Theoretical Analysis and CFD Simulation of the Solid Ball Kill Process in Offshore Blowout Wells

By

Ahmad Akmal Bin Abdullah

14291

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Petroleum)

January 2015

Universiti Teknologi PETRONAS,

Bandar Seri Iskandar,

31750 Tronoh,

Perak Darul Ridzuan.

CERTIFICATION OF APPROVAL

Theoretical Analysis and CFD Simulation of the Solid Ball Kill Process in Offshore Blowout Wells

by

Ahmad Akmal Bin Abdullah

14291

A project dissertation submitted to the

Petroleum Engineering Programme

Universiti Teknologi PETRONAS

In partial fulfillment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(PETROLEUM)

Approved by,

____

(AP Dr Xianhua Liu)

UNIVERSITI TEKONOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2014

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.

____

AHMAD AKMAL BIN ABDULLAH

ABSTRACT

Well blowout results in massive disaster especially for offshore well. The risk for blowout is increasing as drilling for oil and gas moves into more complex and challenging environment. The damages from blowout incident include life, environment and economy. Conventional well kill methods are either not effective or too slow. Thus, fast and reliable well kill method is needed.

This research project is based on the well killing method invented by Xianhua Liu which uses heavy kill balls to be released into the well. These balls will block and suppress the flow of blowout fluids. This method is fast and reliable. The purpose of this project is to study theoretically on the interaction of kill balls with blowout fluids inside the well and also to simulate the behavior of kill balls by using Computational Fluid Dynamics simulation. This research process starts with literature review on blowout incidents and available well killing methods. Then, fluid mechanics theory and calculation are used for theoretical study. After that ANSYS 14 software is used for simulation purpose. Finally, the results from the study and simulation are analyzed. Kill balls are expected to suppress and significantly reduce the flow velocity of blowout fluids so that the well can be completely killed.

The outcome of this project will benefits in solving well blowout problems fast and effectively so that to minimize the property loss of the petroleum company and environmental damage.

ACKNOWLEDGEMENT

All praise upon the God, for His blessings and guidance that has helped me to complete this Final Year Project.

I would like to extend my gratitude to my supervisor, AP Dr Xianhua Liu for his help, motivation and guidance which had made me focused in completing this project. His valuable advice throughout the project shall be remembered.

Not to forget, I am thankful to all the staffs from Petroleum Engineering Department, Universiti Teknologi PETRONAS which had provided with valuable lessons and assistances towards the completion of this project. They have been so helpful since the beginning of my project.

Finally, I would like to express my appreciation to all my fellow classmates for their help and support, also for making my life wonderful throughout the years we have been studying.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

F_D = Drag force.

C_D = Drag coefficient.

v = Relative velocity of the object.

ρ_f = Fluid density.

A = Cross section area of the object.

C_D = Drag coefficient.

Re = Reynolds number.

d_p = Diameter of the sphere.

V = Relative velocity of the sphere to fluid.

μ = Viscosity of the fluid.

F_B = Buoyant force.

γ = Specific weight of fluid.

V_b = Volume of the ball displaced by fluid.

g = Gravitational acceleration.

m = Mass.

r = Radius of the ball.

CHAPTER 1: INTRODUCTION

1.1 Background

Well blowout is an uncontrolled flow of formation fluid out of the well into the atmosphere or between uncased formation layers. This incident can happen when formation pressure exceeds the well bore pressure applied by the weight of drilling fluid and all the technical well barriers have failed. The undesirable flowing of formation fluids out of the well have to be stopped by regaining control of the well. To regain control means to kill the well.

The probability for blowout to occur is always there as long as there are drilling operations. The result of blowout is severe even the most simple blowout can result in the loss of millions of dollars. Blowout can occur in every drilling operation regardless of the depth of the well, either in shallow or deepwater operation.

Blowout starts from a well kick. If the kick is properly controlled, the chance for blowout can be reduced. There are several causes of well kicks and blowouts. The kick can be detected in drilling operation as there are early warnings signals. So, it is important to control the kick before blowout can happen. Other factors that also contribute to blowout are equipment failure and human error.

To regain control of the blowout well, there are two traditional methods of well kill technologies. One method is dynamic top kill which pumps heavy kill mud into the well. Another method is by drilling a relief well to intersect the blowout well and kill the well by pumping kill mud into the bottom of the well. Dynamic top kill is not reliable and drilling a relief well took too much time.

Based on the problems with conventional kill method, there is a need for fast and effective well kill technology for offshore oil and gas blowout. So, this study is based on the "A Rapid Kill and Restoration System for Blowout Wells" invented by Xianhua Liu. This method works by releasing heavy kill balls (solid particles) into the well instead of using kill mud. These balls can be made from environmental friendly materials. These balls can be transported into the well by any transporting fluids like nitrogen, air or water.

1.2 Problem Statement

Well blowout can result in catastrophic consequences. The damages include the loss of life and health of the workers, drilling rigs and pollution to the environments which is the release of hydrocarbons into the sea. Environmental pollutions have short and long term effect. Oil spills cause serious impact on marine wildlife. The effect by this pollution takes a long time to recover. In terms of economy, the cost to restore this environmental impact is as much as the cost to kill the well. Also, there is also litigation issues need to be solve after the well has been successfully killed, and this is another cost.

From the statistics of SINTEF Offshore Blowout Database, a total of 573 offshore blowouts had occurred worldwide since 1955. Also included in this database, from January 1, 1980 until January 1, 2008 there have been 237 blowouts or well releases occurred in US Gulf Of Mexico Outer Continental Shelf and the North Sea. Well blowout is a random event where no one can predict where and when it is going to occur.

As drilling operation moves into more challenging area, this business has become even more risky than ever. Most operators are aware that the day of drilling conventional wells are almost over. Deeper wells are being drilled, with high pressure and high temperature and in harsh environment. Christophe de Margerie, CEO of Total mentioned that "the risk of oil spill was simply too high when it come to Arctic Ocean".

There is currently no fast and effective technology for offshore blowout well control. Dynamic top kill often fails for most of the well where energy is high and intense as the drilling mud will mostly be diluted and blown out of the well by the strong oil or gas flow. Drilling a relief well is an effective method but it is too slow and too costly. The duration taken to successfully killed the well by this method, also the duration of continuous pollution to the environment by free flowing of hydrocarbon to the surrounding area can be about three months.

1.3 Objectives

- Theoretical study on the interaction between the kill balls and the blowout fluids inside the blowout well and the law of balls distribution and suppression of the flow.
- Simulate the behavior of kill balls using Computational Fluid Dynamics (CFD).
- Attempt to determine the optimum kill ball sizes, densities and ball releasing procedure based on the blowout fluids characteristics.

1.4 Scope of Study

1. Balls and fluids interaction and the law of balls distribution.
    - Study of the interaction between kill balls and blowout flow. It will include the behavior of the kill balls in the well by blowout flow, and the accumulation patterns of the kill balls under different values of the blowout velocity. Amount of force acting on the kill balls at certain flow rate can be calculated to determine the direction of the balls whether they will go up or down in the well.
2. Determination of optimum ball size and weight.
    - Based on the characteristics of a blowout well, the kill ball size and weight need to be optimized to the most effective result during the kill and restoration process. The outcome of this part will be in the form of tables, charts or formulas to determine the optimum size and weight of the ball for respective well.

1.5 Relevancy of the Project

Study on new technology for well kill method is important to petroleum industry as currently there is no fast and reliable method for well kill technology. So it is necessary to develop this ball kill process for oil and gas blowout. Advantages of this method are as following:

- Reliability: One of the conventional method of well kill is by pumping heavy kill mud from top of the well, but when encountering strong blowout flow, the kill mud is more likely to be blown out of the well. On the other hand, kill balls are much heavier and bigger than kill mud. Even at the early stage some of these balls might be blown out of the well, they will still be in the system as there is a cage install at the top of the well. Thus eventually the accumulated balls will suppress the blowout flow. So the reliability is guaranteed by the kill process and also the properties of the kill balls.

- Rapidity: This method is effective so that the time taken to control the well is greatly reduced from any conventional method.
- Restorability: Another advantage of this kill method, the blowout well can be restored to normal production by taking out some of the kill balls at a later stage.

1.6 Feasibility of the Project

The total duration given to complete this project is about 28 weeks. This duration is considered sufficient as no chemical materials needed and also no laboratory experiment involved. All the required reference materials and software for simulation is available. Thus, this project is believed to be complete within the time frame.

CHAPTER 2: LITERATURE REVIEW

A blowout of the Macondo well that occurred in the Gulf of Mexico on April 20, 2010 has result in massive impact on the environment, economy as well as the people involved in the drilling operations. Based on National Academy of Engineering (NAE) and the National Research Council (NRC) report on Macondo Well-*Deepwater Horizon* Blowout, this incident had destroyed *Deepwater Horizon* drilling rig which killed 11 workers and 16 others were seriously injured. The explosion sank the drilling rig and caused almost 5 million barrels of oil were released into the gulf as the flow continued for 87 days or just about 3 months before the well was completely killed. Drilling operation in harsh environment as water depth is about 5000 feet bring a lot of challenges to the operator, in this case is British Petroleum (BP). The leak resulted disaster into the environment.

2.1 Well Kill Methods

One of the technologies to kill the well is to drill relief wells. The term "relief wells" were given because originally the reason to drill these wells is to relieve reservoir pressure. This directional well will intercept the blowout well at the bottom to relieve the pressure. Then, kill mud can be pumped into the well and effect a kill. This method usually works but it takes too much time. From the report by (Christou & Konstantinidou, 2012, p. 17), blowout at IXTOC I well at Gulf of Mexico in 1979 took 9 months to kill the well where two relief wells were drilled. The IXTOC I accident where 3.5 million barrels of oil released was the biggest single spill in this gulf before the event of Macondo well blowout. From Hagerty (2010), during *Deepwater Horizon* blowout, first relief well was drilled 12 days after the the rig exploded. The well was successfully killed 87 days after the blowout occured. This clearly indicate that drilling a relief well is a time consuming operation.

Another example, Wells A-1/A-1D located in Main Pass Block 91 (MP 91), Gulf of Mexico, off the Louisina Coast was observed leaking with gas on August 22, 2007. A relief well was drilled which took about 1 months of the drilling operation to completely killed the well. This well intersected the blowout well at 5391 feet true vertical depth

(TVD) and drilling mud was pumped followed by cement into the well (Josey et al. 2008). Based on the depth of the intersection which is not very deep, we can estimate the time taken to drill a relief well when we double that intersection depth. Based on Hagerty (2010), blowout in the Montara oil field located in Timor Sea on August 21, 2009 was killed by drilling a relief well. This relief well was drilled to intersect the blowout well at the depth about 13,000 feet below the ocean floor. The leaking of the well finally stopped on November 3, 2009 which is about 10 weeks later. According to Herbst (n.d), on July 23, 2013 natural gas blowout occurred on Hercules 265 jack-up rig located in the Gulf of Mexico off the coast Louisiana. The rig was working on sidetrack well during the event.. Relief well took 74 days to complete. From these three wells described above, we can conclude that drilling a relief well takes too much time to complete.

Another conventional well kill method is top kill or also called bullhead. “Bullheading” is defined as pumping the kill fluid directly into the well against the pressure of the well by not considering the obstacles in the well. Kill fluid is usually heavy mud weight with high density. The idea of this heavy mud is to create high hydrostatic pressure and reduce the flow which eventually the flow will stop. This technique is not always successfully worked when the annulus in a well is completely filled with gas. During the pumping operation the kill mud will bypasses the gas in the annulus. There is possibility the well will blowout again after the well is shut in. (Grace, 2003).

Top kill has several disadvantages. The suitable situation on when this technique should be applied is not completely understood. In addition, the pumped fluid may not follow the targeted point as they tend to go into the weakest formation interval. Also, even when the bullheading operation is complete, it is not fully indicate that the well is completely killed. The correct mud weight should be determine as if the weight is too high it will fracture the last casing shoe and if the mud is underweight the flow will not stop. (Adams & Kuhlaman, 1994). Proper condition is a must to apply bullhead even this method is consider the simplest and cost-effective. Top kill generally will fracture the formation. So, this method preferably applied for wells with perforated cased hole or well having short interval of openhole. (Watson, Brittenham, & Moore, 2003).

2.2 Causes of Blowout

Kick during drilling operation can result in well blowout. According to (Wilson, 2012), kick can be defined as uncontrolled flow of formation fluid into the well and also the influx of gas into the formation is more risky than any other hydrocaron or formation water. There are several factors for kick to happen. One of the example is failure to keep the hole full while tripping, mud weight less than formation pressure, and several other reasons. Indication of kick can be any warning signals such as sudden increase in drilling rate, reduction in drill pipe weight and more. (Grace, 2003). Another factor that can lead for kick is insufficient mud weight during drilling and completion operation. Kick can develop into blowout, so this is why it is important to control the kick.

Drilling rigs are equipped with blowout preventer (BOP) to prevent the kick to become a blowout by sealing the well in case of emergency. BOP is a heavy stack of valves assemblies attached on top of the well. BOP is designed to control the excess pressure in the wellbore, but when the system not properly designed or fail to function will result in the release of drilling mud and hydrocarbons out of the well. (Dyb, Thorsen, & Nielsen, 2012). During the Macondo Well blowout, BOP failed to completely seal the well. One of the reason is blind shear ram was not able to seal the well because of trapped drillpipe inside the BOP stack. (Turley, 2014). BOP is designed to be the last barrier of the well so it is necessary to make sure it is able to function at all time.

One of the causes of blowout is the poor cemented job. This is what happened in Montara well blowout in Timor Sea. According to the report by Montara Commission of Inquiry, cemented job at the casing shoe had failed. Pressure test is not been done after the cementing job to test for cement integrity. The result is the flow of hydrocarbons into the well through this failed cemented job. (Borthwick, 2010).

Studied from (Kato & Adams, 1991) revealed that most of blowout occurrences are during drilling operation. There is only slight difference between drilling and tripping out operation in term of number of blowout rate. Figure below shows the operations that related to blowout occurrence in all areas except in Alberta, Canada.

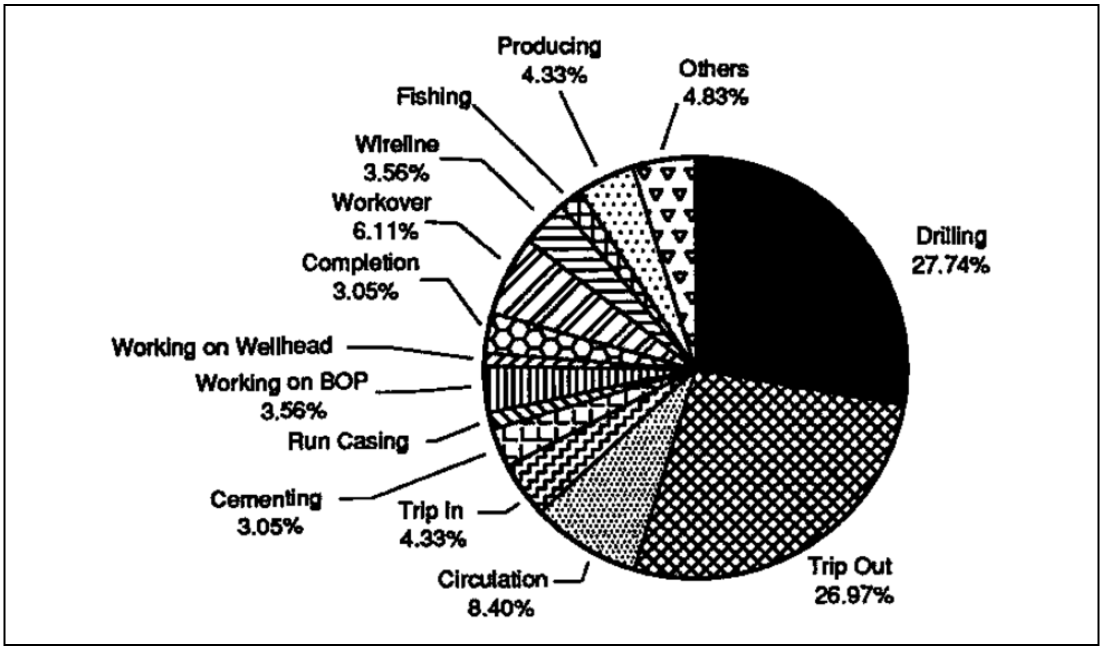

Figure 1: Operation related to blowout occurrence from (Kato & Adams, 1991)

Based on (Johnsen, 2012), from historical data, blowout risk is higher in exploration wells drilling operation compare to a development well. As an exploration well is the first well to be drilled in a particular area, there is a high uncertainty related to formation pressure and also the possibility of hydrocarbons trap.

2.3 Blowout Consequences on Economy and Environment

Legal action has been taken to the company involved in the blowout of Apache Key which involved hundred of litigants. The legal issue took 17 years to be resolved and also cost about hundreds of millions of dollars. (Grace, 2003). This is an example that blowout incident causes a loss in term of economy to the companies involved in the tragedy. Apart from legal issue to be solved, the company involved in the blowout cases also suffers the loss of facilities and the equipments.

From (Al-Jassim, 1991), during Kuwait oil wells blowout there are about 615 wells are on fire. The fire plume from burning oil wells resulted in severe environment pollution. In addition, the plume dispersion and composition studies from several professional agencies discovered the existence of the plume about 1000 km away from the source. Sulphur dioxide, carbon monoxide and other associated burning matter are carried along within the plume. Other noticeable pollutions are on marine and soil ecosystem. Oil spillage later formed crude oil lakes affect the condition of the soil and plant life. Oil spills along the coastline of Kuwait affect the wildlife marine species. This occurrence had clearly showed that oil wells blowout give negative impact to the environment.

2.4 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is one of important tools used widely in understanding fluid dynamics. Application of CFD in engineering is to model and solve problems related to fluid flow. ANSYS CFX 14 is used for the simulation work. This the software packages for application of CFD.

In this project, the main equations used in the simulation are momentum, continuity and energy equation. In petroleum engineering, CFD has been used in calculating pressure drop across the well annulus, simulate the transportation of drilled cuttings and other drilling applications.

CHAPTER 3: METHODOLOGY

3.1 Project Activities

Activities and process flow of this project are planned to ensure this project is within the specified duration of time.

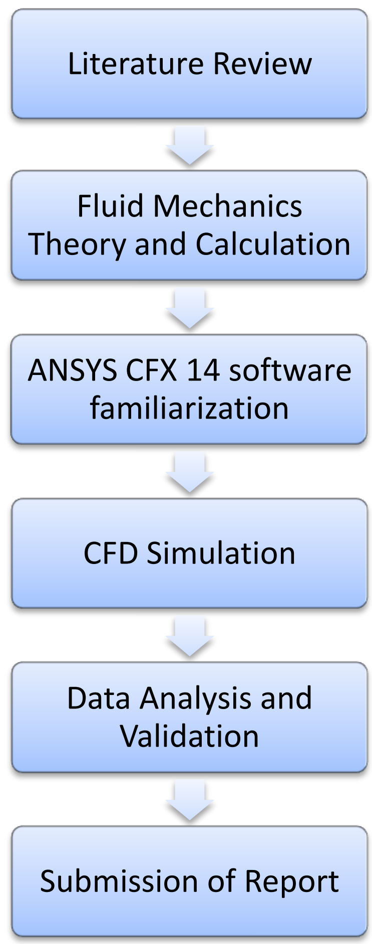

Figure 2: Process Flow

Activities involve in this project are further explain below:

- Literature Review:

  Literature review will include study on blowout history and also to determine the reasons that caused the blowouts in the industry. Method that had been used to control the blowout either success or fail should also be review.

- Fluids Mechanics Theory and Calculation:

  Interaction between the kill balls and blowout flows are analyzed from theoretical and mathematical approach. Equations and laws involve will be identified.

- CFD Simulation:

  CFD simulation will be use to visualize the behavior of kill balls in the blowout well. Modeling the project based on input parameters.

- Data Analysis:

  The findings of interaction between the kill balls and the blowout fluids will be analyzed. This method is going to analyze the outcome data of the CFD simulation. Based on the result, the optimum kill ball and restoration process of the blowout well can be determine.

3.2 Process flow of ANSYS CFX 14

Below are the summarized steps involved in the simulation process.

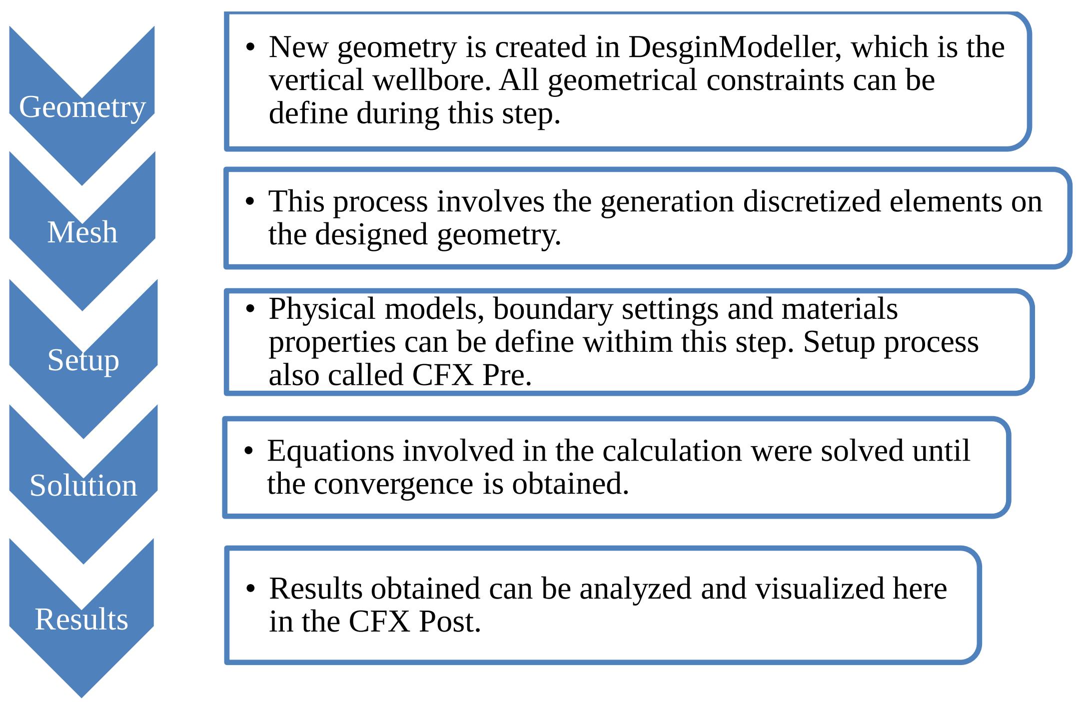

Figure 3: Workflow for simulation process

3.3 Model Setup

First we have to design the geometry. Vertical section of casing measured 3 m long with inside diameter (ID) of 0.104 m is designed in DesignModeler.

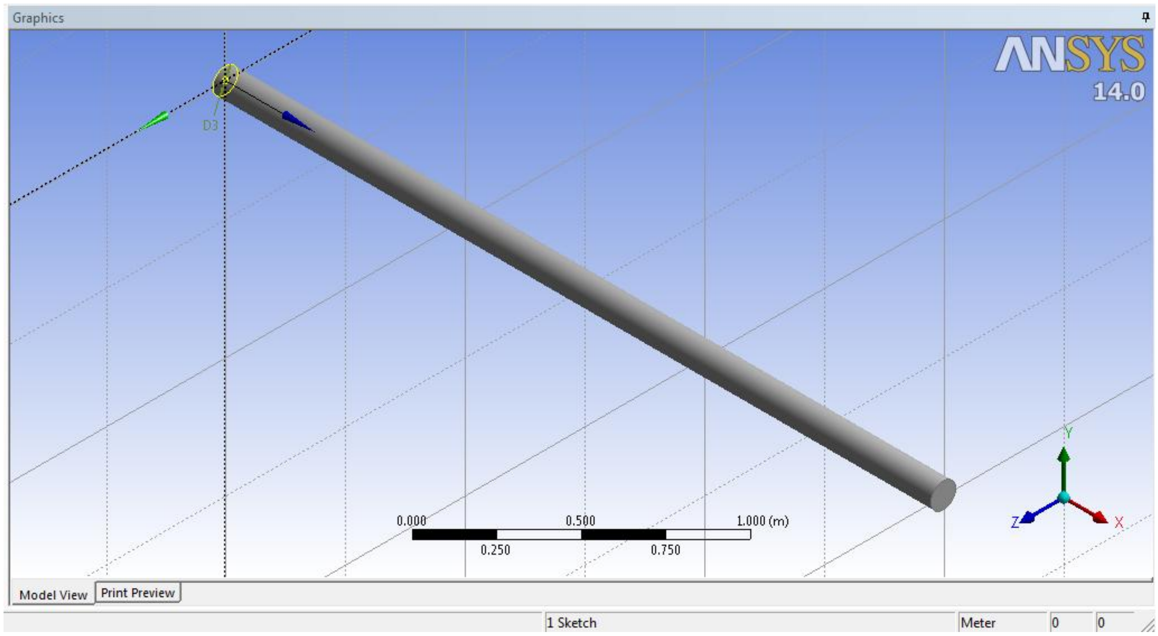

Figure 4: Designed geometry

Then, the model is discretely generated in to form a mesh. Surface boundary and regions of interest can be define during this particular step.

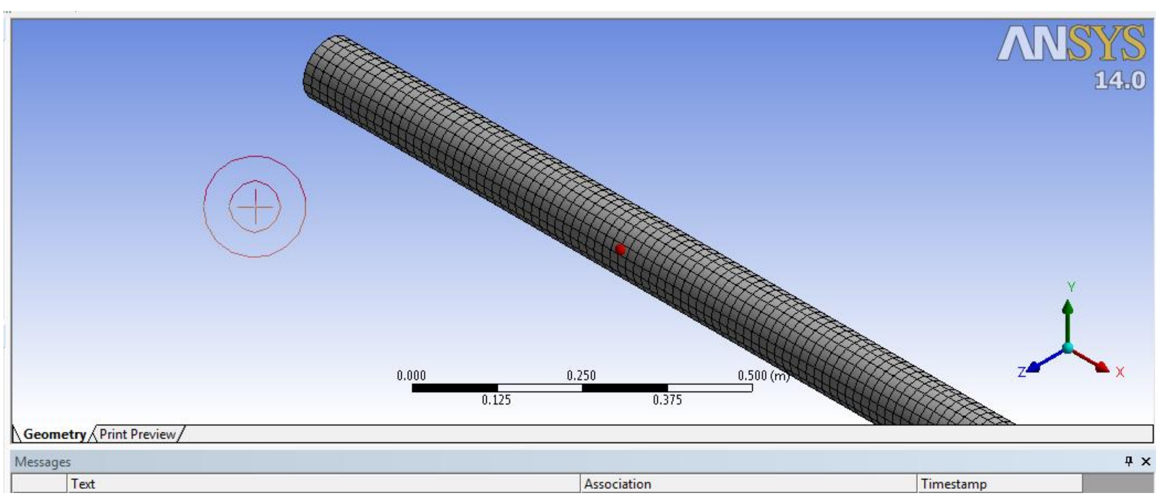

Figure 5: Meshing

After that, we can proceed with CFX Pre where several properties have to be defined. Here, properties such as domain, materials and boundary condition (inlet and outlet) should be specified.

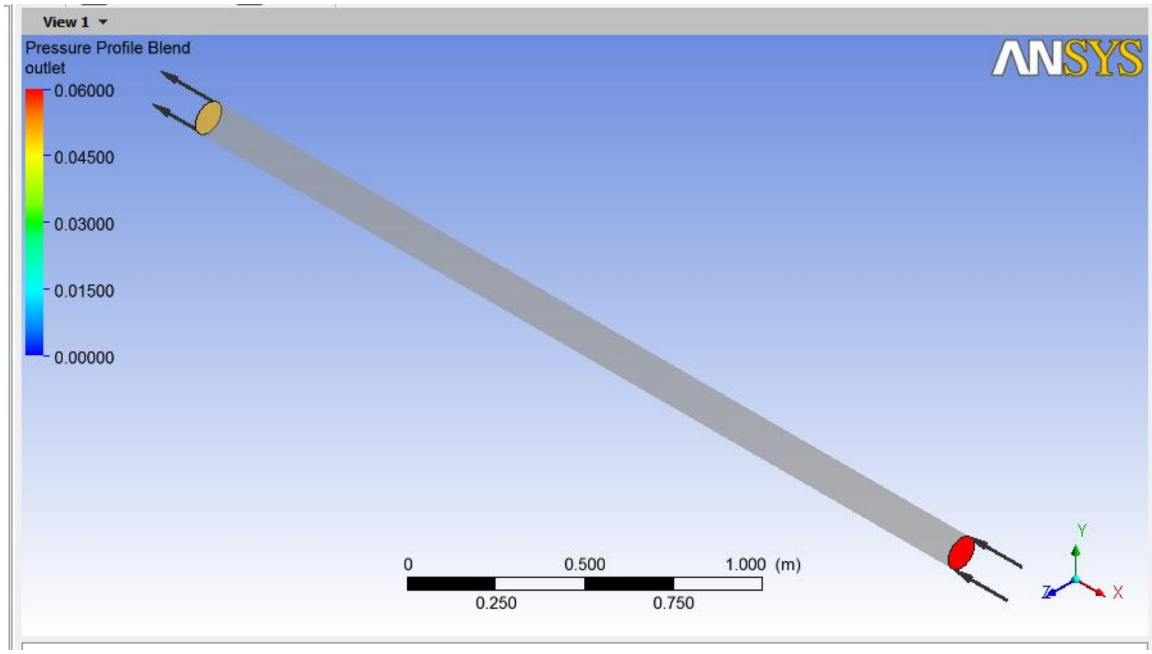

Figure 6: CFX Pre

Simulation is ready to run after all the required properties have been defined in CFX Pre. CFX Solver is initiated in ANSYS Workbench. Then, run the simulation.

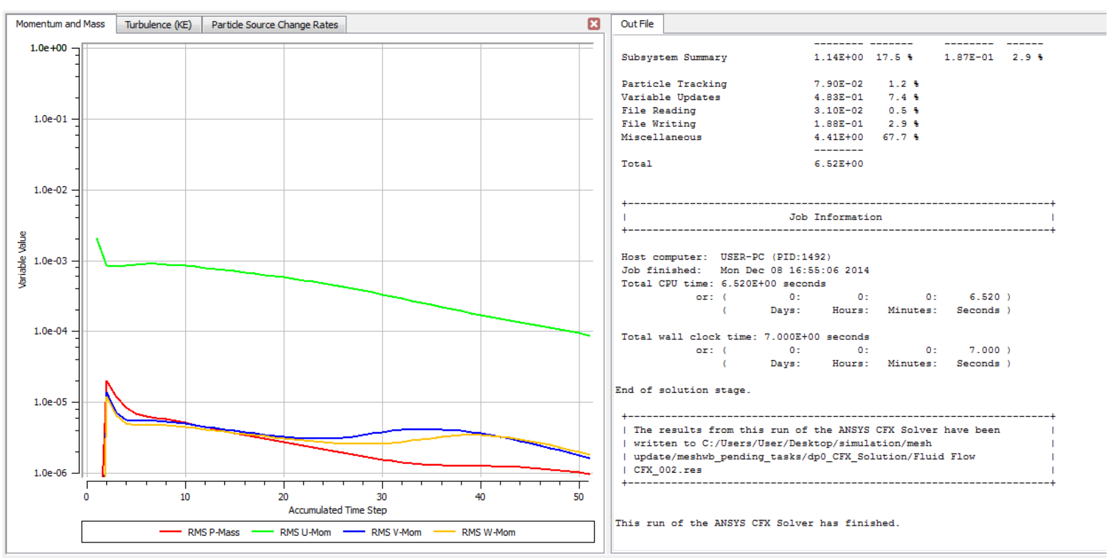

Figure 7: CFX Solver

Results are obtained in CFX Post and ready to view and analyze.

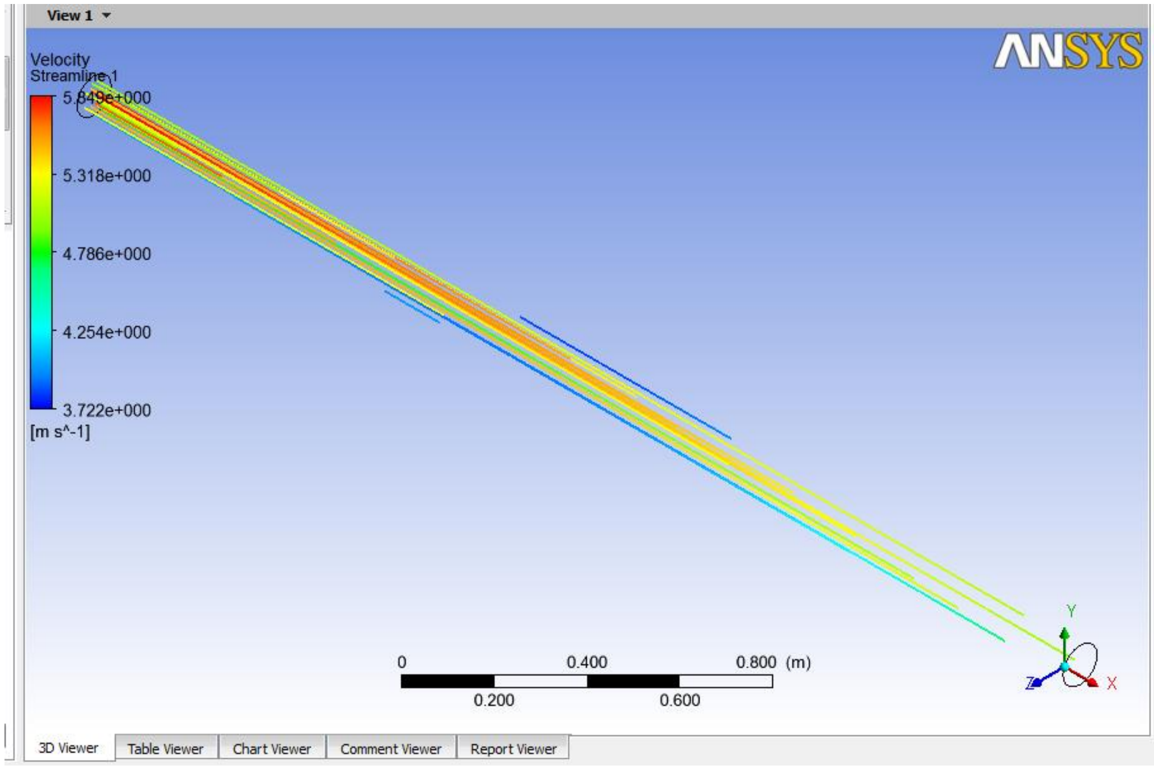

Figure 8: CFX Post

3.4 Key Project Milestone

Final Year Project timeline is as follow:

Table 1: Important date for Final Year Project I

Final Year Project 1		
1.	Extended Proposal Submission	10th July 2014
2.	Proposal Defense	21st July 2014
3.	Interim Draft Report Submission	11th August 2014
4.	Interim Report Submission	20th August 2014

Table 2: Important date for Final Year Project II

Final Year Project II		
1.	Progress Report Submission	5th November 2014
2.	Pre-SEDEX/Poster Exhibition	19th November 2014
3.	Submission of Final Draft/Submission of Technical Paper	10th December 2014
4.	Viva	22nd - 23rd December 2014
5.	Submission of hardbound copies	5th January 2015

For project activities, there are few key milestones identified for this project.

- Theoretical and calculation study on the balls and fluids interaction.
- Simulation process using CFD analysis.
- Analysis of the result obtains.
- Submission of the final report.

3.5 Project Timeline (Gantt Chart)

Table 3: Project Gantt Chart

Task	Month					
	1	2	3	4	5	6
Data Gathering						
Literature Review						
Ball and fluids interaction and distribution laws						
Software Familiarization						
CFD Simulation						
Determination of optimum ball size and weight. (Optional)						
Data Analysis						
Poster Presentation						
Submission of Technical Paper and Oral Presentation (Viva)						
Completion and Submission of Final Report						

Key Milestone

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Theories and Calculations

Drag Force

A fully immersed body in a fluid will experience forces from relative motion between the body and the fluid. These forces are called drag and lift. There is no significant difference of caused forces in term of relative motion either the body is moving through a stationary fluid or a fluid moves past a stationary body. Here, we only concern with the drag force. Drag can be defined as resistant force acted on a body by the fluid in the direction of relative motion of the fluid. (Mort, 2006). Equation of drag force is given by:

$$F_D = \frac{1}{2} C_D \rho v^2 A$$

F_D = Drag force

C_D = Drag coefficient

v = Relative velocity of the object

ρ = Fluid density

A = Cross section area of the object

Cross sectional area of the ball is given as πr^2 where r is the radius of the ball. Fluid density in this research is based on the type of blowout fluid.

Drag Coefficient

Drag coefficient, C_D relies on several factors like shape, Reynolds number, size and so on. It is dimensionless and usually determined through experimental with the wind tunnel. For a sphere, drag coefficient usually determines from a graph of C_D against Reynolds number which is resulted from laboratory experiments. From the graph, smooth and rough surface are plotted differently. On the other hand, a new correlation of C_D versus Reynolds number from (Morrison, 2013) is applicable for every values of Reynolds number. For this project, I will use the correlation from Morrison, 2013. The equation is given as follow:

$$C_D = \frac{24}{Re} + \frac{26(\frac{Re}{5.0})}{1 + \frac{Re}{5.0}^{1.52}} + \frac{0.411(\frac{Re}{263000})^{-7.94}}{1 + (\frac{Re}{263000})^{-8.00}} + \frac{Re^{0.80}}{461000}$$

C_D = Drag coefficient

Re = Reynolds number

In general drag coefficient for sphere is assumed to be 0.5. the surface of the balls is assumed to be smooth.

Reynolds Number

Reynolds number measures the ratio of inertia force to the viscous force. It is also a dimensionless quantity which is important in the field of fluid mechanics. In this research, Reynolds number calculation is specifically for a sphere moving through a fluid. So, the equation can be defined as below:

$$Re = \frac{d_p V \rho}{\mu}$$

d_p = diameter of the sphere

V = relative velocity of the sphere to fluid

ρ = density of the fluid

μ = viscosity of the fluid

Buoyancy

Buoyant force can be denoted base on Archimedes principles:

- An immersed body in a fluid experienced a buoyed force by the weight of fluid displaced.

- For a floating body to be able to float, the buoyancy force must be more than or equal its own weight.

Buoyancy force can be written as a single equation:

$$F_B = \gamma V_b$$

And

$$\gamma = \rho g$$

Where:

F_B= Buoyant force, N.

γ = Specific weight of fluid, $(\frac{N}{m^3})$.

V_b= Volume of the ball displaced by fluid, m^3.

ρ = Density of the fluid, $\frac{kg}{m^3}$

g = gravitational acceleration, $(\frac{m}{s^2})$.

Weight of the Kill Ball

The weight of the solid kill ball is dependent on the size and type of material used. Size of the ball is defined as the volume which is the function of the diameter. Different materials will have different density. So, to know the weight we have first to calculate the mass of the ball.

$$m = \rho \times V_b$$

Where:

m = mass, kg. V_b = volume of the ball, m^3.

ρ = density, $(\frac{kg}{m^3})$.

Volume of the ball is the same as volume of a sphere.

$$V_b = \frac{4}{3}\pi r^3$$

r = radius.

Some materials for the ball with their density are shown in the table below:

Table 4: Ball materials with their respective density

Material	**Density ($\frac{g}{cm^3}$)**
Lead	11.34
Brass	8.55
Copper	8.3-9.0
Steel	7.86
Iron	7.8
Zinc	7.14
Aluminum	2.7

Ball sizes:

In this research, ball with different size will be used as the parameter. Ball diameter will be as the following table:

Table 5: Ball diameters with their respective cross=sectional area

Ball Diameter (mm)	**Ball Diameter (meter)**	**Cross Sectional Area (m^2)**
25	0.025	4.909*10-4
30	0.030	7.069*10-4
35	0.035	9.621*10-4
40	0.040	1.257*10-3
45	0.045	1.590*10-3

Gravitational force on the ball is the same as the weight of the ball. Then, weight of the kill ball can be written as:

$$W = mg$$

W = weight, N.

m = mass, kg.

Gravitational acceleration constant is g = 9.8$\frac{m}{s^2}$.

Falling object will be accelerated due to gravity. There is a force resisting the movement of the object called drag force because of the medium in which the ball is dropping. Free body diagram is drawn to show the forces acting on the falling ball.

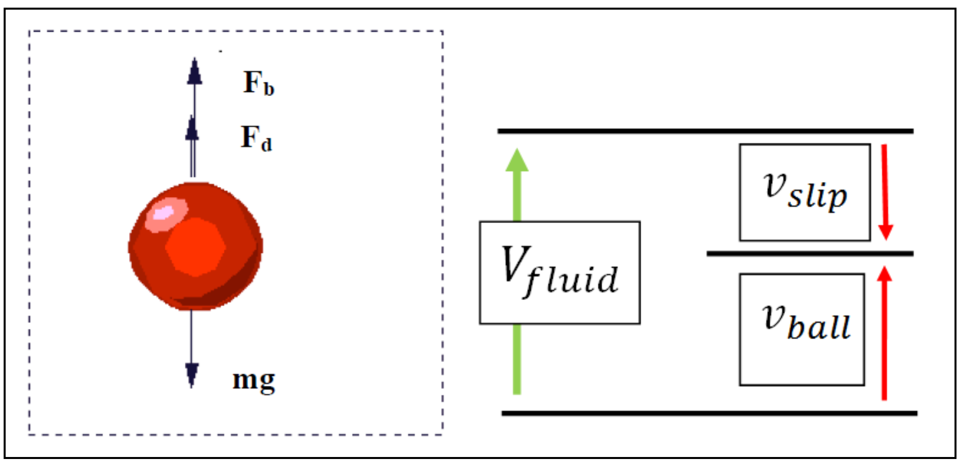

Figure 9: Free body diagram of falling sphere through the fluid.

As the ball is displacing the fluid, there is also buoyancy effect that result in buoyant force. Two forces acting upward and one force acting downward which is weight of the ball. The forces in vertical direction can be summed up with the following equation:

$$mg = F_b + F_D$$

$$mg = \gamma V_b + \frac{1}{2} C_D \rho v^2 A$$

$$v = \sqrt{\frac{2(mg - \gamma V_D)}{C_D \rho_f A}}$$

When the upward force and downward force are equal, the net force on the ball is zero. At this condition, the velocity of the ball is constant. Initially, the ball is moving with increasing velocity due to gravitational force. Eventually, the ball will reach constant velocity or also called terminal velocity. This particular velocity is the slip velocity of the kill ball relative to the fluid velocity. Slip velocity is the function of ball sizes, fluid density, ball density and drag coefficient.

Several crude oil properties from different oil field in Malaysia were used as the type of blowout fluid. (Kelechukwu & Md Yassin, 2008) have listed some of Malaysian crude as shown in the following table. Density of water is 1 g/cm3.

Table 6: Some of Malaysian crude oil physical properties

Types of crude	**Density ($\frac{g}{cm^3}$)**	**Viscosity (cSt) @ 70 ℃**	**API Gravity**
Penara	0.9165	32.50	22.8
Tapis	0.8036	2.251	44.5
Dulang	0.9814	3.817	12.6

API stands for American Petroleum Institute and API gravity is used to measure the "weight" of oil. Classifications of crude oil based on API gravity are shown as follow:

- Light – API is more than 31.1
- Medium – API is between 23.3 and 31.1.
- Heavy – API is less than 22.3
- Extra heavy – API is below 10.

Casing sizes:

The flow of blowout fluid is assumed to flow through the casing.

Table 7: Casing sizes with their cross-sectional area

Size OD (inches)	Size ID (inches)	Size ID (mm)	Area (m^2)
4.5	4.090	103.89	0.00848
7	6.538	166.07	0.02166
8 5/8	8.097	205.66	0.03322
9 5/8	9.063	230.20	0.04162
13 3/8	12.715	322.96	0.08191

Fluid velocity based on the casing size:

Table 8: Fluid velocity for different casing sizes

Casing Sizes		4 ½ inches	7 inches	8 5/8 inches	9 5/8 inches
Flow rate (bbd)	Flow rate (m3/s)	Velocity (m/s)	Velocity (m/s)	Velocity (m/s)	Velocity (m/s)
5000	0.009201	1.085	0.425	0.277	0.221
10000	0.0184	2.170	0.849	0.554	0.442
15000	0.0276	3.255	1.274	0.831	0.663
20000	0.0368	4.340	1.699	1.108	0.884

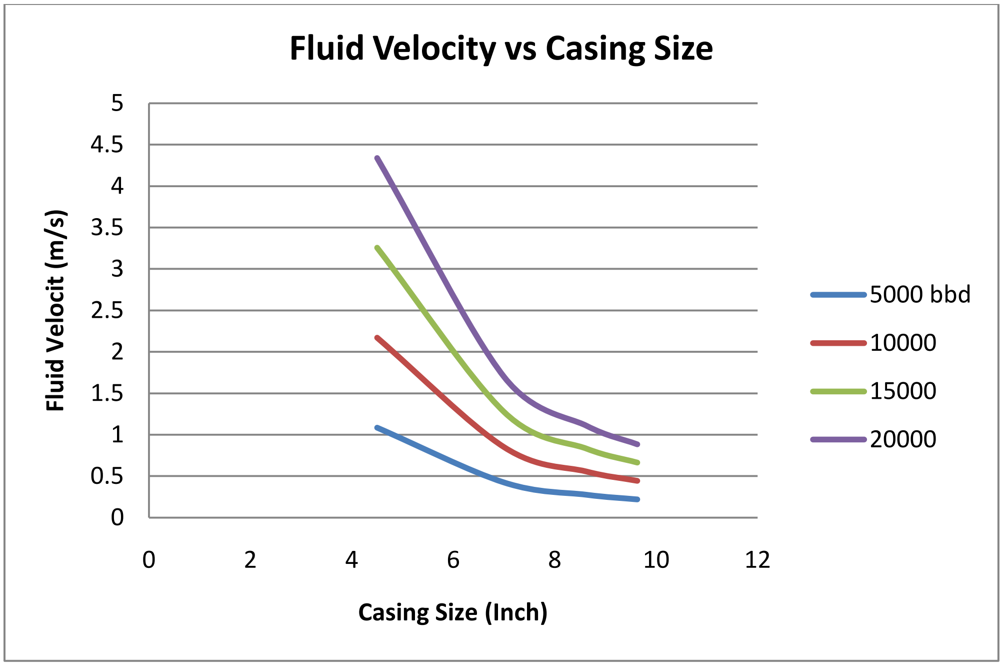

Figure 10: Fluid Velocity vs Casing Size graph

Conversion from bbd to m3/s: 1 bbd = 0.00000184 m3/s

As this research is based on the blowout fluid, so the flow rates are assumed to be high and the flow regime will be in the state of turbulent flow. Based on (Theron, Conort, & Ferguson, 1996) laminar flow usually occurred close to bottom of the wellbore. Most of the wells flow with turbulent condition.

Slip Velocity

For the first calculation of slip velocity, all the parameters are kept constant except for the ball diameter and flow rate. Slip velocity is the resultant velocity of between the velocity of the fluid and the ball. In order for the ball to go downward towards the bottom of the well, slip velocity must be higher than fluid velocity.

As this project assumed flow in vertical well, these velocities have only one axial component.

$$v_{slip} = v_{fluid} - v_{ball}$$

Minimum Ball Diameter

Minimum diameter required for the ball to move in the downward direction in the well can be calculated with the specified flow rate, fluid density and material of the ball. The condition for the calculation is when the velocity of the ball is zero. Thus, slip velocity will equal to the fluid velocity. So, the minimum density can be obtained from the following equation.

$$mg = F_b + F_D$$

$$\rho_b \frac{4}{3}\pi r^3 g = \rho_f g \frac{4}{3}\pi r^3 + \frac{1}{2} C_D \rho_f v^2 \pi r^2$$

$$r = \frac{3}{8}\left(\frac{C_D v^2 \rho_f}{\rho_b g - \gamma}\right)$$

Minimum Ball Density

The calculation will result in minimum ball density required for the ball to move in downward direction with specified ball diameter, flow rate and fluid density. This calculation is based on the condition where the velocity of the ball is zero. Thus, fluid velocity will equal to slip velocity. The determination of required minimum ball density is needed when ball diameter has already been specified. So, calculation of ball density will determine the movement direction of the ball. Desired density can be achieved by choosing the right ball materials. So, minimum ball density can be obtained from the following equation.

$$mg = F_b + F_D$$

$$\rho_b \frac{4}{3}\pi r^3 g = \gamma \frac{4}{3}\pi r^3 + \frac{1}{2} C_D \rho_f v^2 \pi r^2$$

$$\rho_b = \frac{1}{g}\left(\frac{3 C_D v^2 \rho_f}{8r} + \gamma\right)$$

4.2 Results and Discussions

For the first calculation of slip velocity, all the parameters are kept constant except for the ball diameter and flow rate. Slip velocity is the resultant velocity of between the velocity of the fluid and the ball.

Table 9: Data for calculation parameters

Calculation Parameters	
Ball material	Steel
Ball density ($\frac{kg}{m^3}$)	7860
Type of fluid	Tapis and Dulang crude
Fluid density ($\frac{kg}{m^3}$)	803.6 and 981.4
Flow rate (bbd)	5000, 10000, 15000 and 20000
Casing size OD (inches)	4.5 and 7
Ball diameter (mm)	25, 30, 35, 40 and 45

Tapis crude is classify as light oil whereas Dulang crude as heavy oil. These two types of oil will show the comparison between high density and low density oil that will affected the kill balls movement. Calculation of ball velocity is assumed for a single ball. In practical, there will be several number of balls drop into the well.

Steel ball with density of 7.86 ($\frac{g}{cm^3}$), Tapis and Dulang crude with density of 0.8036 ($\frac{g}{cm^3}$), and 0.9814 ($\frac{g}{cm^3}$), has been used as the input parameters for the calculation. These two values of crude oil density are to represent light and heavy oil. Ball sizes, casing sizes and flow rate is used as the variables for the calculation. The well is assumed to be in vertical position with only oil is flowing.

The resultant slip velocity is calculated for the two sizes of casing with different ball diameter. Flow rate is fixed at four values which are 5000, 10000, 15000 and 20000 bbd. Then, the ball velocity can be determined. Negative sign of the ball velocity indicate that the ball is going in downward direction and positive sign shows that the ball is going in upward direction. This ball velocity sign is depending on the size of the ball, flow rate of the well and density of hydrocarbon for particular casing size.

Table 10: Calculation result from Tapis crude and 4.5 inch casing

Ball diameter (mm)	Flow Rate (bbl)	5000	10000	15000	20000
	Slip Velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)
25	2.395	-1.310	-0.225	0.860	1.945
30	2.624	-1.539	-0.454	0.631	1.716
35	2.834	-1.749	-0.664	0.421	1.506
40	3.030	-1.945	-0.860	0.225	1.310
45	3.213	-2.128	-1.043	0.042	1.127

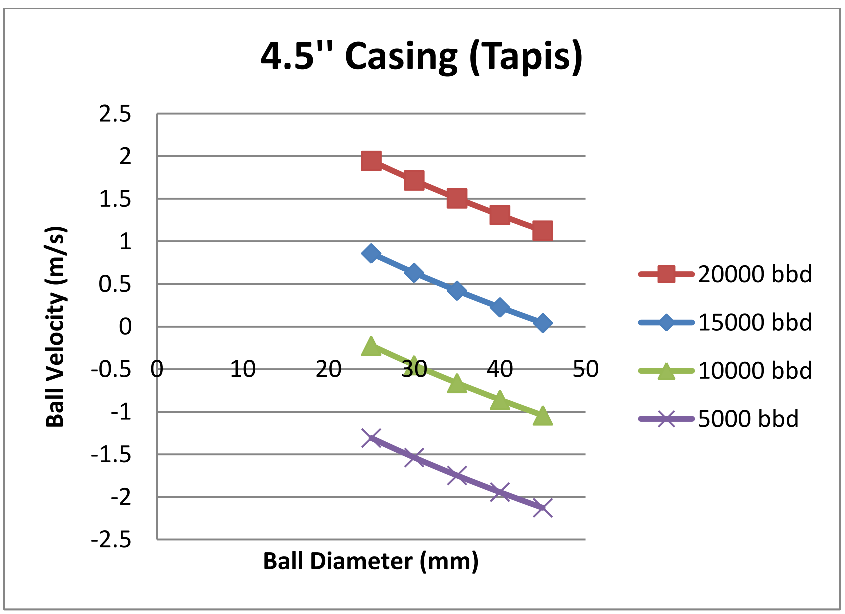

Figure 11: Ball velocity vs. ball diameter for 4.5 inch casing with Tapis crude

Table 11: Calculation result from Tapis crude and 7 inch casing

Ball diameter (mm)	Flow Rate (bbl)	5000	10000	15000	20000
	Slip Velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)
25	2.395	-1.970	-1.546	-1.121	-0.696
30	2.624	-2.199	-1.775	-1.350	-0.925
35	2.834	-2.409	-1.985	-1.560	-1.135
40	3.030	-2.605	-2.181	-1.756	-1.331
45	3.213	-2.788	-2.364	-1.940	-1.514

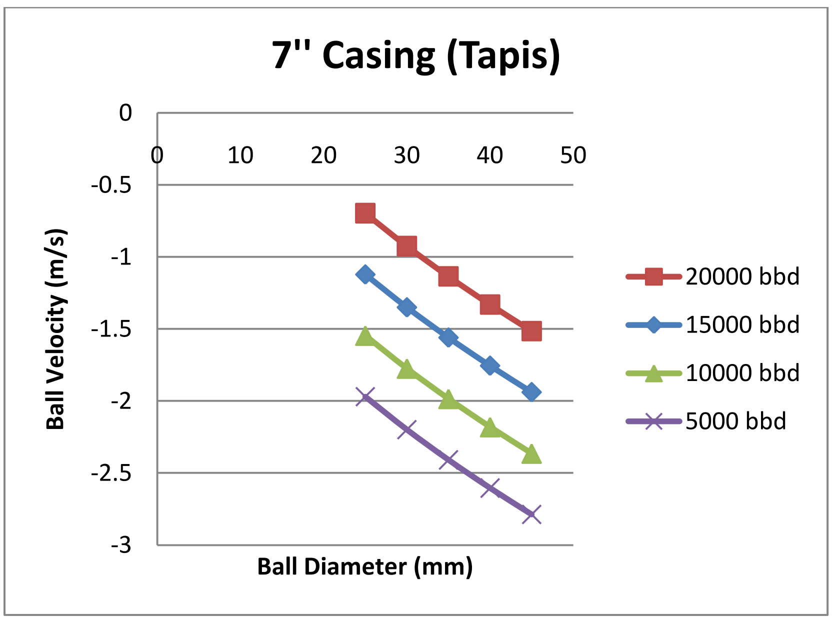

Figure 12: Ball velocity vs. ball diameter from 7 inch casing with Tapis crude

For 4.5 inch casing with Tapis crude, we can see from the Figure 11 that for the flow rate of 15000 bbd and 20000 bbd, the ball velocity is moving in upward direction for every size of the kill balls. The different is on the speed of the moving ball. Lighter ball will move with higher velocity upward whereas heavier ball is moving with slower velocity. For 10000 bbd and 5000 bbd, the ball is moving into downward direction of the well for all sizes of the ball. These balls also moving with different speed for different ball diameter.

Next, for 7 inch casing with Tapis crude, we can see from the figure that for all flow rates the ball is moving downward direction of the well for all specified ball diameter. The difference is only at the speed the ball is moving.

Same calculation parameters are used in the calculation for both of the casing size. With the same flow rates, as the size of casing is increase, fluid velocity is decrease. This is due to that the flow area is higher for 7 inch casing compare to 4.5 inch casing. Because of this, for 7 inch casing, the ball is moving in downward direction for all diameters of the ball. In 4.5 inch casing, it is noticed that, as the flow rate is increase, the ball will change the direction from downward to upward.

Casing size gives significant effect on ball velocity calculation. As we can see from Figure 12 and 11, at flow rates of 20000 bbd and 15000 bbd, with 4.5 inch the ball is moving towards upward direction but with 7 inch casing, the ball is moving towards downward direction. This showed, casing size greatly affect the ball direction and speed. This is because as the flow rate increase, it is mean that fluid velocity also increases. When fluid velocity is higher than slip velocity, the ball will be moving towards upward direction.

Table 12: Calculation result from Dulang crude and 4.5 inch casing

Ball diameter (mm)	Flow Rate (bbl)	5000	10000	15000	20000
	Slip Velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)
25	2.140	-1.054	0.030	1.115	2.200
30	2.344	-1.259	-0.174	0.911	1.996
35	2.532	-1.447	-0.362	0.723	1.808
40	2.707	-1.622	-0.537	0.548	1.633
45	2.871	-1.786	-0.701	0.384	1.469

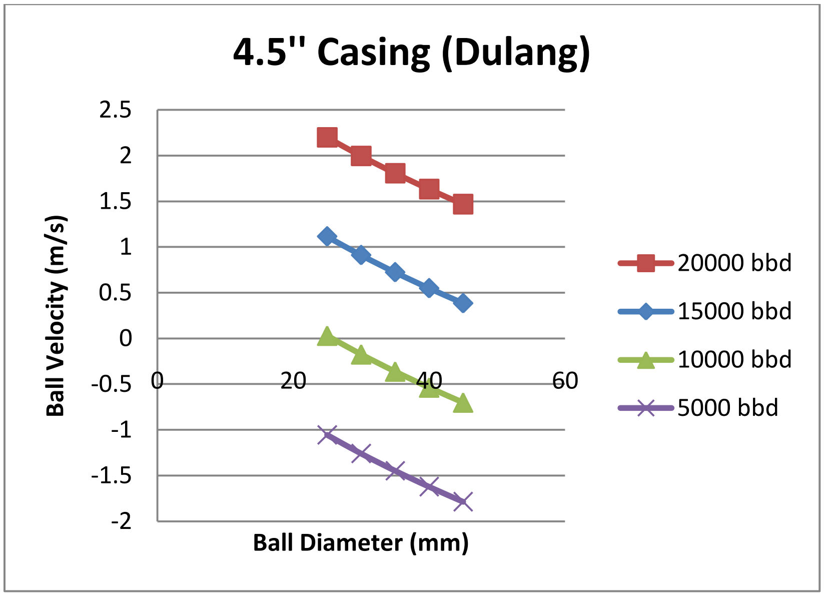

Figure 13: Ball velocity vs. ball diameter for 4.5 inch casing with Dulang crude

Table 13: Calculation result from Dulang crude and 7 inch casing

Ball diameter (mm)	Flow Rate (bbl)	5000	10000	15000	20000
	Slip Velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)	Ball velocity (m/s)
25	2.140	-1.715	-1.291	-0.866	-0.441
30	2.344	-1.919	-1.495	-1.070	-0.645
35	2.532	-2.107	-1.683	-1.258	-0.833
40	2.707	-2.282	-1.858	-1.433	-1.008
45	2.871	-2.446	-2.022	-1.607	-1.172

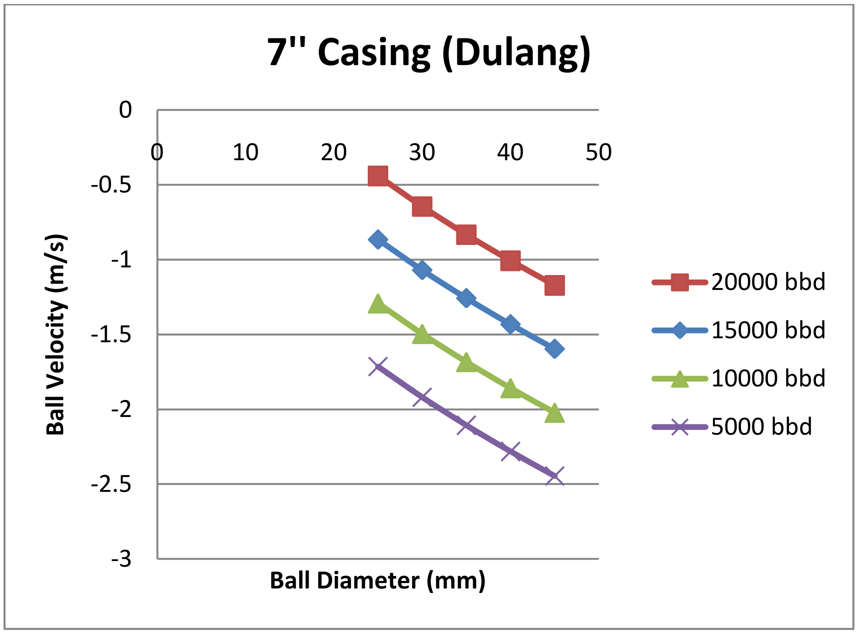

Figure 14: Ball velocity vs. ball diameter for 7 inch casing with Dulang crude

For 4.5 inch casing with Dulang crude, we can notice from the Figure 13 that for flow rate of 10000 bbd, the ball is moving towards downward direction except at the ball diameter of 25 mm where the velocity is almost zero. For 5000 bbd, the ball is moving into downwards direction for all the defined ball diameters. Then, for 20000 bbd and 15000 bbd, the ball is moving towards the upward direction.

As for Dulang crude in 7 inch casing shown in Figure 14, the result is much the same as for Tapis crude. The ball is moving downward direction for all the flow rates and ball diameters assigned. The difference is only at the speed of the moving ball.

Dulang crude is used for comparison purpose to see the effect of high density hydrocarbon on the ball velocity calculation. From the Figure 12 and 14, at 7 inch casing for both Tapis and Dulang crude, the ball is moving towards downward direction, the difference is only at the speed. At 20000 bbd flow rate with 45 mm ball diameter, the difference is ball velocity in difference fluid density is 0.342 m/s which is only at 20%. So, here we can say that fluid density does give much effect on movement of the ball.

Minimum Ball Diameter

Table 14: Minimum ball diameter for 4.5 inch casing

Type of Crude	Flow Rate (bbl)	5000	10000	15000	20000
Tapis	Minimum Ball Diameter (mm)	5.130	20.520	46.170	82.081
Dulang	Minimum Ball Diameter (mm)	6.427	25.708	57.843	102.833

Table 15: Minimum ball diameter for 7 inch casing

Type of Crude	Flow Rate (bbl)	5000	10000	15000	20000
Tapis	Minimum Ball Diameter (mm)	0.787	3.141	7.073	12.579
Dulang	Minimum Ball Diameter (mm)	0.986	3.935	8.861	15.759

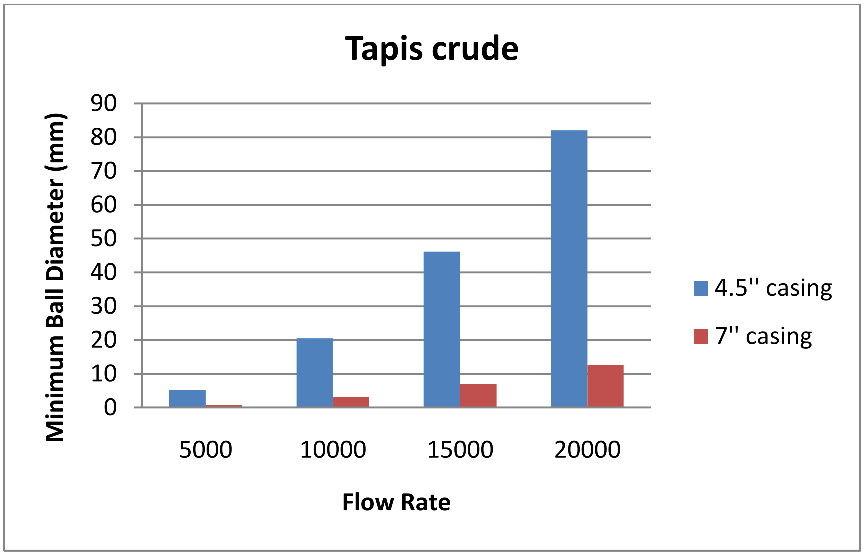

Figure 15: Minimum ball diameter bar chart for Tapis crude

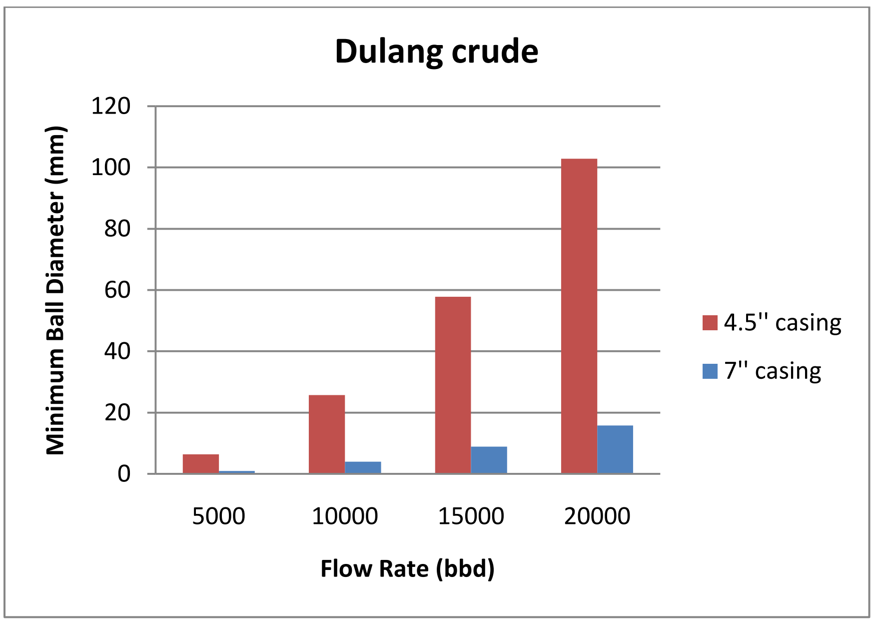

Figure 16: Minimum ball diameter bar chart for Dulang crude

Minimum ball diameter for the specified flow condition is also calculated. The result will help us to determine the suitable size of kill balls to be used. As the flow velocity is high, the minimum ball diameter is also become larger. These calculated diameters help us to select the size of the ball so that the ball will be moving downward direction of the well. If the diameter used for the ball is less than this minimum diameter, the ball will be moving upward direction of the well.

With different ball sizes used in the calculation, we can see that the ball sizes will affect the direction of the ball with the specified ball density. Also, different ball sizes will affect the speed at which the balls are moving regardless of their direction. In addition, we can determine minimum ball diameter with our desire ball velocity either moving upward or downward direction of the well.

As we can see from Figure 15 and 16, casing size gives significant effect on minimum ball diameter calculation. At 20000 bbd, the difference in ball diameter between 4.5 inch and 7 inch casing is about 84.67%. This value is the same for both Tapis and Dulang crude. This is due to that at certain flow rate, decrease in casing size will increase fluid velocity.

Minimum Ball Density

Table 16: Minimum ball density for 4.5 inch casing

Type of Crude	Ball Diameter (mm)	25	30	35	40	45
	Flow Rate (bbl)	Minimum Ball Density (kg/m3)	Minimum Ball Density (kg/m3)	Minimum Ball Density (kg/m3)	Minimum Ball Density (kg/m3)	Minimum Ball Density (kg/m3)
Tapis	5000	2251.59	2010.26	1837.88	1708.59	1608.04
	10000	6595.55	5630.22	4940.71	4423.57	4021.35
	15000	13835.48	11663.50	10112.09	8948.53	8043.53
	20000	23971.39	20110.09	17352.02	15283.47	13674.59
Dulang	5000	2749.76	2455.03	2244.51	2086.63	1963.82
	10000	8054.84	6875.93	6033.86	5402.30	4911.09
	15000	16896.64	14244.10	12349.43	10928.43	9823.20
	20000	29275.16	24559.54	21191.23	18665.00	16700.16

Table 17: Minimum ball density for 7 inch casing

Type of Crude	Ball Diameter (mm)	25	30	35	40	45
	Flow Rate (bbl)	**Minimum Ball Density (kg/m3)**	**Minimum Ball Density (kg/m3)**	**Minimum Ball Density (kg/m3)**	**Minimum Ball Density (kg/m3)**	**Minimum Ball Density (kg/m3)**
Tapis	**5000**	1025.77	988.74	962.29	942.46	927.03
	10000	1690.19	1542.42	1436.88	1357.72	1296.15
	15000	2799.98	2467.25	2229.59	2051.34	1912.70
	20000	4354.12	3762.37	3339.69	3022.67	2776.11
Dulang	**5000**	1252.72	1207.50	1175.20	1150.98	1132.14
	10000	2064.15	1883.69	1754.79	1658.12	1582.93
	15000	3419.49	3013.14	2722.89	2505.21	2335.90
	20000	5317.49	4594.81	4078.61	3691.45	3390.34

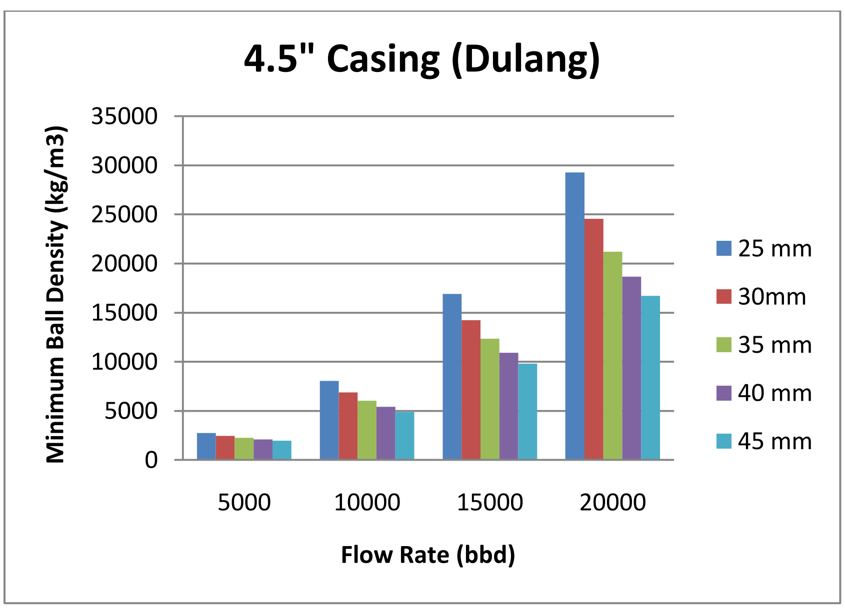

Figure 17: Minimum Ball Density Bar Chart for 4.5" Casing with Dulang crude

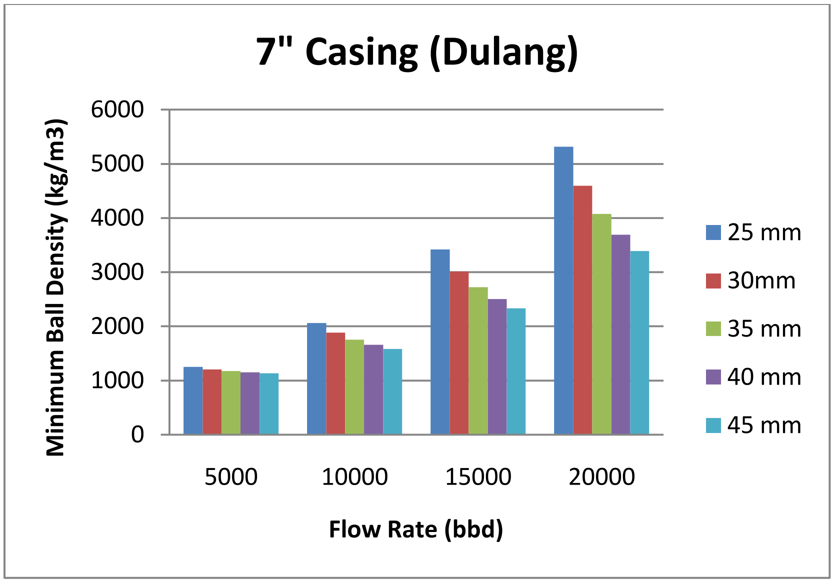

Figure 18: Minimum Ball Density Bar Chart for 7" Casing with Dulang crude

As the minimum ball diameter is too high for a certain situation which made the size of the ball is not practical to be applied, the ball density can be increased to reduce the size of the ball. Minimum ball density is calculated for casing sizes with specified flow rate, ball size and fluid density.

In addition, if we already fixed the ball sizes because in the case where tubing or pipe diameter used for ball transportation has been specified, the control variable that determines the direction of the ball is the density. We can see in Table 17, for 7 inch casing at 20000 bbd flow rate with 25 mm ball diameter, the minimum density for Tapis crude is only 4354.12 $\frac{kg}{m^3}$ and for Dulang crude is 5317.49 $\frac{kg}{m^3}$. Any materials use for the ball with density higher than this are supposed to make the ball move in downward direction.

In the case where, minimum density is too high, we can increase the ball sizes until this density is achievable. We can see from the Table 16 for 4.5 inches casing, for 25 mm ball with 20000 bbd, the minimum density is 23971.39 $\frac{kg}{m^3}$ for Tapis and 29275.16 $\frac{kg}{m^3}$. for Dulang. As we increase the ball diameter, the minimum density is reduced to 13674.59 kg/m3 and 16700.16 $\frac{kg}{m^3}$ each.

In minimum ball density calculation, casing size gives large effect on the result. As we can see from the Table 16 and 17, for Dulang crude at 20000 bbd with 25 mm ball diameter, for 4.5 inch casing, the resultant density is 29275.16 $\frac{kg}{m^3}$ whereas for 7 inch casing, the minimum density is 5317.49 $\frac{kg}{m^3}$. The difference is about 81.84%.

Types of crude not affect much on the result. From Table 17 at 20000 bbd flow rate with 25 mm ball diameter and 7 inch casing, resultant density for Tapis is 4354.12 $\frac{kg}{m^3}$ whereas for Dulang is 5317.49 $\frac{kg}{m^3}$. The difference is only about 18.12%.

CFD Simulation

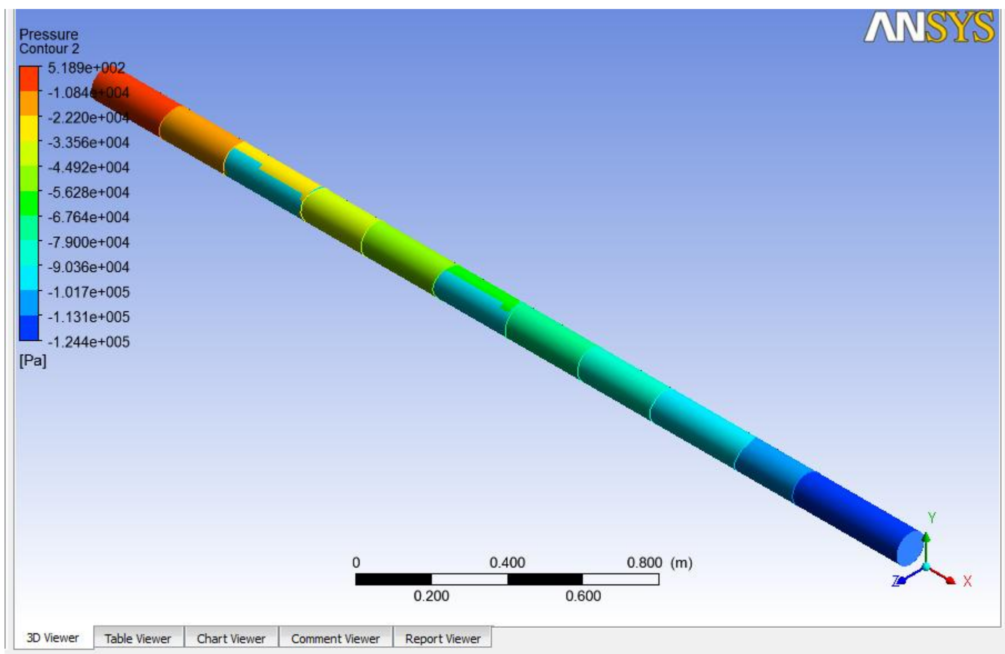

Figure 19: Pressure distribution across the well

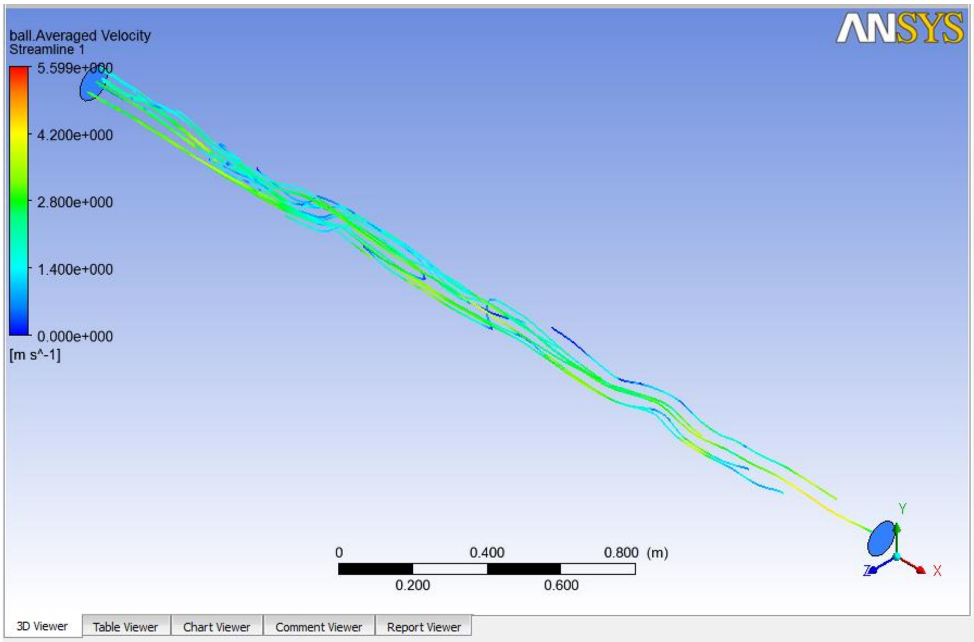

Figure 20: Ball averaged velocity

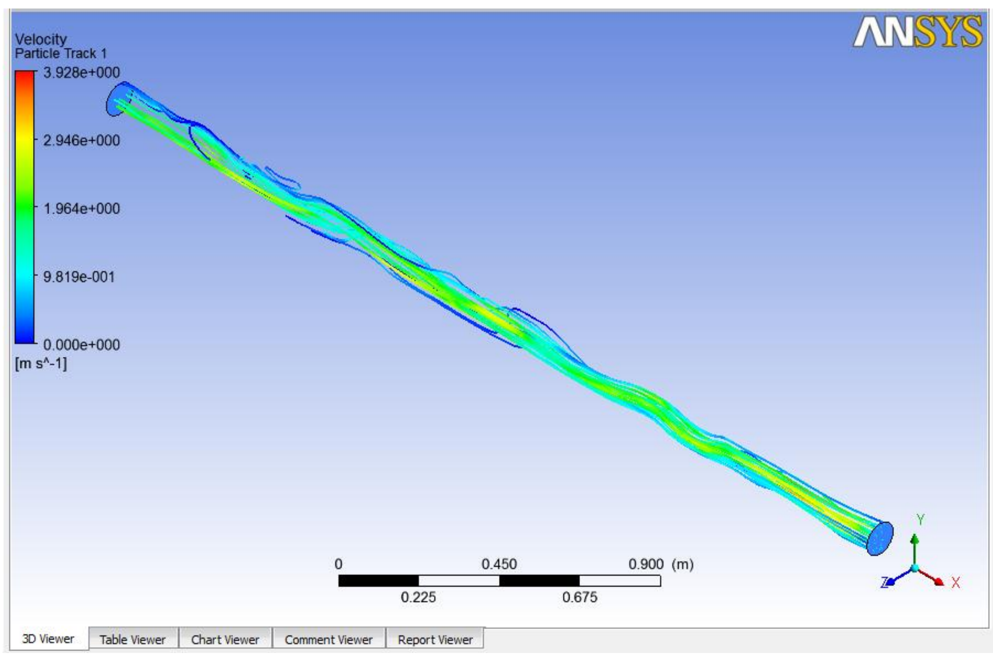

Figure 21: Velocity of particle track

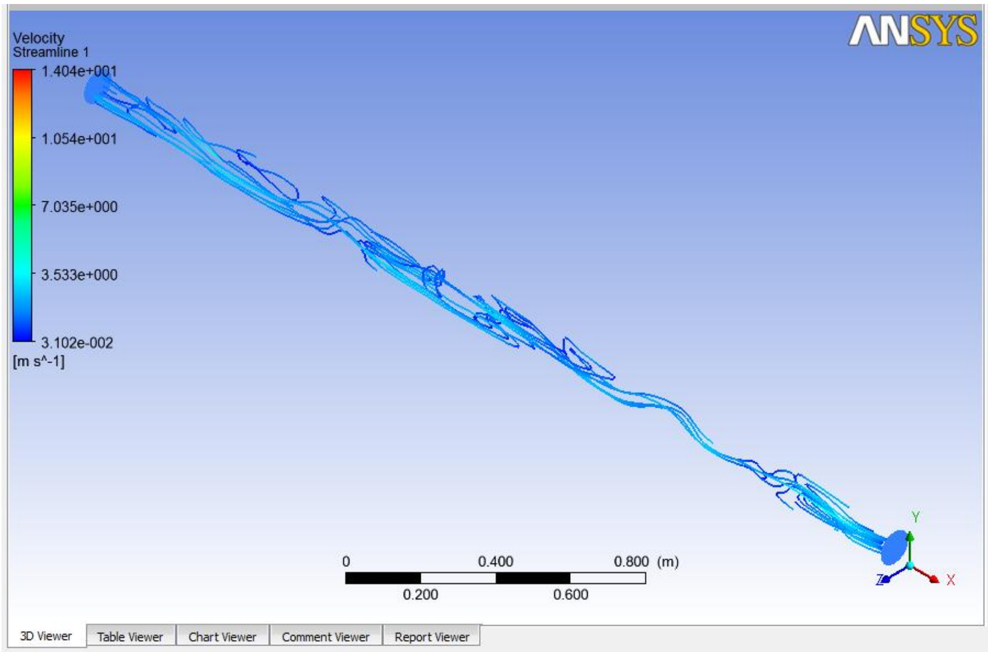

Figure 22: Velocity streamline

From Figure 19 we can see the pressure distribution across the well. Pressure at the middle section is lower compare to the top and bottom of the well. This is due to that that is where the interaction between the balls and the fluid occur the most.

Figure 20 showed ball averaged velocity across the well. In this case, ball starts flowing from the bottom of the well. We can see the highest velocity is at the bottom because that is where the balls start flowing. As the ball flow, the velocity is decreasing and will reach constant velocity.

As in Figure 21, it is shown the velocity of particle track. Also, in here we can notice the high velocity is at the bottom and it is decreasing as it is flowing to the top. This is because the fluid starts flowing from the bottom. In addition, there also regions where particle reach zero velocity in the middle and top section of the well. This means that there are some balls that changing direction as they flow to the top.

Figure 22 shows velocity streamline across the well. Velocity is quite constant with no much change except there is a certain area where the velocity fluctuated. The velocity profile is increase and decrease with constant rate across the well.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Offshore well blowout brings a lot of disaster especially to the environment. Oil spill has always become a major issue when blowout happened. Time taken to control the blowout is very important to prevent polluting the environment. There is a need for fast and effective well kill method. Dynamic kill balls provide fast and effective method as compared to other conventional kill mud technology. This method works by pumping heavy kill balls into the well to suppress the blowout flow. The balls can be use from any environmental friendly materials.

The purpose of this project is to study on the interaction between kill balls and the blowout fluids inside the blowout well. The behavior of the kill balls then is simulated with CFD using ANSYS CFX 14. According to the results obtained, the following conclusions are arrived.

- Movement direction of the balls can be determined with specified flow conditions and ball properties.
- Minimum ball density and diameter can be calculated with specified flow condition and ball properties.
- Balls behavior in the well has been simulated using ANSYS CFX 14.

5.2 Recommendations

Several recommendations and improvements have been identified by the author in order to improve the accuracy and quality of the study.

- It is better to consider two phase behavior of the flowing fluids which include oil and gas phase to give more accurate condition.
- Calculation of the ball velocity relative to the depth of the well should yield more accurate condition and result.
- As in ANSYS CFX simulation, by applying different particles injection region would give more desirable condition.

- For future studies, adequate attention should be given more on the simulation part so that better and accurate result could be obtained.
- For future work, this project can be further continues with laboratory experiment where experimental well will be set up. This is to test the validity and rationality of the outcomes from the simulation

REFERENCES

Adams, N., & Kuhlaman, L. (1994). *Kicks And Blowout Control.* Tulsa, Oklahoma: PennWell Publishing Company.

Al-Jassim, F. (1991). Kuwait Oil Wells Blowout-Aspects and Effects. *13th World Petroleum Congress.* World Petroleum Council.

Biello, D. (2011, April). *How Science Stopped BP's Gulf of Mexico Oil Spill.* Retrieved July 3, 2014, from Scientific American: http://www.scientificamerican.com/article/how-science-stopped-bp-gulf-of-mexico-oil-spill/

Borthwick, D. (2010). *Montara Comission of Inquiry.* Australia: Montara Comission of Inquiry.

Christou, M., & Konstantinidou, M. (2012). *Safety of offshore oil and gas operations: Lessons from past accident analysis.* Luxermborg Publications Office of the European Union.

Dyb, K., Thorsen, L., & Nielsen, L. (2012). *Blowout Risk Evaluation in the Labrador Sea.* Acona Flow Technology AS.

Grace, R. D. (2003). *Blowout and Well Control Handbook.* Elsevier.

Hagerty, C. L. (2010). *BP Deepwater Horizon Explosion and Oil Spill.* DIANE Publishing.

Herbst, L. *Effective Well Control - Prevention & Response.* Bureau of Safety and Environmental Enforcement.

Johnsen, S. (2012). *Probabilistic blowout risk in former disputed area southeast in the Norwegian part of the Barents Sea.* Faculty of Science and Technology, University of Stavanger.

Josey, R., Hoshman, R., Patton, F., & Ranney, R. (2008). *Investigation of Blowout Main Pass Block 91 OCS-G 14576.* New Orleans: U.S Department of the Interior.

Kato, S., & Adams, N. J. (1991). Quantitative Assessment of Blowout Data as it Relates to Pollution Potential. *First International Conference on Health,Safety and Environment.* The Hague: Society of Petroleum Engineers.

Kelechukwu, E. M., & Md Yassin, A. A. (2008). Potntial Risk Of Paraffin Wax - Related Problms In Malaysian Oil Fields. *Jurnal Teknologi* , 1-7.

Liu, X. (2012). *Patent No. WO 2012/023074 A1.* Australia.

Morrison, F. A. (2013). *Data Correlation for Drag Coefficient for Sphere.* Department of Chemical Engineering, Michigan Technological University.

Mort, R. L. (2006). *Applied Fluid Mechanics.* Prentice Hall.

SINTEF Offshore Blowout Database. (2009). Retrieved July 2014, from SINTEF: http://www.sintef.com/home/Technology-and-Society/Projects/Projects-SINTEF-TS-2001/SINTEF-Offshore-Blowout-Database/

Theron, B., Conort, G., & Ferguson, J. (1996). Fluid Flow Fundamentals. *Oilfield Review* , 61-64.

Turley, J. A. (2014). An Engineering Look at the Cause of the 2010 Macondo Blowout. *IADC/SPE Drilling Conference and Exhibition.* Texas, USA: Society of Petroleum Engineers.

Watson, D., Brittenham, T., & Moore, P. L. (2003). *Advanced Well Control.* Society of Petroleum Engineers.

West, L. (2014). How Do Oil Spill Damage the Environment. *Environmental Issues* .

Wilson, S. M. (2012). A Wellbore Stability Approach For Self-Killing Blowout Assessment. *SPE Deepwater Drilling and Completions Conference.* Texas, USA: Society of Petroleum Engineers.

APPENDICES

Figure below is the patent from Xianhua Liu of "Rapid Kill and Restoration System for Blowout Wells". As shown in the figure, the system consists of a pump, a ball injection device, a tubing system and a cage.

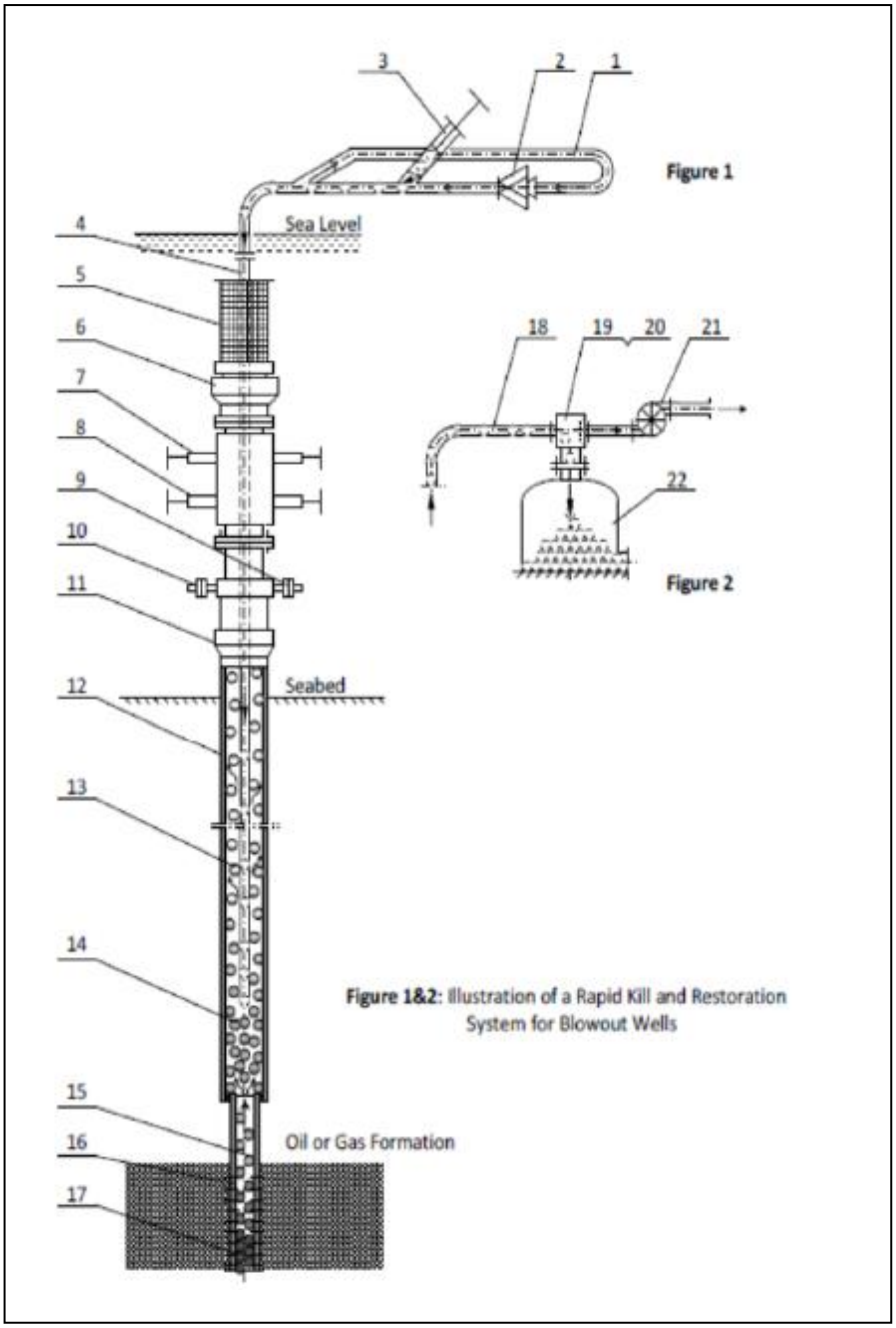

Figure 23: Balls Kill System from Xianhua Liu.