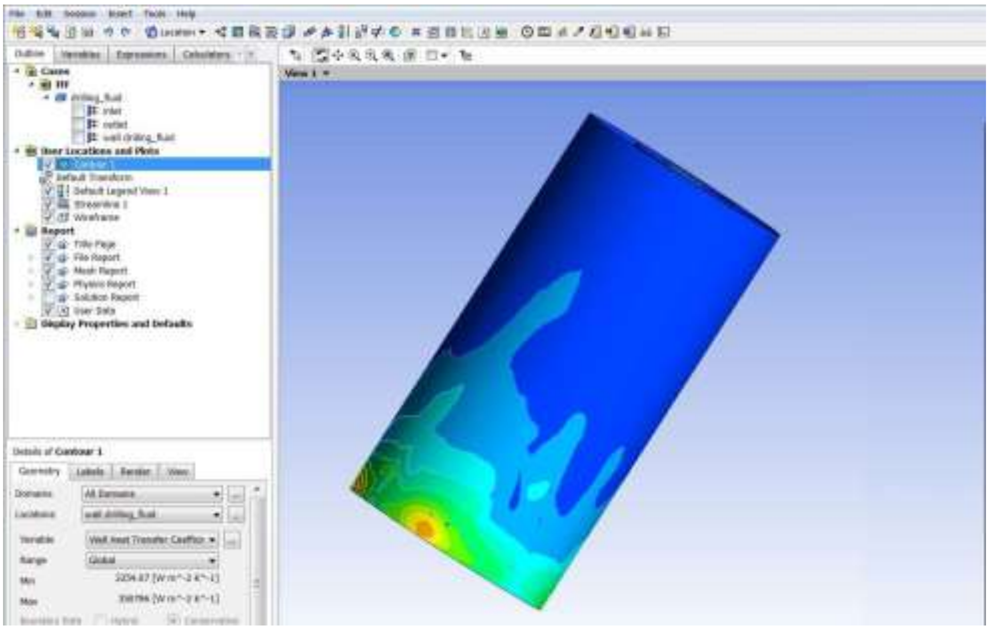


Figure 29 *Contour representing the heat transfer coefficient*

3.9 Tools and Equipment

Tools and equipment used in this project are dull *PDC* bit, *3D* VIUscan Scanner, *3D* Printer and simulation software.

Figure 30 *Dull PDC drill bit*

Figure 31 *VIUscan Scanner*

3.10 Gantt Chart and Key Milestone

Table 10 *Gantt Chart for FYP1 and FYP2*

No	**Activities / Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Literature Review														
2	Preliminary Research Work														
3	Drill bit model selection														
4	Scanning Drill Bit														
5	Convert cloud model into 3D CAD model														1
No	**Activities / Week**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
1	Literature Review														
2	Optimization of Drill Bit Design				2										
3	Analysis on the new Drill Bit									3					
4	Field Visit to Kemaman Supply Base (KSB)														
5	PDC Bit Simulations													4	

Process Suggested Milestone

Table 11 *Key milestones*

1	Key Milestone 1: Completed reverse engineered *PDC* bit
2	Key Milestone 2: Completed modified *3D CAD* model of PDC bit
3	Key Milestone 3: Completed analyze the new *PDC* bit
4	Key Milestone 4: Completed the simulation of the new *PDC* bit

CHAPTER 4

RESULT AND DISSCUSSION

The output parameter for this project is the rate of penetration (ROP). In the drilling industry, the rate of penetration (ROP) is the speed at which a drill bit breaks the rock under it to deepen the borehole. ROP is also known as penetration rate or drill rate. It is normally measured in feet per minute or meters per hour, but sometimes it is expressed in minutes per foot.

$$ROP = \frac{Meterage(m)}{Drilling\ Time\ (hr)}$$

In this project, the simulation was carried by ANSYS Explicit Dynamic. Total velocity under solution is expressed as rate of penetration. It is measured in meter per second. Generally, ROP increases in fast drilling formation such as sandstone (positive drill break) and decreases in slow drilling formations such as shale (reverse break). ROP decreases in shale due to diagenesis and overburden stresses.

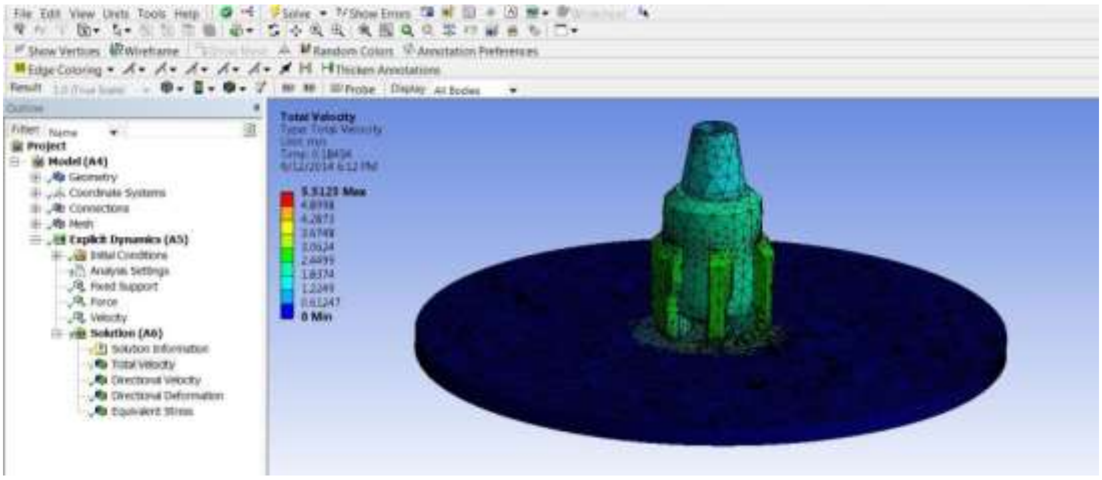


Figure 32 Penetration of the drill bit

4.1 Results for Original PDC Bit

Data from total velocity represent the rate of penetration for the original PDC bit is extracted from ANSYS and tabulated in Table 13. The total simulation time is 1 second. At this period of time, the original PDC bit able to drill all the three layer of rock formation. They are sandstone, dolomite and limestone. The rate of penetration (ROP) of original PDC bit differs for every type of rock formation.

Table 12 *Analysis data of original drill*

Time (s)	ROP (m/hr)	Time (s)	ROP (m/hr)	Time (s)	ROP (m/hr)
0	**85.62**	0.35	**18.54**	0.7	**24.22**
0.05	**75.60**	0.4	**18.75**	0.75	**24.25**
0.1	**68.32**	0.45	**17.56**	0.8	**24.35**
0.15	**21.24**	0.5	**17.56**	0.85	**24.98**
0.2	**21.78**	0.55	**16.75**	0.9	**25.02**
0.25	**21.21**	0.6	**15.45**	0.95	**25.38**
0.3	**20.36**	0.65	**16.51**	1	**24.20**

From Table 13, the average rate of penetration for original drill bit is 22.4 m/hr. A graph of ROP vs Time is plotted to analyze the interaction between rate of penetration and time for original PDC bit.

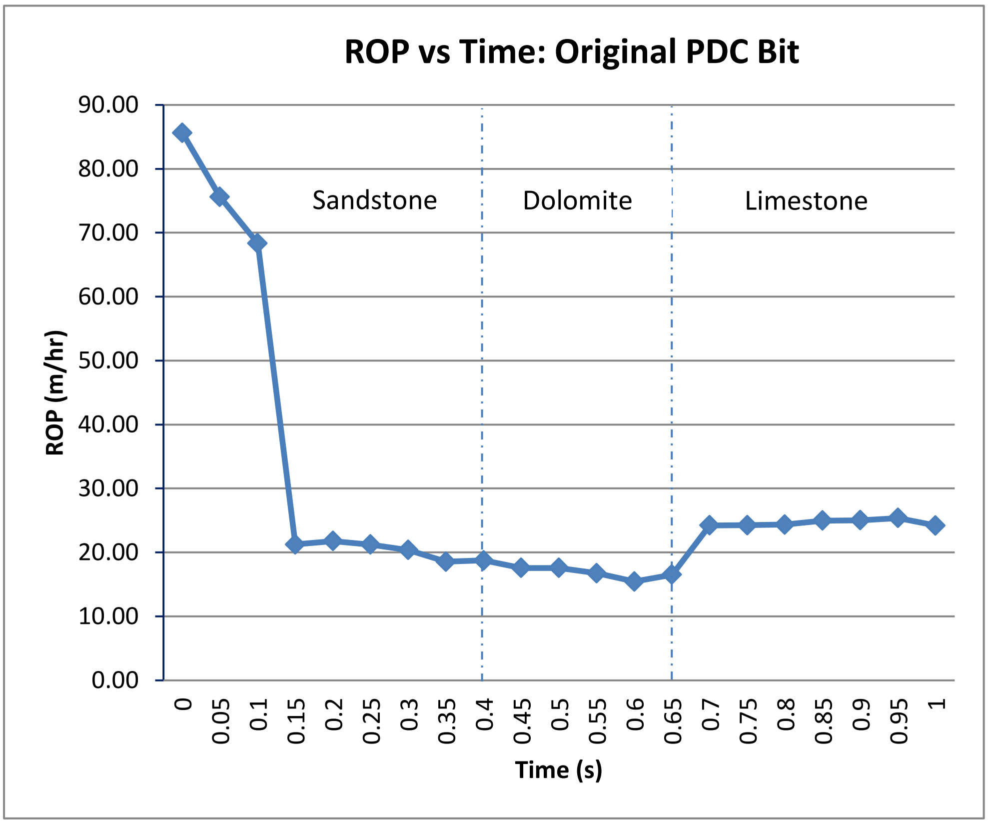


Figure 33 *Graph of ROP vs. Time for original PDC*

4.2 Results for the Optimized PDC Bits

For the optimized PDC bits, the same method applied. Data from total velocity represent the rate of penetration for the optimized PDC bits is extracted from ANSYS and tabulated in table 14 below.

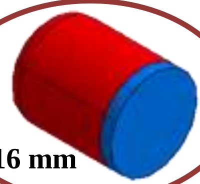
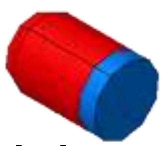
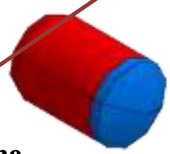
***Table 13** Analysis data of the optimized PDC bit*

Time (s)	Run 1 (m/hr)	Run 2 (m/hr)	Run 3 (m/hr)	Run 4 (m/hr)	Run 5 (m/hr)	Run 6 (m/hr)	Run 7 (m/hr)	Run 8 (m/hr)	Run 9 (m/hr)
0	87.65	86.20	78.90	87.45	80.00	85.45	88.00	87.45	85.90
0.05	82.46	76.90	77.80	76.84	77.78	83.47	78.05	76.84	74.60
0.1	81.45	76.90	77.57	76.84	77.57	81.30	70.45	66.85	74.90
0.15	28.56	19.81	29.57	25.74	29.57	31.51	26.67	28.78	17.81
0.2	28.63	20.22	30.24	26.32	30.24	35.45	25.87	27.62	19.20
0.25	32.32	24.24	32.45	26.42	32.45	34.15	24.67	28.45	20.65
0.3	32.51	24.52	31.45	24.21	31.56	32.22	26.78	24.21	20.78
0.35	31.40	23.20	25.24	19.78	24.76	33.15	23.56	19.15	10.56
0.4	30.14	20.86	19.74	19.84	19.56	32.90	12.78	19.48	10.86
0.45	20.58	21.56	20.47	19.64	10.98	20.50	12.56	19.48	11.56
0.5	20.98	22.35	20.24	19.02	21.45	20.78	12.09	19.45	12.35
0.55	20.74	22.36	20.54	19.78	20.54	20.74	12.25	19.63	11.76
0.6	21.02	22.10	21.57	19.87	20.23	21.02	12.04	19.65	11.89
0.65	21.24	21.56	21.45	18.75	20.15	21.24	11.67	19.74	12.02
0.7	31.20	32.60	21.05	18.56	20.24	22.50	11.98	19.87	28.69
0.75	30.45	33.00	36.01	34.50	47.59	48.92	34.50	30.65	27.90
0.8	30.56	32.10	37.58	32.45	47.56	46.87	32.89	32.48	28.60
0.85	29.65	30.15	36.15	32.45	40.15	47.84	32.34	32.78	28.15
0.9	29.87	31.15	35.45	32.68	40.45	47.82	33.84	33.67	30.00
0.95	29.57	30.23	35.12	32.79	40.12	48.74	31.78	32.89	28.24
1	29.86	30.23	34.78	30.45	39.78	45.75	30.54	30.00	28.00
Avg ROP	39.93	37.54	39.16	37.23	40.61	45.13	34.92	36.98	32.40

The average rate of penetration (ROP) for all the optimized PDC bits are shown at the end of table 14. From there, it is obviously shows that Run 6 gives the highest rate of penetration, 45.13 m/hr followed by Run 5, 40.61 m/hr and Run 8, 39.93 m/hr.

Run 6 is the combination of steel-matrix bit material, 16mm cutter, two rows of back-up cutter and curved cutter. Steel is a material which has a high strength whereas matrix is resistant to wear. The combination of both steel and matrix has proven to give a higher ROP. Furthermore, cutter which has a bigger size has a bigger volume of diamond on it therefore, it will drill faster. This concept is applied to rows of cutter as well. Two rows of back-up cutter has more diamond content, thus the ROP is higher. For the shape of cutter, the curved shape shows a higher ROP because the edge of the curve touches the formation first, which lead to a faster drilling operation.

***Table 14** Input parameters for Run 6*

Parameter	Level 1	Level 2	Level 3
Bit Material	**Steel** 	**Matrix** 	**Steel – Matrix** 
Size of Cutter	 **8 mm**	 **13 mm**	 **16 mm**
Back-up Cutter	 **Zero**	 **One**	 **Two**
Shape of Cutter	 **Standard**	 **Curve**	 **Cone**

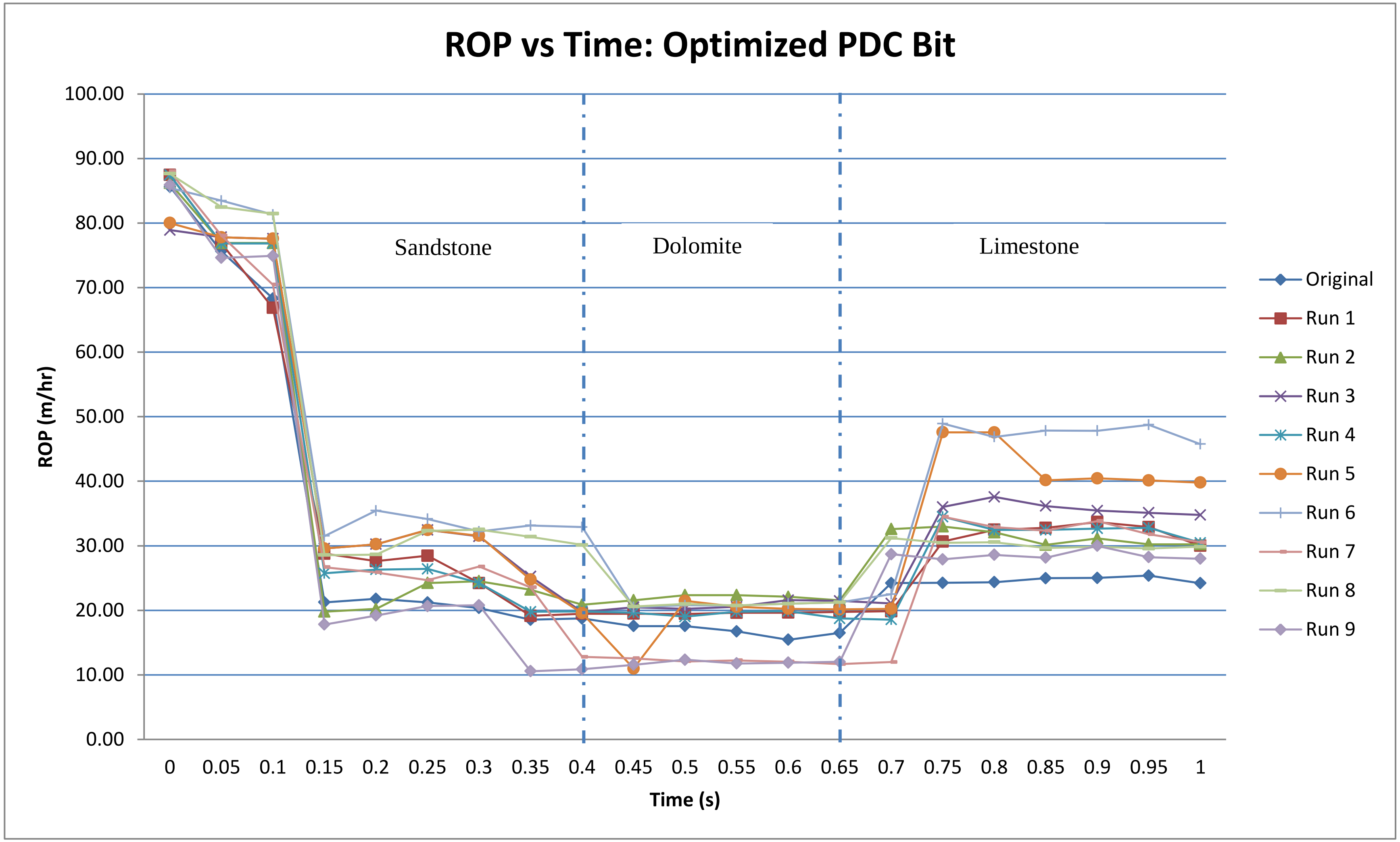


Figure 34 *Graph of ROP vs Time: Optimized PDC*

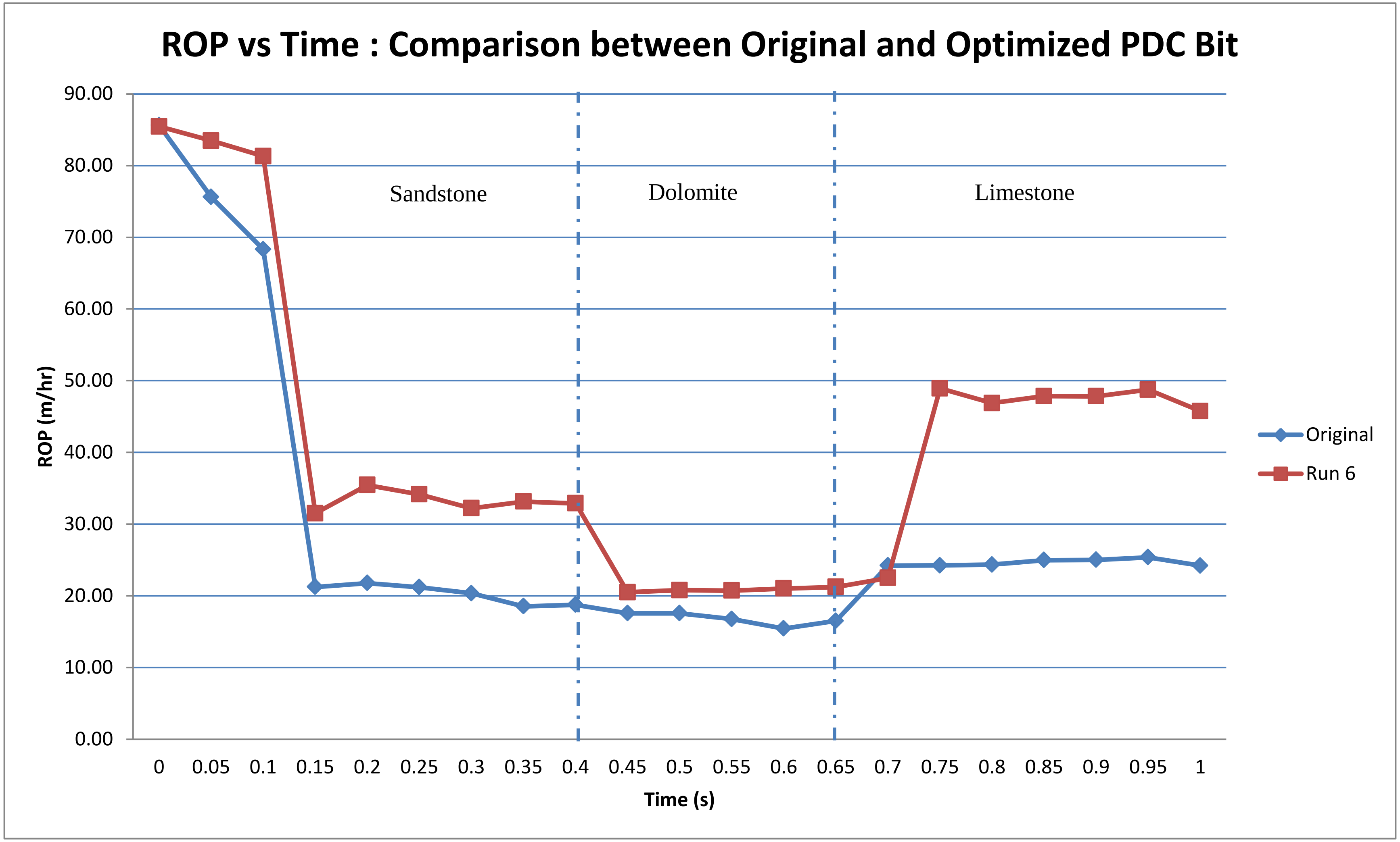


Figure 35 *Graph of ROP vs Time: Comparison between original and optimized PDC bit*

The average rate of penetration (ROP) for Run 6 and original PDC bit are 45.13 m/hr and 33.01 m/hr. A graph of analysis data of optimized and original PDC bit is plotted in figure 38 and figure 39 for comparison purpose.

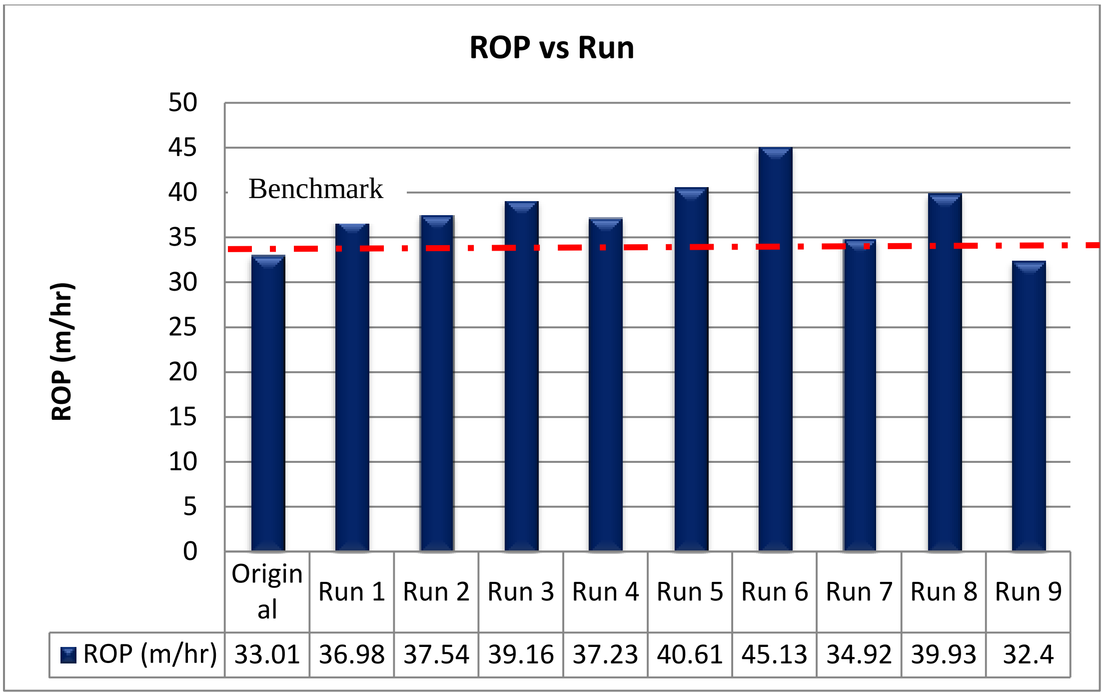


Figure 36 *Graph of ROP vs Total Run*

A calculation is made to calculate the percentage of rate of penetration (ROP) improvement.

$$\frac{Optimized\ ROP - Original\ ROP}{Original\ ROP} X\ 100\%$$

$$\frac{45.13\ m/hr - 33.01\ m/hr}{33.01\ m/hr} X\ 100\%$$

$$Percentage\ of\ Improvement = 36.72\ \%$$

From calculation, the percentage of improvement for the optimized PDC bit and the original PDC bit is 36.72%. Therefore, the combination of steel-matrix body material, 16mm size of cutter, two rows of back-up cutter and curve-shaped cutter have proven to improve the rate of penetration for multi-layer formation.

4.3 Results for the Drilling Fluid

The cooling of the cutters is dependent on the drilling fluid flowing past the cutters. It is important to place the cutters in relation to each other in such a way to maximize the cooling of all the cutters. The rate of cooling of the cutters is dependent on heat transfer coefficient. Figure below shows contours of heat transfer coefficient for Run 6 design. The heat transfer coefficient is very high near the cutting edge of the PDC cutter. This will ensure good cooling along the side of cutter and stud body. This is due to the high velocity around each cutter. Heat transfer coefficient is proportional to the velocity of the drilling fluid.

Velocity is the rate at which mud circulates, and the annular velocity us an important factor in transporting cuttings to the surface as well as acts as a coolant to the drill bit. Considerable heat is generated by friction in the bit where drillstring is in contact with the formation or casing. There is a slight chance for this heat to be conducted away by the formation. Hence, the circulating drilling fluid must remove it.

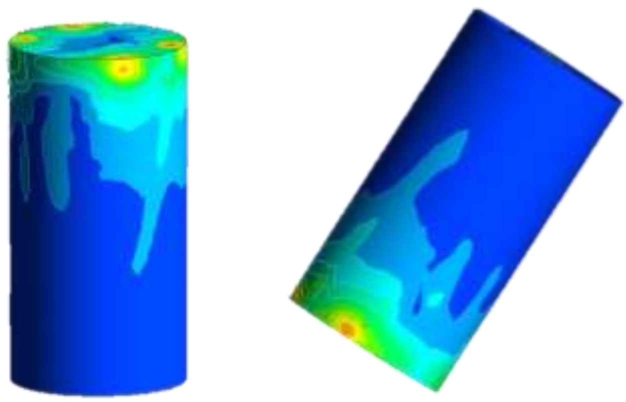


Figure 37 *Side and isometric view of the heat transfer coefficient*

Based on the above figure, it can be seen that the part which is red and yellow has a higher heat transfer coefficient. The value of the heat transfer coefficient for this design, which is Run 6 is $3.508x10^5$ $Wm^{-2}K^{-1}$. Since heat transfer coefficient is proportional to the velocity of the drilling fluid, the table and the graphs for the velocity versus heat transfer coefficient of the drilling fluid is tabulated as below.

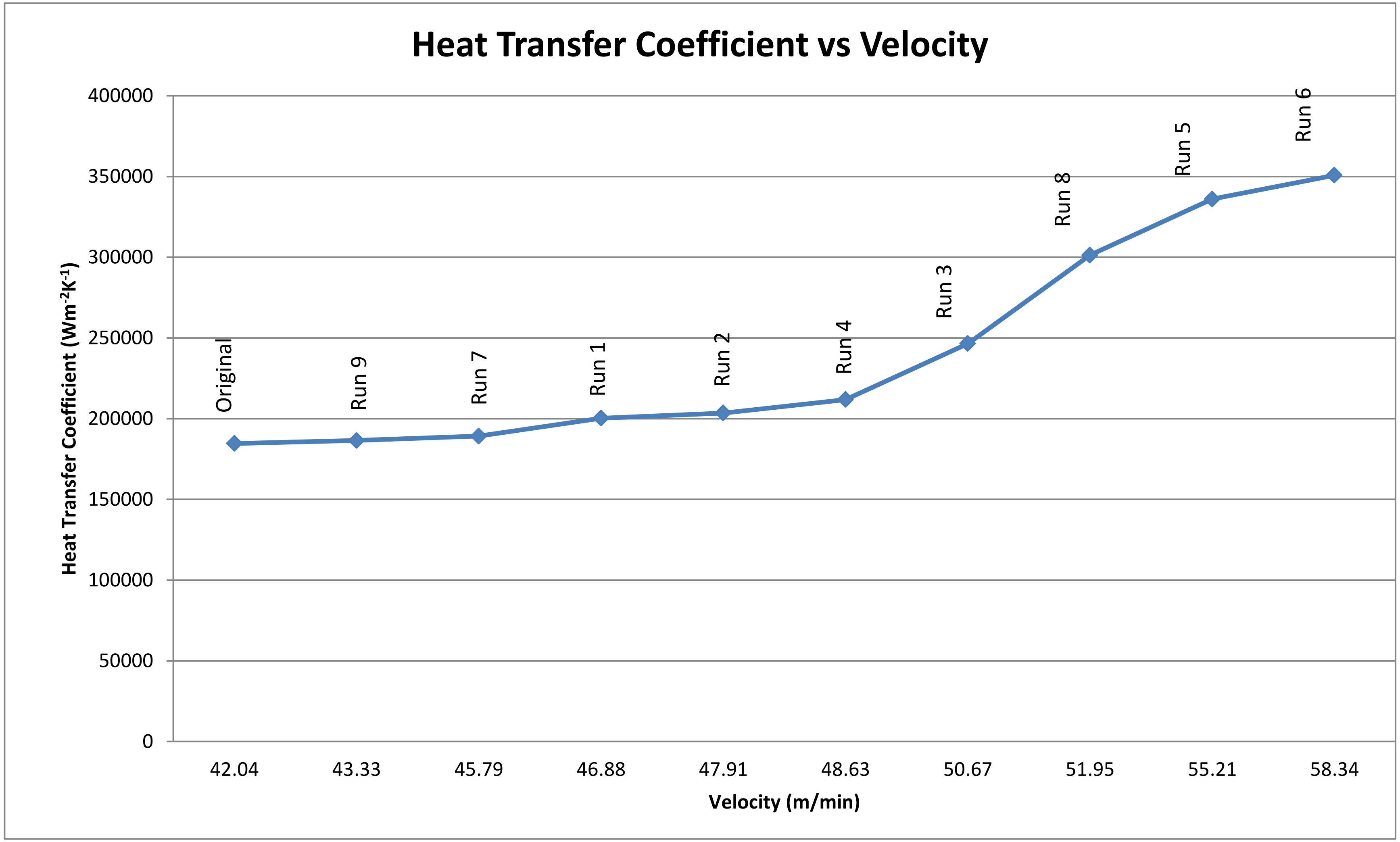


Figure 38 *Graph of Heat Transfer vs Velocity*

Table 15 Heat transfer coefficient and velocities for each run

Run	Heat Transfer Coefficient ($Wm^{-2}K^{-1}$)	Velocity (m/min)
Original	42.04	184670
9.00	43.33	186500
7.00	45.79	189230
1.00	46.88	200340
2.00	47.91	203540
4.00	48.63	211800
3.00	50.67	246500
8.00	51.95	301300
5.00	55.21	336000
6.00	58.34	350800

Based on the above table and figures, it has been proven that the heat transfer coefficient is proportional to velocity. The higher the heat transfer coefficient, the higher the velocity.

The circulating fluid rising from the bottom of the wellbore carries the cuttings towards the surface. With the influences of gravity, cutting tends to sink through the ascending fluid, but by circulating a sufficient volume of drilling fluid fast enough to overcome this effect, the cuttings are brought to the surface. By comparing original PDC bit design with the optimized design, the results of the velocity of the drilling fluid are as follow.

Table 16 Velocities for each run

	Velocity (m/min)								
Original	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
42.04	46.88	47.91	50.67	48.63	55.21	58.34	45.79	51.95	43.33

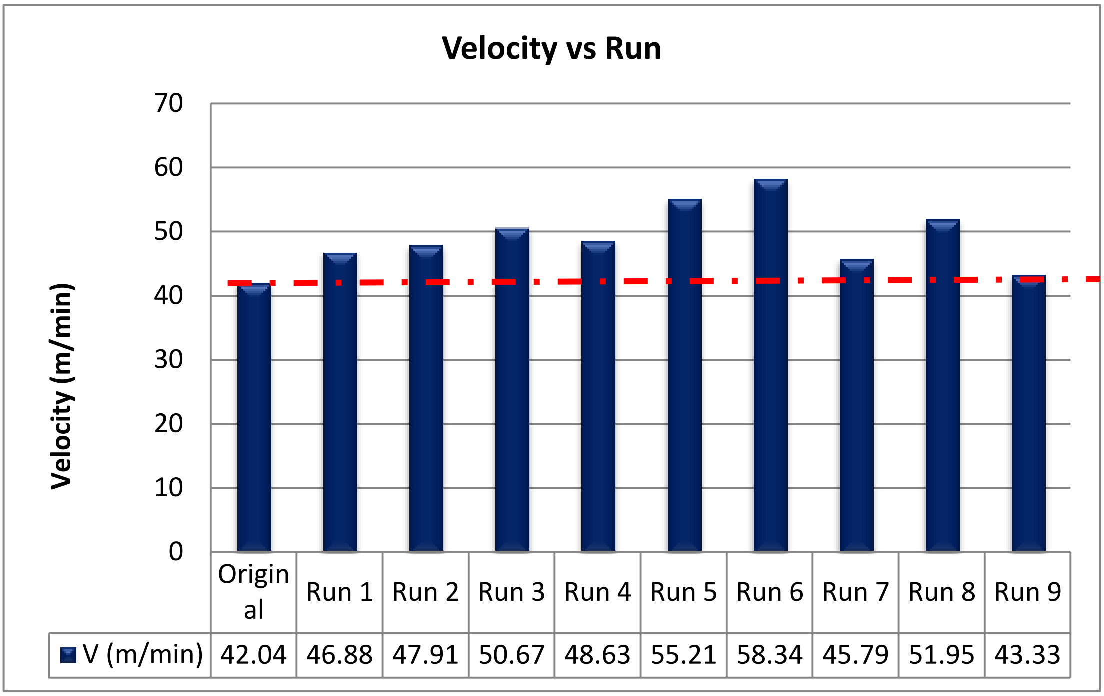


Figure 39 *Graph of Velocity vs Run*

A calculation is made to calculate the percentage of velocity improvement.

$$\frac{Optimized\ Velocity - Original\ Velovcity}{Original\ Velocity} X\ 100\%$$

$$\frac{58.34\ m/hr - 42.04\ m/hr}{42.04\ m/hr} X\ 100\%$$

$$Percentage\ of\ Improvement = 38.77\ \%$$

Based on the above figure, it can be seen that Run 6 has a highest velocity of 58.34 m/min. Run 6 is a combination of combination of steel-matrix body material, 16mm size of cutter, two rows of back-up cutter and curve-shaped cutter.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This project has provided a review of the literature associated with the *PDC* bit performance in multi-layer formation. Some important conclusions can be drawn as follows:

1. Bit performance is strongly influenced by rock properties. An optimum bit for multi-layer formation field must combine a balance of mechanical characteristics and durability.
2. Reverse engineering method successfully generated the 3D CAD of the dull PDC drill bit.
3. A unique combination of *PDC* technologies by Taguchi method can competently drill multi-layer formation with high *ROP*.
4. Optimizing bit body material, shape of the cutter, size of cutter and rows of cutter have been shown by simulation software, able to improve the rate of penetration (ROP).
5. The higher the heat transfer coefficient, the higher the velocity.

It is recommended that the same optimized PDC bit is simulated but including the properties of drilling fluid. The possible output parameter is the wear rate of the bit to analyze the durability of each of the optimized PDC bit.

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