# A COMPARATIVE STUDY OF DRILLING FLUIDS POWER DELIVERY OF WATER, AIR AND SC-CO2 IN COILED TUBING DRILLING

By

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(Petroleum)

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# CERTIFICATION OF APPROVAL

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Approved by,

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(AP. Dr. Xianhua Liu)

UNIVERSITI TEKNOLOGI 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.

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NATAPONG SORNPROM

# ACKNOWLEDGEMENT

In completion of this Final year project, I would like to express my deepest gratitude to all parties that involved in making this project as a meaningful and great achievement for me. Throughout the project timeframe, I have learned a lot of new things and gained so much experience that will be a huge value for me in the future.

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# ABSTRACT

Recently, coiled tubing drilling becomes one of the most exciting technological developments and a preferred technique in oilfield. Coiled tubing drilling has a wide range of potential applications. However, it requires drilling fluids to supply sufficient power for the down-hole drilling motor and to circulate cuttings out of wellbore. Water, which is generally used as the drilling fluid, becomes a major problem when drilling small deep holes in hard formation. Additionally water is incompressible fluid and can only deliver hydraulic power. Hence, a comparative study of drilling fluids power delivery in coiled tubing drilling by using water, air and supercritical carbon dioxide (SC-CO2) as drilling fluids is proposed. Based on studies, both SC-CO2 and air are compressible and low viscosity fluid. The water drilling fluid is then taken as the benchmark. The properties of fluids are considered in order to enable achieving sufficient energy delivery, prolong the coiled tubing lifetime as well as the associated drilling components. Thus, in this project, calculation and comparison of water, air and SC-CO2 will be carried out in terms of energy delivery in relation to inlet and outlet pressure.

# TABLE OF CONTENTS

# LIST OF FIGURES



# LIST OF TABLES

# NOMENCLATURE

$A$ = cross section area m2

$D$ = diameter m

$E$ = energy flow rate kJ/s

$Ef$ = friction energy loss per unit time kJ/s $Ek$ = kinetic flow rate kJ/s

$Ep$ = pressure energy flow rate kJ/s

$Ez$ = gravitational potential energy flow rate kJ/s

$f$ = Fanning friction factor dimensionless

$g$ = gravitational acceleration m/s2

$H$ = enthalpy flow rate kJ/s

$L$ = length m

$p$ = pressure Pa

$Ql$ = heat energy loss per unit time kJ/s

$Qm$= mass flow rate m3/s

$Qv$ = volume flow rate m3/s

$Re$ = Reynolds number dimensionless

$U$ = internal energy flow rate kJ/s

$u$ = internal energy per unit mass kJ/kg

$z$ = height m

$\varepsilon$ = wall roughness m

$\rho$ = fluid density

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Traditionally, the conventional drilling is to drill large diameter wells with drilling rigs those equipped with big, heavy, and expensive devices. Currently, the advance of drilling technology has introduced a coiled tubing drilling (CTD) method which offers the potential to drill cheaper, smaller wells with more portable drilling rigs and have a significantly less environmental footprint. This will allow access to areas those were previously too environmentally sensitive and faraway. Coiled tubing drilling has become an outstanding technology to drill more wells for less investment, accessing parts of reservoirs that would otherwise never be produced.

The target of drilling operations is to drill the wells and bring the wells to life. Drilling fluids are generally used for many purposes in drilling operations, for example, it is used to cool the drill bits, transport cuttings out of bottom-hole, provide a good rate of penetration, and supply enough power to drive the down-hole motor etc. However, the power delivery of drilling fluids is one of the most important functions that this project will concentrate. Basically the main roles of drilling fluids power are to drive the high speed down-hole motor and lift cuttings up to the surface during coiled tubing drilling (CTD) operation. There are many types of drilling fluids used at the moment such as oil-based, air and gas, but serious problems encountered when water is used as drilling fluids to supply power. Due to water is incompressible and high viscous. The water-based drilling fluid could be brine, fresh water, or saturated brine. Incompressibility is a common property of liquids, but water is especially incompressible. Besides, the viscosity of water is due to the friction between neighboring particles in water that are moving at different velocities. Therefore, a significant pressure difference between the two ends of the coiled tubing is needed to overcome friction and provide power to down-hole motor. However, too much applied pressure could potentially affect coiled tubing lifetime. The air and SC-CO2 are, hence, brought up to utilize as drilling fluids because they are more compressible and less viscous compared to water. The associated equation will be derived and the comparison will be discussed in order to demonstrate the ability of each drilling fluids in delivering the power to coiled tubing drilling operation.

As the power of drilling fluids drives down-hole drilling motor, however, the greater pressure is applied, the lesser lifetime of coiled tubing is generated. To be more efficient and more powerful drilling fluids, air and SC-CO2 which are more compressible and low viscous, are discussed in this project to compare with the water which is assigned as a benchmark. Lastly, the calculation will determine the pressure needed for pumping a drilling fluid into coiled tubing to get desired ROP and not reduce the lifetime of coiled tubing.

## 1.2 Problem statement

### 1.2.1 Problem Identification

Even though water is universally used in oilfield, but there is a limitation of applying this kind of drilling fluid in coiled tubing drilling. It is believed that because of its incompressibility and high viscosity resulting insufficient power delivery through a very long but small diameter coiled tubing. Moreover, the merging of water and drilled cuttings will increase the viscosity of drilling fluid in the narrow return annulus. Because of these, the higher pressure rate needs to be supplied. However, high pressure has potential in reducing the lifetime and likewise bursting the coiled tubing.

### 1.2.2 Significance of the Project

This project will aim at a comparative study of power delivery's ability of water, air and SC-CO2. In order to make the comparison, properties and relative calculations will be identified to achieve the efficient energy for down-hole drilling motor and to transport cuttings out of the bottom hole. By considering the amount of energy in a unit mass at the selected pressure difference between the inlet pressure of coiled tubing and outlet pressure of annulus will be resulting the desired penetration rate as well as extend lifetime of coiled tubing.

## 1.3 Objectives

1. To study the coiled tubing drilling technology and to investigate the properties of water, air and SC-CO2 drilling fluid in coiled tubing drilling
2. To compare the efficiency of power delivery of water, air, and SC-CO2 in terms of energy delivery in order to identify the best drilling fluid in coiled tubing drilling.

## 1.4 Scope of study

1. Study the coiled tubing drilling technology.
2. Understand the properties of selected drilling fluids, water, air and SC-CO2 in coiled tubing drilling operation.
3. Focus on derivation of the power equation, the friction energy loss of drilling fluids inside coiled tubing and annulus and power output of down-hole turbine.
4. Study the advantages and disadvantages of water, air and SC-CO2 in order to achieve the goal of identifying the best drilling fluid.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Coiled Tubing Drilling (CTD)

Over the lifetime of production in oil and gas fields, it is necessary to conduct maintenance within the drilled and completed wells. Coiled tubing has been a helpful apparatus in this operations. With a very small size of tube, it is easy to be inserted into the well without removing the surface equipment. The typical application is to load one end of the coiled tubing into a wellbore, lowering the end by unreeling the coiled tubing at the surface and reeling the tubing end back up the surface to store it (Mark et al,. 1994). Lately, coiled tubing has been employed in conjunction with down-hole motors for drilling operations and other maintenance. Coiled tubing drilling (CTD) significantly reduces drilling costs and provide time-effective solution comparing to a conventional drilling. Some of the potential cost saving factors include the running speed of coiled tubing units, which is normally much faster than conventional drilling rigs and the reduced pipe handling time, pipe joint make up time, and leakage risks. Moreover, using coiled tubing could avoid some drilling stops (e.g., to make up a joint) and also diminish formation damage caused by interrupted mud circulation.

**Figure 1:** Portable Coiled Tubing Drilling Unit

(Source: Sichuan Honghua Petroleum Equipment Co.,Ltd, 2014)

Kolle (2002) claimed that it is because of the light weight of coiled tubing, the thrust and torque capacities of coiled tubing drilling have lower capacities than conventional drilling. This causes restricted ability of coiled tubing drilling to penetrate rock formation. In order to increase the ability of penetration, the diameter of tube need to be enlarged. However, the diameter can only be increased up to the point at which the tube will be able to pass through the surface equipment. Although, by delivering high pressure fluid jets at the drill bit can highly minimize the thrust and torque needed but the lifetime of coiled tubing is inversely proportional to the operating pressure.

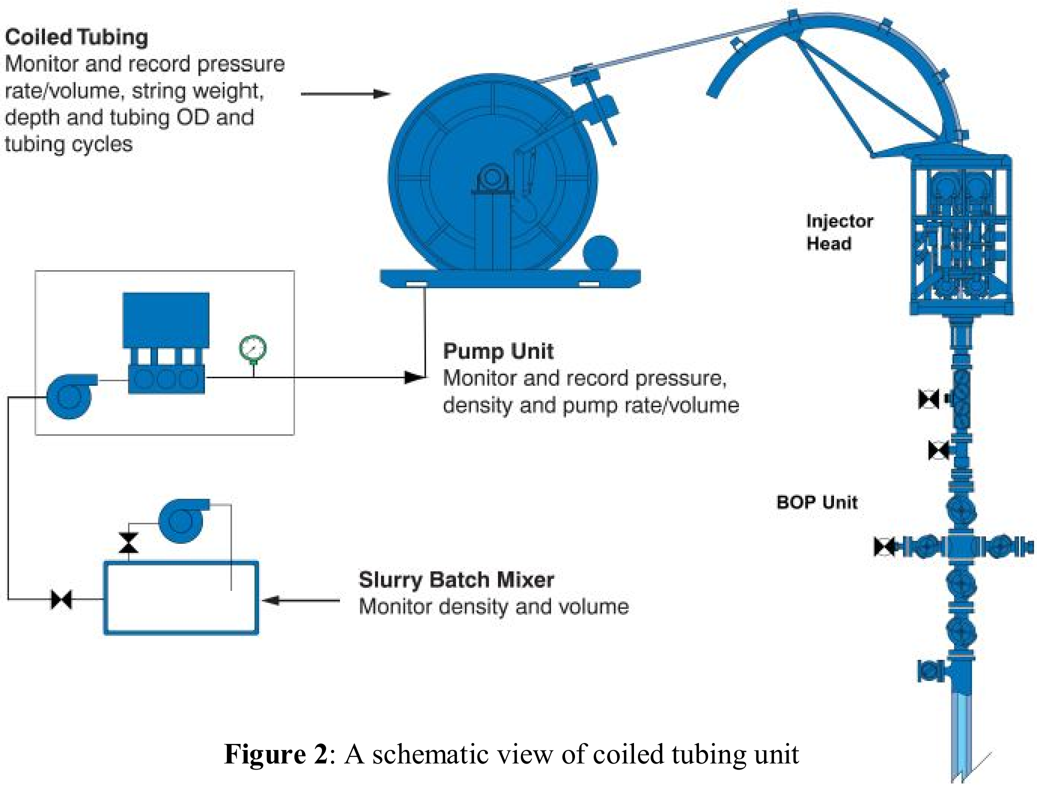



**Figure 2**: A schematic view of coiled tubing unit

(Source: CTES, 2005)

According to Amir et al. (2013) the coiled tubing unit comprises of four main components: 1) Reel, it is used to store the coiled tubing in order to be conveniently transported, 2) Injector head, its application is to provide the surface drive force to run and retrieve the coiled tubing, 3) Control cabin, it is used for equipment operator to control and monitor the coiled tubing, and 4) Power pack, to generate hydraulic and pneumatic power needed to operate the coiled tubing unit. The purposed size of coiled tubing is from 2.54 cm. or 1 inch to 11.4 cm or 4 ½ inch (NETL, 2005).

### 2.1.1. The difference of CTD and conventional drilling techniques

The significant different between two methods is that coiled tubing drilling must use a downhole motor because it is unable to rotate. Coiled tubing does not require connections which enable it to continuously circulate during tripping in or out of the well. However these advantages are balanced by the additional equipment that is needed for coiled tubing drilling. In the case of normal drilling with pipes, circulation must be stopped during connecting pipes. Problems like lost circulation and drill pipe slicking can happen during this time. Moreover, coiled tubing can also provide weight on bit by itself and can also use an injector to apply snubbing force during horizontal drilling. (Qamar, 2010)

### 2.1.2. The Pros and Cons of coiled tubing drilling

Coiled tubing drilling has several advantages over conventional drilling; some of them are as following:

- Continuous circulation.
- Small footprint
- Faster tripping operation as CT is continuous pipe without connections.
- Safer operations while drilling underbalanced, especially with multiplphase fluids such as foam and nitrified fluids.
- Coiled tubing drilling can monitor and control downhole pressure more efficiently.
- Improved pipe reliability for slim hole operations.
- Real-time downhole measurements of surveys, logging data (GR,CCL), and pressure data at high-data rates using integral wireline inside the coiled tubing.
- Superior directional control due to steering at bottomhole assembly.

On the other hand, coiled tubing drilling also has disadvantages as stated following:

- Hole size is limited by pump requirements.
- Owing to sliding friction, the horizontal-reach potential is decreased.
- Coiled tubing has limited life, especially tubes of large diameter.
- Additional operating cost due to downhole motor

## 2.2 Drilling Fluid

The drilling fluid system plays an important role in drilling operations. It could be said that drilling fluid is the only constituent that stays in contact with the wellbore all over the drilling operation, as it also serves various purposes such as a medium to transport of cuttings and deliver power to the down-hole drilling motor. In the process of drilling, fluid is pumped from the surface into the borehole through coiled tubing and leaving at the nozzle of drill bit. The drilling fluid is, then, circulated through the annulus and flown up to the surface in order to separate the solids and retreat the fluids (Zakaria, Husein, & Harland, 2012).

### 2.2.1 Water-Based drilling fluid

Water-based drilling fluid is environmentally friendly and the managing cost of this drilling fluid is lesser than other drilling fluid as it does not need to apply advance equipments and processes to handle the cuttings. The water-based drilling fluid could be fresh water, brine or any formulated brine. The kind of water is dependent on interval of the well that is being drilled and well conditions. For instance, seawater is utilized in the surface interval as it does not require several additives that cause more expenditure. Howard (2014) claimed that, even though, incompressibility is a typical liquids' property but water-based drilling fluid is highly incompressible, when it is under normal condition. However, water-based drilling fluid could be directly affected by pressure and temperature. It could be pumped into a tiny hole and tremendously shot out in order to break the solids, such as hard-rock formation, as high velocity of water can produce a great amount of pressure. Moreover, flow of water also depends on the viscosity, which is a value indicating resistance to flow. Water viscosity is variable, as temperature and pressure increase, for water, the viscosity decrease.

Darley and Gray (2014) claimed that water is the beginning of the most basic water-based drilling fluids system, after that other chemicals are added into the water in order to formulate a homogeneous mixture of drilling fluids to enhance the ability and properties. The most common additive is bentonite or frequently referred to in the oilfield as gel. Gel likely makes reference to the fact that while the fluid is being pumped, it can be very thin and free-flowing (like chocolate milk), though when pumping is stopped, the static fluid builds a gel structure that resists flow. When an adequate pumping force is applied to break the gel, flow resumes and the fluid returns to its previously free-flowing state. Many other chemicals, such as potassium formate are added to a water based drilling fluids system to achieve various effects, including: viscosity control, shale stability, enhance drilling rate of penetration, cooling and lubricating of equipment.

### 2.2.2 Supercritical Carbon dioxide (SC-CO2) drilling fluid

Gupta (2006) define a supercritical fluid as a substance which is above its critical pressure and critical temperature. The critical point represents the highest temperature and pressure at which the vapor and liquid phase of a substance can co-exist in equilibrium. Above the critical point, the distinction between gas and liquid does not apply and the substance can only be described as a fluid. The physical properties of supercritical CO2, such as, density, viscosity and diffusivity coefficient can be varied between limits of gas and near liquid properties by controlling temperature and pressure. The phase diagram of carbon dioxide is demonstrated in the Figure 3. Carbon dioxide becomes supercritical state above 73.8 bar and 31.1 degree Celsius.

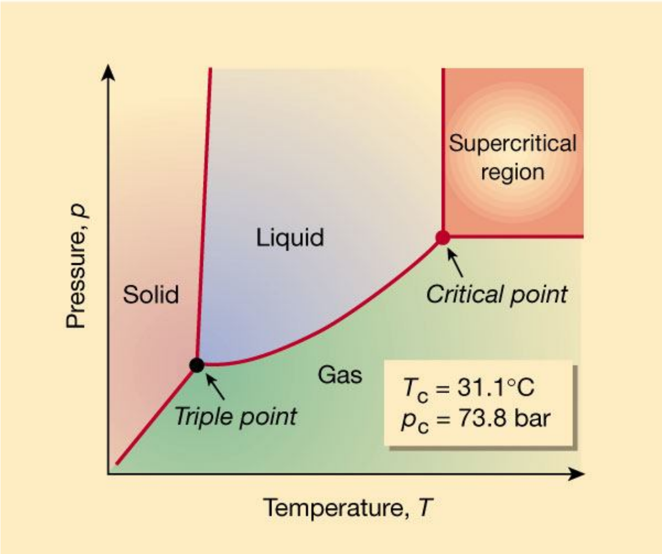



**Figure 3**: Phase diagram of carbon dioxide

(Source: Nature International weekly journal of science, 2000)

Colina et al, (2003) stated that supercritical carbon dioxide (SC-CO2) is a fluid state of carbon dioxide, which its density behaves like liquid and its viscosity is comparable to gas. The supercritical carbon dioxide drilling fluid is anticipated to be supercritical all the way through tubing and become vapor in the return annulus as Colle et al (2000) found that the very low viscosity and high density of supercritical carbon dioxide could be an effective coolant for drill bit, and could efficiently remove the cuttings as it is quite turbulent at the bottom hole. From the study, it also shows that supercritical carbon dioxide is capable of assisting mechanical drilling. This is due to the dramatically higher diffusivity that supercritical carbon dioxide has in porous formation. Besides, when supercritical carbon dioxide is ejected from drill bit, it can make jet erosion extremely more effective than water's. In order to make certain that supercritical carbon dioxide is exist in the wellbore. It is significant to maintain temperature and pressure at its specific condition (above 31.1 degree Celsius and 73.8 bar or 7.38 MPa). At the drill site, supercritical carbon dioxide, which is in down hole, is handled by employing a chock manifold or mud cap drilling equipment as said by kolle (2002). Owing to its adjustable properties and reusable material, supercritical carbon dioxide becomes a very famous and much useful drilling fluid in coiled tubing.

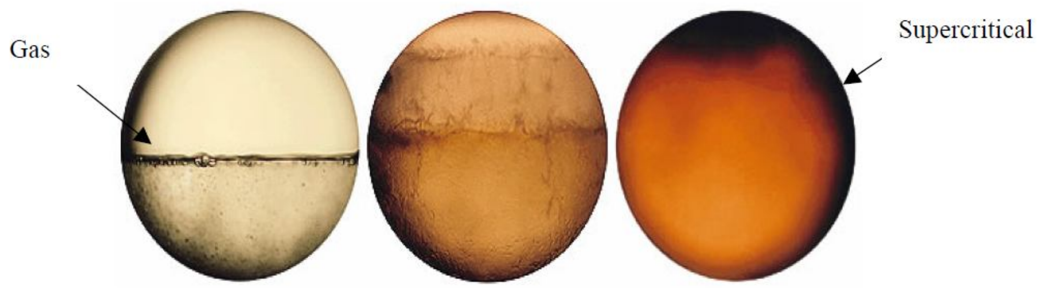



**Figure 4:** Phase change of carbon dioxide to Supercritical state

(Source: A thesis of Gupta,2006)

#### 2.2.2.1. Example case study

Supercritical carbon dioxide has draged the attention from researchers owing to its having unique properties for some drilling operation. The present work addresses the potential advantages and feasibility of using SC-CO2 as a drilling fluid in underbalanced drilling of depleted pressure formations. An effective application which the use of supercritical $CO_2$ as a drilling fluid may be of great value is emphasized by the following case study.

The depleted gas well at the Darbun field in Mississippi cloud be referred for this case study, this place having depletion of the reservoir over time which had brought to an extremely low pressure of 700 psi at a depth of 14,340 feet. By the reason of an extreme pressure unbalance resulted in collapsing of casing. The operator decided to drill a sidetracked well branch, from the existing completed well so that this depleted gas reservoir could be recovered. After the sidetrack operation, conventional drilling through the depleted sixty feet thick reservoir section was unsatisfactory. It is due to excessive overbalance resulting from the large hydrostatic pressure exerted by a tall column of mud, this would have caused lost circulation problems and differential sticking as well as it could also cause severe reduction in productivity due to potential water-blockage and formation damage.

Drilling the depleted zone with nitrogen as drilling fluid was selected in order to overcome these problems and to maintain wellbore pressure below the reservoir pressure while drilling. Coiled tubing drilling (CTD) was one of the best operation that has been chosen as it provided pressure control while tripping and allowed continuous operation without the time consuming tripping operation for making connections as is done for conventional drillpipe.

Operational problems have unexpectedly created while drilling the target reservoir section with pure nitrogen. It is because of low density of nitrogen which did not allow generation of sufficient torque to turn the downhole motor and the drill-bit. However, drilling with foam of nitrogen and water have been selected to overcome this problem and address the motor torque problem. Even though the motor was efficiently powered by the foam, the increased frictional losses and hydrostatic pressure exerted, due to the addition of water, made it difficult to maintain the desired underbalanced conditions in the annulus. $CO_2$ is known to have unique properties in the supercritical phase and this case study offered an opportunity to investigate its utility as a drilling fluid.

#### 2.2.2.2. The use of SC-CO2 as drilling fluid

When using water or mud as drilling fluids in a wide variety of rock types, this obtained penetration with minimal thrust or torque, the efficiency and speed of the erosion of rock using water drilling fluid is very slow, and drilling fluid systems have not reached commercial points. Kolle (2000) claimed that applying supercritical carbon dioxide as drilling fluids provides the improvement of efficiency for drilling fluid jet erosion of hard rock. This is due to the dramatically higher diffusivity that SC-CO2 has in porous materials. The process of drilling fluid jet erosion is greatly enhanced by the diffusion of the fluid into micro cracks and pores in the rock, and because of its much higher diffusivity, SC-CO2 is a far superior jet erosion fluid than water.

At the rage of pressures of 20 to 100 MPa, the SC-CO2 is pumped through coiled tubing. At these pressures, SC-CO2 drilling fluid will erode rock and other hard materials. The SC-CO2 drilling fluid is employed not only to erode rock, but the drilling fluid can also be applied to remove drilled cuttings which forms on the interior of the steel casing with a well, and the buildup of cuttings reduces the production capacity of the well. Such cuttings is currently removed from the casing using an abrasive entrained in a 10 to 20 MPa water drilling fluid. Conventional hard abrasives will cut through coiled tubing and steel casing as well as the cuttings, and cannot be used for this application. However, costs and handling issues are significant to be considered. Ultra high-pressure which is more than 100 MPa, water drilling fluid is effective in removing hard drilled cutings from tubing. However, conventional CT cannot handle the pressures required.  SC-CO2 flows through coiled tubing at a pressure ranging from 10 to 100 MPa. The SC-CO2 supply power to downhole motor, which drives a drill head. Preferably, a minimal amount of drilling fluids are employed, because the flow rate and pressure available through a long length of CT is limited by turbulent pressure losses. Drilling fluids may be offset from the rotation axis to provide rotational torque to downhole motor. Scale deposits are fragmented into debris that can be transported away from the work area in the same manner as drilled cuttings.

### 2.2.3 Air drilling fluid

Generally, air that has been used in the site is from atmosphere. It could be said that air is the lightest form of drilling fluid. At the time that circulating with air, the specific gravity closing to zero is achieved, as claimed by air drilling association (2014). The purpose of employing air drilling fluid is to decrease the hydrostatic pressure in the wellbore. It becomes a very suitable drilling fluid that provides circulation system in the dry formation. Weatherford (2014) claimed that a great volume of air is compressed into the coiled tubing instead of conventional drilling fluid. The main benefit is to increase the rate of penetration, this increased penetration rate is owing to the low density of air which reduces hydrostatic pressure and assist fracturing at all times. Moreover, it can definitely diminish the damage of formations and prolong drill bit lifetime. It is possible to achieve excellent economy and optimum outcome from air drilling by considering the related factors, which is to be applied under the hard formation that contains very small amount of liquids. Nevertheless, when there is only few liquid in that formation, the liquid could be absorbed into the return annulus flow together with the cuttings as dust form.

On the other hand, huge water-bearing formation is the biggest enemy of air drilling. The rate of formation water influx which can be handled is not defined. When water is encountered, mist (foam), aerated or slug drilling can be used. Mist drilling can handle up to about 200 barrels per hour water influx. When surface pressures exceed the limit of the air compressor equipment, aerated or slug drilling can accommodate larger volumes of water.

Adewumi and Tian (1990) claimed that that there are two fundamental differences between well bore hydraulics associated with air drilling and conventional drilling. The first is air having high compressibility compared with water based drilling fluids, and the second is the huge difference of density between air and drilled cuttings. These differences preclude the wide experience already acquired for conventional drilling from being directly applied to air drilling. Cleaning the wellbore becomes the major function of the circulating drilling fluid. Additionally, a good penetration rate can be reached. In order to effectively conduct this task, air, which is employed as the circulating fluid in air drilling, must be circulated in adequate quantity. On the other hand, applying excessive air will result in unnecessary additional pressure loss in the wellbore. Thereby, compression power will be wasted.

In addition, maximum penetration rate is achieved at minimum bottomhole pressure, which will correspond to the optimum air volumetric flow rate. Furthermore, higher air velocity will impart an unnecessarily high velocity on the particles which could cause faster equipment erosion and hence greater maintenance costs. It is indisputable that the key to achieving the optimal drilling rate is to use an optimal air volumetric flow rate.

Conversion of a conventional rotary rig to an air drilling operation is a simple matter. Most of the liquid and solids handling equipment, normally used for water drilling fluids can be removed for an air drilling operation. When air drilling is being carried on in populated areas, dust control is necessarily employed. Although there is no method of complete control, the most effective control method is the use of a water spray device on the end of the flow line. If sufficient water is properly applied, almost all of the dust is wet down and carried off as mud.

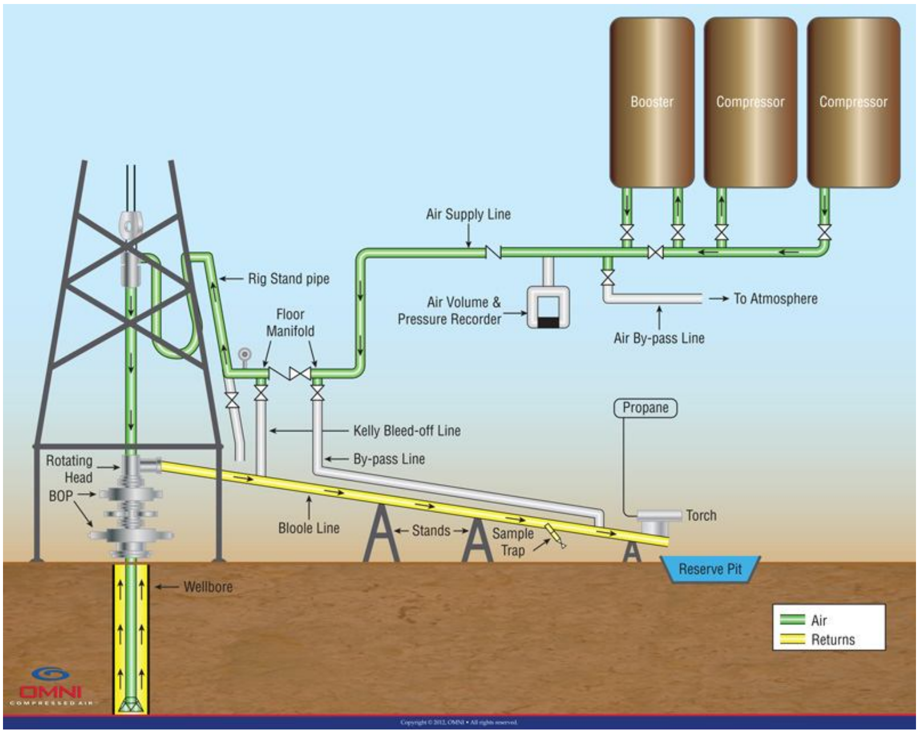



**Figure 5**: A schematic of air drilling components

(Source: Omni compressed air website, 2014)

#### 2.2.3.1. The Basic Design Variables

Air volumetric requirement and compression power requirement are the two important variables which are necessary to consider in designing air drilling. In terminology of hydrodynamic, these could be translated to air velocity and pressure loss, respectively. In addition, there are other important hydrodynamic variables which affect the design variables, but the previous researchers have rarely mentioned about them, it may be due to the difficulties involved in predicting them. Their effects, even though perceived to be significant, could not be quantified. These variables include particulate velocity and concentration distribution. Beyond the discussion stage, little or no effort was given to the understanding of which independent variables affect these basic design parameters. These include:

I. The geometrical configuration and size of the well bore/ drillstring annulus.

2. The geometrical and physical properties of drilled cuttings including size and size distribution, density and shape.

3. Penetration rate as it determines the solid generation rate and hence solid loading.

4. Particle attrition as it traverses the vertical height of the wellbore.

#### 2.2.3.2. Downhole Fires and Explosions due to air drilling

It is a well-known fact that three conditions must be met in order to start a fire. There must be fuel, oxygen, and ignition or combustion. When gas is encountered during air drilling, the first two conditions are met-fuel in the form of natural gas and oxygen in the form of compressed air. The main concern, when gas is encountered while drilling with air, is to prevent ignition. In order to do this, the causes of ignition while drilling with air must be known. Three things will cause ignition during an air drilling operation. These are as follows: (1) a mud ring (seal between bore hole and drill string), (2) downhole sparks, and (3) a small hole in the drill string.

Even though downhole equipment is damaged or destroyed, there is no damage to surface equipment. Most of the time all that is known at the surface is that the drill string is stuck, and a surface recording temperature survey may have to be run through drill string to determine if a fire occurred. Because of damages incurred to downhole equipment after a burn-off, fishing operations are difficult and sidetrack operations are necessary in order to drill deeper. This type operation is expensive and time consuming. Therefore, the prevention of a downhole fire or explosion is of primary importance. (Cooper et al, 1977)

**2.3 Water based drilling fluid VS Supercritical carbon dioxide drilling fluid**

In normal case for water drilling fluid system in coiled tubing drilling, a positive displacement motor is employed in the system. Additionally, the water drilling fluid system could be considered as: Water Tank - Pump - Coiled Tubing – Down-hole Motor - Drill Bit - Annulus – Well Head - Mud Separator - Water Tank.

The beginning of using CO2 as drilling fluid system in coiled tubing operation is to compress CO2 in compressor under a critical pressure and temperature to transform CO2 gas to super critical state which is above 7.4 MPa and more than 32 degree Celsius. In the system of CO2 loop, any CO2 loss is replenished either before or after the compressor. After that it will flow down through the coiled tubing to the down-hole turbine. Once the SC-CO2 enters the turbine, it would rotate the turbine while expanding and reducing temperature as it passes over the blades with some of its pressure and thermal energy transforming to mechanical rotation energy in the turbine; the cooling and expanding CO2 then passes through the holes of the drill bit further expanding and cooling down; the CO2 flow then assists drill bit breaking the rock, removes drilled cuttings and cools the drill bit; the CO2 drilling fluid also absorbs thermal energy from the drilled cuttings and further expands as it circulates up through the annulus to bring drilled cuttings to the surface as it flows past and out of the wellhead. The CO2 fluid is then going to the separator to f separate fluid from drilled cuttings and further filtered in a fines filter before it reaches the inlet of the compressor for being recompressed. The drilled cuttings at the separator are dry mineral samples for analysis and it is worthwhile noting here that separation of cuttings from a gas using conventional filtration methods is far easier than cuttings from water.

For SC-$CO_2$ drilling fluid system, Liu, Evans and Barifcani (2013) proposed that most of energy are efficiently reserved for drilling and cutting carrying with the following advantages:

- The $CO_2$ could be reused because it is operated in a closed loop system.
- The energy of $CO_2$ from pressure and thermal energy being converted into mechanical shaft rotation energy of the downhole turbine.
- The heat from cutting of formation is absorbed by the $CO_2$ which causes expansion and increased flow speed for transporting drilled cuttings.
- The high density compressed supercritical carbon dioxide fluid is suitable for efficiently driving the high speed turbine and is more effective in terms of energy transfer than water.

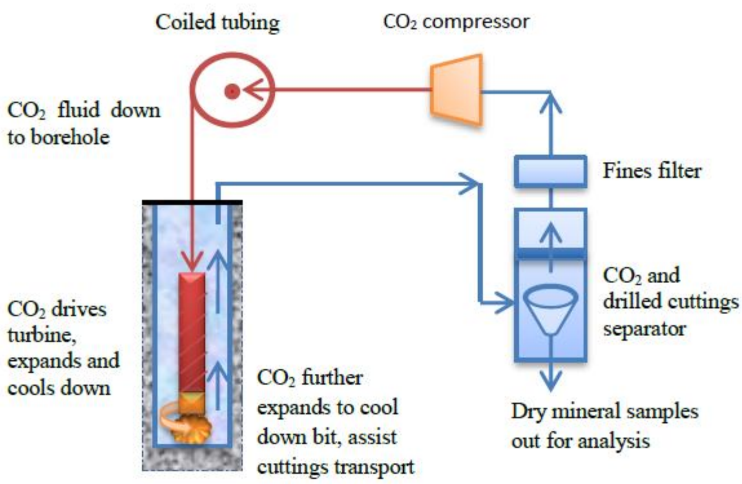



**Figure 6:** The $CO_2$ drilling fluid system

(Source: Liu, Evans and Barifcani, 2013 )

The usage of combining compressor, pump and cooler is one of the method to control the inlet pressure, temperature and flow rate of the drilling fluid. The outlet pressure of the annulus can be monitored by a valve before or after the separator. The question of most interest to us is that given a set of defined inlet pressure, temperature and flow rate, how capable the $CO_2$ can be in energy delivery as compared with water.

## 2.4 Water based drilling fluid VS air drilling fluids

**Table 1:** Comparison of water-based and air drilling fluid

| Criteria | Water based drilling fluid | Air drilling fluid |
|---|---|---|
| **Rate of penetration** | Rate of penetration lower than when using underbalanced drilling; air drilling. | Increases ROP due to improved bit performance and reduces the regrinding of cuttings. ROP have been as much as three times the penetration rates experienced in the same formations drilled Conventionally. (Hole, 2006) |
| **Formation damage** | Causing formation damage when mud cake forms in the production zone and drilling fluids and cuttings go into the formation blocking permeability. | Reduces the probability of Formation damage because the borehole pressure is less than the formation pressure. |
| **Annular velocity** | Lower annular velocity | Need more annular velocity |
| **Additional equipment** | Mud tank, hopper, mud pump. | Needs additional equipment than for conventional drilling: air compressors and booster to compress air, mist pump, separator etc. |
| **Operation** | Check valve is put at the bottom of the drill string; operation as conventional drilling. | Needs a skilled person to operate air drilling. Because of the high pressure of air drilling and the need to maintain the pressure. Check valve is needed to put in a drill string. |
| **Monitoring of pressure** | Water based drilling fluid has higher density than air drilling fluid and hydrostatic pressure depends on the density of the drilling fluid. | Air drilling fluid has lighter density thus leads to lower annular pressure than formation pressure. It is flexible in controlling formation pressure as pressure in annulus can be maintained by reducing the pressure at the throttle valve at the flow line. |
| **Corrosion** | Less drill pipe corrosion. | Causes somewhat higher drill pipe corrosion. |

## 2.5 The conservation of energy

The fact of this law could be simply stated that energy neither be created nor destroyed, it can only be converted from one state to another. Changing of form is the only thing that can occur to energy in a closed system. The following Bernoulli equation could be considered to be a statement of the conservative energy for flowing fluids (Nave, 2014).

**Energy per unit volume before = Energy per unit volume after**

$$\mathbf{P_1 + \frac{1}{2}\rho V_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g h_2}$$

In the equation, it is known that **P** is the pressure energy, $\frac{1}{2}\rho V_1^2$ is the kinetic energy per unit volume and $\rho g h_1$ is the potential energy per unit volume.

Since, water is considered as an incompressible fluid as Nave (2014) claimed that water contains 2.2 GPa of bulk modulus, which is regarded as very large value. The mass flow rate of water, 1 Kg/s, can be directly converted to1 Liter/s of volume flow rate. Conversely, SC-CO2 and air are considered as compressible fluids. Therefore, the volume flow rate $Q_v$ is a function of the mass flow rate $Q_m$. The energy of fluids can be considered at one end of either inlet or outlet. The following equation shows the energy delivered by a unit mass flow rate of water.

$$\mathbf{E = E_p + E_k + E_z = pQ_v + \frac{1}{2}Q_m V^2 + Q_m g z}$$

The difference $\Delta E$ between inlet and out let is the energy delivered by fluid.

$$\mathbf{\Delta E = E_{in} - E_{out}}$$

For SC-CO2 and air which are compressible fluids, there is another energy stored in the compressible fluids. That is the internal energy, denoted as U. When considering cross section of coiled tubing or annulus of the compressible fluid.

The equation below is employed to compute the energy delivery of compressible fluids, SC-CO2 and air.

$$\mathbf{E = U + E_p + E_k + E_z = uQ_m + pQ_v + \frac{1}{2}Q_vV^2 + Q_mgz}$$

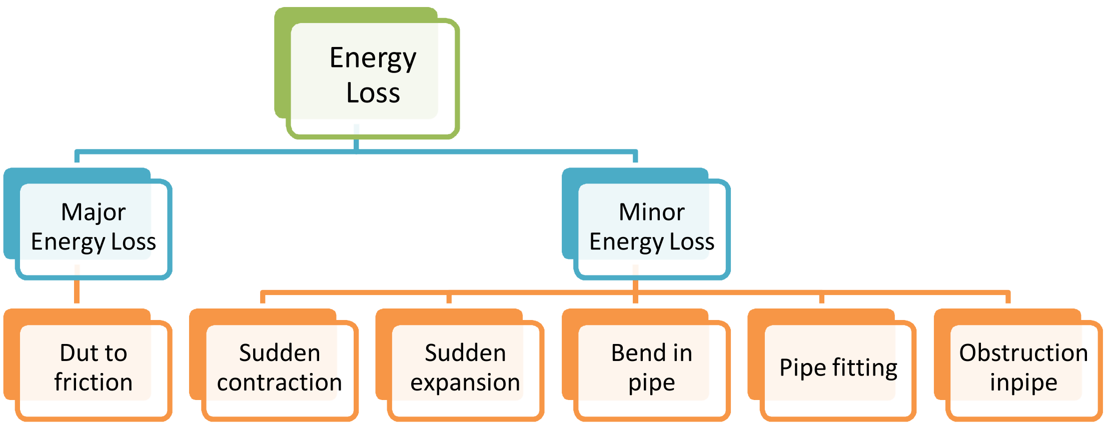
As the equation stated above, the enthalpy, H, in thermodynamics can be derived by the combination of the internal energy and the pressure energy. Therefore, the calculation of the energy delivery of compressible fluid can be simplified as below.

Since, $\mathbf{H = U + E_p}$

$$\mathbf{E = H + E_k + E_z = H + \frac{1}{2}Q_mV^2 + Q_mgz}$$

**2.6 Friction Energy Loss in coiled Tubing**

When fluid is flowing through a pipe, the fluid experiences some resistance due to which some of the energy of the fluid is lost.



The friction energy loss, which happens in both coiled tubing and annulus, significantly decreases the energy delivered from drilling fluids. The amount of friction energy loss is getting bigger while the drilling operation goes deeper. However, the friction energy loss can be derived in terms of friction pressure loss in pipe as shown in the equation below (Azar and Samuel, 2014).

$$\Delta \mathbf{P} = \boldsymbol{f} \frac{\mathbf{2\rho L V^2}}{\mathbf{D}}$$

The simplified Colebrook equation below as claimed by Tomita (1959) shows that the function of fanning friction factor $\boldsymbol{f}$ is in terms of the wall roughness $\boldsymbol{\varepsilon}$ and the fluid flow Reynolds number $\boldsymbol{Re}$.

$$\frac{\mathbf{1}}{\sqrt{\boldsymbol{f}}} = \mathbf{2.28 - 4\log}\left(\frac{\boldsymbol{\varepsilon}}{\boldsymbol{D}} + \frac{\mathbf{21.25}}{\boldsymbol{Re}^{\mathbf{0.9}}}\right)$$

The following Reynolds number is a function of the fluid density $\boldsymbol{\rho}$, dynamic viscosity $\boldsymbol{\mu}$ and flow speed **V**.

$$\mathbf{Re} = \frac{\mathbf{\rho V D}}{\mathbf{\mu}}$$

# CHAPTER 3

# METHODOLOGY

## 3.1 Phases of Methodology

Methodology is divided into six main phases which are problem statement, literature review, consultation, calculation and comparison and conclusion. The phases are briefly described below:

### 3.1.1 Problem Statement

To express a clear description of issue that will be solved to determine the objectives and deploy the feasibly potential solution.

### 3.1.2 Literature Review

To provide background information on research and identify what have been discovered before. It contains all relevant theories and facts which are involving with the objective of the project.

### 3.1.3 Consultation

To request for assistance from supervisor and experts in the associated field to obtain advices and direct experiences. However, meeting needs to be held to discuss about the direction and requirements of the project.

### 3.1.4 Calculation

To utilize the relevant equation and graph the result so that the gathered data will be easily displayed to further compared and discussed.

### 3.1.5 Comparison

To analze the data that obtained from calculation, make comparison and discuss the possibility and reliability of the best result.

### 3.1.6 Conclusion

To summarize the most significant findings in relation to the objective of the project and give the recommendation for future work.

### 3.2 Calculation

The calculations are based on the same mass flow rate and at specified pressure differentials. The differentials of pressure is defined between the inlet pressure of coiled tubing and outlet pressure of the annulus. The drilling parameters are defined below.

- Borehole diameter: 50 mm
- Borehole depth: 2 km
- Diameter of coiled tubing: 38.1 mm (1.5 inch)
- Wall thickness of coiled tubing 4.45mm (0.175 inch)
- The internal wall roughness of coiled tubing: 0.00254 mm (0.001 inch)
- Mass flow rate for drilling fluid: 1 kg/s

#### 3.2.1 Calculation of total energy delivery

a) For incompressible fluid, hydraulic energy would be calculated by using the following equation.

$$\mathbf{E} = \mathbf{E_p} + \mathbf{E_k} + \mathbf{E_z}$$

$$= \mathbf{pQ_v} + \frac{1}{2}\mathbf{Q_m V^2} + \mathbf{Q_m g z}$$

The difference $\Delta E$ between inlet and outlet is the energy delivered by fluid. The outlet pressure of water drilling fluid is set to be 0.5 MPa

$$\mathbf{\Delta E} = \mathbf{E_{in}} - \mathbf{E_{out}}$$

b) For compressible fluids; $CO_2$ and air, the energy would be calculated by the following equation.

$$\mathbf{E} = \mathbf{H} + \mathbf{E_k} + \mathbf{E_z}$$

$$= \mathbf{H} + \frac{1}{2}\mathbf{Q_m V^2} + \mathbf{Q_m g z}$$

To obtain the property of drilling fluids in different pressure and temperature, the peace software by Berndt Wischnewski is available to conduct the computation.

**Input**

Calculation of thermodynamic state variables of carbon dioxide

lower limit for calculation: -55 C, 1 bar    upper limit: 900 C, 1000 bar

Pressure: 30 MPa

Temperature: 100 Celsius

Calculate

**Output**

| Property | Value | Unit |
|---|---|---|
| Medium : | **carbon dioxide** | |
| state of aggregation : | **overcritical fluid** | |
| Pressure : | 300 | [ bar ] |
| Temperature : | 100 | [ Celsius ] |
| Density : | 662.3 | [ kg / m$^3$ ] |
| Specific Enthalpy : | 391.7 | [ kJ / kg ] |
| Specific Entropy : | 1.496 | [ kJ / kg K ] |
| Specific isobar heat capacity : cp | 2.05 | [ kJ / kg K ] |
| Specific isochor heat capacity : cv | 0.9085 | [ kJ / kg K ] |
| Isobar coefficient of thermal expansion : | 6.14 | [ $10^{-3}$ (1 / K) ] |
| Heat conductance | 73.58 | [ $10^{-3}$ (W / m * K) ] |
| Dynamic viscosity : | 54.17 | [ $10^{-6}$ (Pa s) ] |

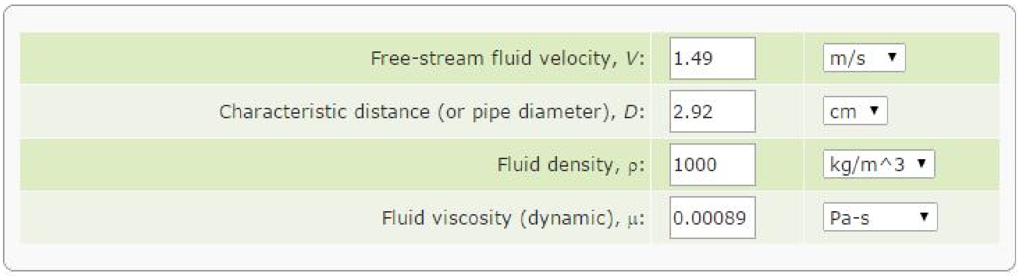
### 3.2.2 Calculation of friction energy loss in coiled tubing

a) Calculate the Reynolds number of each drilling fluids by the following formula.

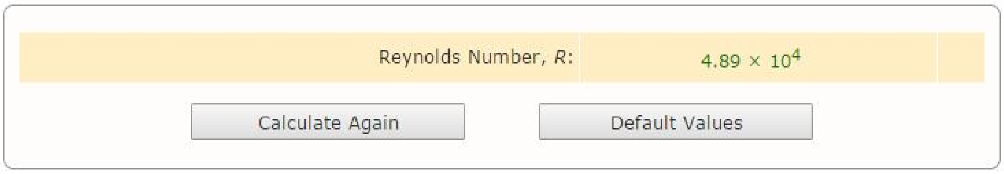
$$\mathbf{Re} = \frac{\boldsymbol{\rho}\mathbf{VD}}{\boldsymbol{\mu}}$$

The calculation of the Reynolds number could be done by assistance of eFunda, Inc. online calculator as shown below.

**<u>Input</u>**




**<u>Output</u>**

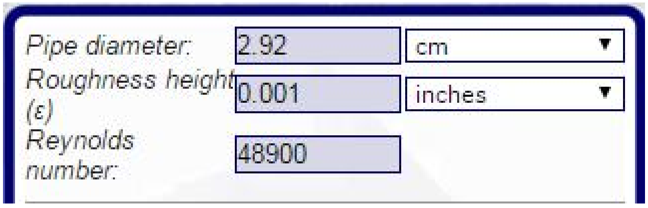



b) Substitute value of the Reynolds number into fanning friction formula as following.

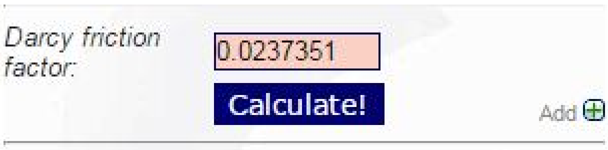
$$\frac{\mathbf{1}}{\sqrt{\boldsymbol{f}}} = \mathbf{2.28} - \mathbf{4}\,\mathbf{log}\left(\frac{\boldsymbol{\varepsilon}}{\boldsymbol{D}} + \frac{\mathbf{21.25}}{\boldsymbol{Re}^{\mathbf{0.9}}}\right)$$

By using online calculator which is suggested by Andy and Steve in calctool website to compute friction could be conducted by placing each required parameters as shown below.

**Input**




**Output**

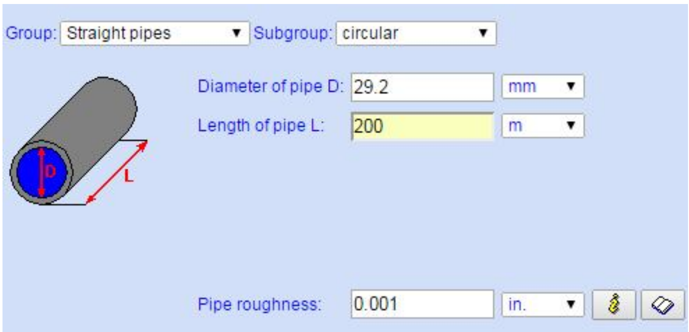



C) Compute the friction pressure drop in coiled tubing.

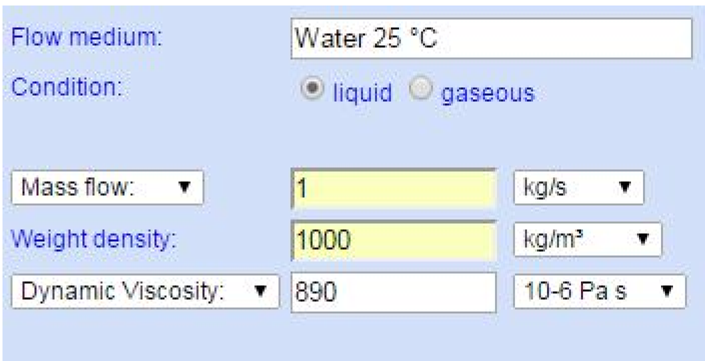
$$\Delta \mathbf{P} = \boldsymbol{f}\,\frac{\mathbf{2\rho L V^2}}{\mathbf{D}}$$

The online pressure-drop calculator is available to compute as following

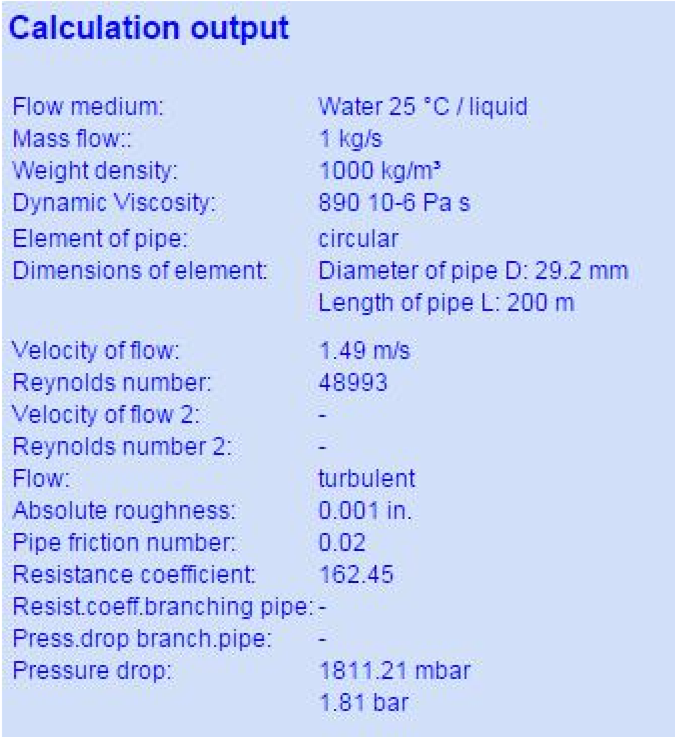
**Input**: Element of pipe




**Input**: Flow medium parameters



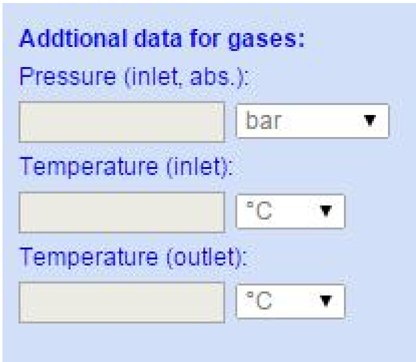
**Output**



**Calculation output**

| | |
|---|---|
| Flow medium: | Water 25 °C / liquid |
| Mass flow:: | 1 kg/s |
| Weight density: | 1000 kg/m³ |
| Dynamic Viscosity: | 890 10-6 Pa s |
| Element of pipe: | circular |
| Dimensions of element: | Diameter of pipe D: 29.2 mm<br>Length of pipe L: 200 m |
| Velocity of flow: | 1.49 m/s |
| Reynolds number: | 48993 |
| Velocity of flow 2: | - |
| Reynolds number 2: | - |
| Flow: | turbulent |
| Absolute roughness: | 0.001 in. |
| Pipe friction number: | 0.02 |
| Resistance coefficient: | 162.45 |
| Resist.coeff.branching pipe: | - |
| Press.drop branch.pipe: | - |
| Pressure drop: | 1811.21 mbar<br>1.81 bar |

For drilling fluids that their properties vary with pressure and temperature, it is necessary to put additional data as provided in the software below.



## 3.3 Research Tools

**Table 2:** Research Tools

| Sequence | Material | Function |
|---|---|---|
| **1** | Internet | To search for online database and study through internet |
| **2** | Library books | To find previous researches and other references |
| **3** | Personal computer | to access internet and calculate complex equation |
| **4** | Microsoft office | To create document and facilitate to graph the result |
| **5** | Scientific Calculator | To solve advance problem in mathematics, physics and engineering |

## 3.4 Gantt Chart

The specific time and dates need to be elaborately scheduled in order to ensure that the project will be run smoothly within the boundary of time. As time management is significant in completing this project. Thereby, the Gantt chart and key milestone are provided below in order to introduce the details of work process and execution of the whole period.

**Table 3:** Gantt chart for FYP1

| **Description of Planning** | **Weeks** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| Selection of Project Topic | ■ | ■ | ■ | | | | | | | | | | | |
| Preliminary Research Work | | | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | |
| Submission of Extended Proposal | | | | | | | | ■ | | | | | | |
| Proposal Defense | | | | | | | | | ■ | | | | | |
| Project work continues | | | | | | | | | ■ | ■ | ■ | ■ | ■ | |
| Submission of Interim Draft Report | | | | | | | | | | | | | ■ | |
| Submission of Interim Report | | | | | | | | | | | | | | ■ |

**Table 4:** Gantt chart for FYP2

| Description of Planning | Weeks | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Proceed on the research works | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | |
| Submission of Progress report | | | | | | | ■ | ■ | | | | | | | | |
| Pre-SEDEX | | | | | | | | | ■ | | | | | | | |
| Project work continues | | | | | | | | | ■ | ■ | ■ | ■ | | | | |
| Submission of final draft and technical report | | | | | | | | | | | | ■ | ■ | | | |
| Viva | | | | | | | | | | | | | | ■ | | |
| Hardbound report | | | | | | | | | | | | | | | | ■ |

■ = Process

# CHAPTER 4

# RESULT AND DISCUSSION

## 4.1 RESULTS

### 4.1.1 Drilling fluid system

In this discussion, water is taken as the benchmark in order to evaluate the power delivery of CO2 and air drilling fluid. Water has $2.2x10^9$ Pa bulk modulus and it is incompressible fluid with 1kg/s mass flow rate. The CO2 and air are compressible which its density depends on its pressure and temperature. The system of compressible drilling fluid begins at the compressor, CO2 gas is compressed to a pressure and temperature in the rage of a supercritical fluid which pressure is above 7.4Mpa, at 31.1degree Celsius. Atmospheric air is compressed and then cooled to approximately 26 degree Celsius. Then, it would flow through the coiled tubing to the down-hole turbine; when it enters the turbine, it rotates the turbine while expanding and reducing temperature as it passes through the blades. Additionally, some of its pressure and thermal energy transforming to mechanical rotation energy in the turbine; the cooling and expanding fluids then passes through the nozzles of the drill bit further expanding and cooling down; the drilling fluids flow then diffuse into the formation and aids drill bit breaking the rock, transports drilled cuttings and cools the drill bit; the compressible drilling fluid also absorbs thermal energy from the drilled cuttings and further expands as it circulates up through the annulus to bring drilled cuttings to the surface. The CO2 fluid is then separated from drilled powdered cuttings in a separator and further reuse by transported to the compressor for being recompressed. However, air drilling that is mixed with powdered cuttings come out from the annulus like dust. The air drilling fluid will leave the cuttings at the bottom of container then air will separate into the atmosphere. The drilled cuttings separation process from both CO2 and air drilling fluids is much easier than filtrating drilled cutting from water.

### 4.1.2 Total energy delivery

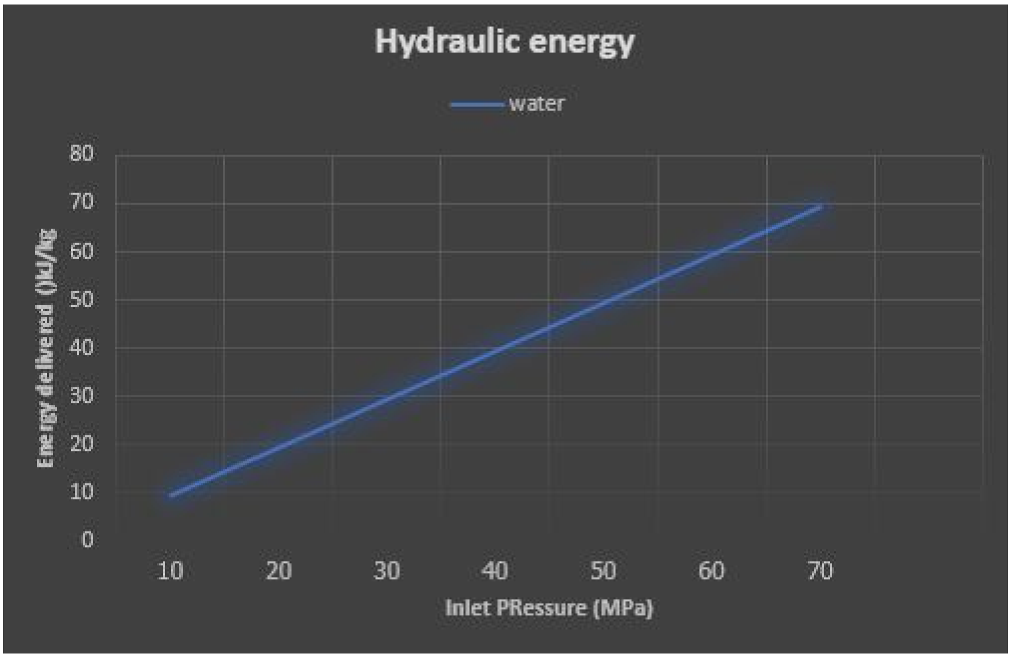



**Figure 7: Hydraulic energy of water drilling fluid**

Relationship between energy delivered by water against its inlet pressure is shown in the figure with straight line above. Assuming that water to have fully developed turbulent flow and capable of delivering hydraulic power. The inlet and outlet water is being set at the same level in the calculation which results in the potential energy being cancelled out. As there is a slight difference in velocity, only a small value of kinetic energy generated is being detected. An increase of 1 kJ/kg in pressure energy of the downstream drilling system is produced when there is an increase in 1 MPa of inlet pressure for flow rate of a mass of 1 kg. The power of water delivery relies almost entirely on the differential pressure between outlet and inlet pressure. Due to water being incompressible fluid, hence the internal energy is not stored. The work done by the pump and by the pressure difference is driven down to the subsurface.

Fluids such as CO2 and air, on the other hand, are compressible fluids. The energy delivery mechanism in a function of temperature, thermodynamic properties and pressure of the fluid requires the involvement of the internal energy.

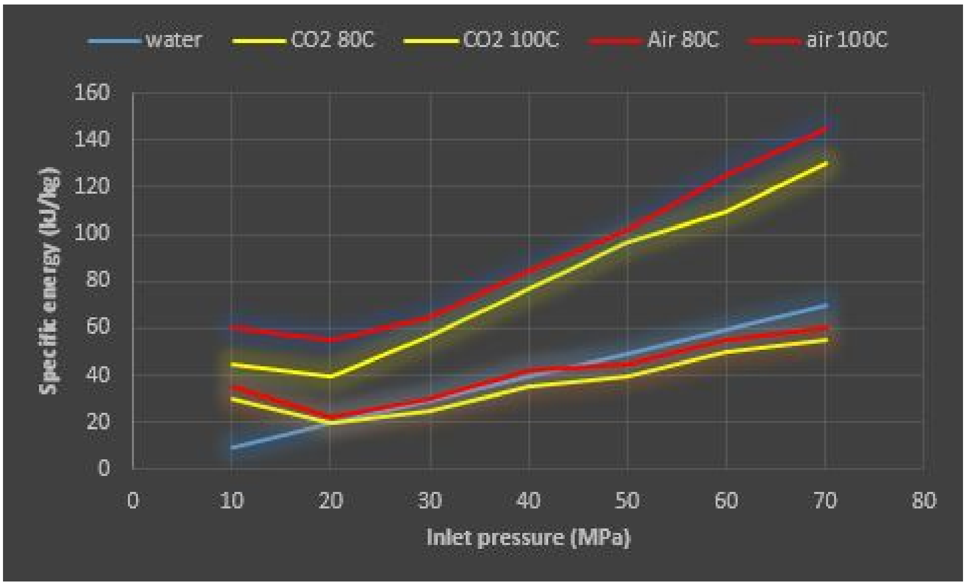



**Figure 8: Energy delivery comparison of water, CO2 and Air**

As shown in Fig. 6, within the common operation pressure range of 20 to 40MPa and at 100 degree Celsius, CO2 drilling fluid could provide approximately two times more energy than that of water whereas air can provide about 2.5 times more energy than water. While at 80, air and CO2 drilling fluid provide about the same energy as water. Hence, temperature being a measure of thermal energy contained in compressible fluids is important for air and CO2 fluid in providing drilling power. Air and CO2 drilling fluid could offer much more energy than water, and air could operate at lower pressure than CO2 in delivering the same amount of energy. Note that author has reserved a significant amount of energy in the CO2 and air by setting the outlet pressure to be constant value.

### 4.1.3 Friction energy loss inside the coiled tubing

The friction energy loss inside coiled tubing could reduce the energy for cuttings transportation. In addition, the deeper the hole is drilled, the bigger amount of friction energy loss will occur. The friction energy loss for various temperature in various depth are plotted in the graphs.

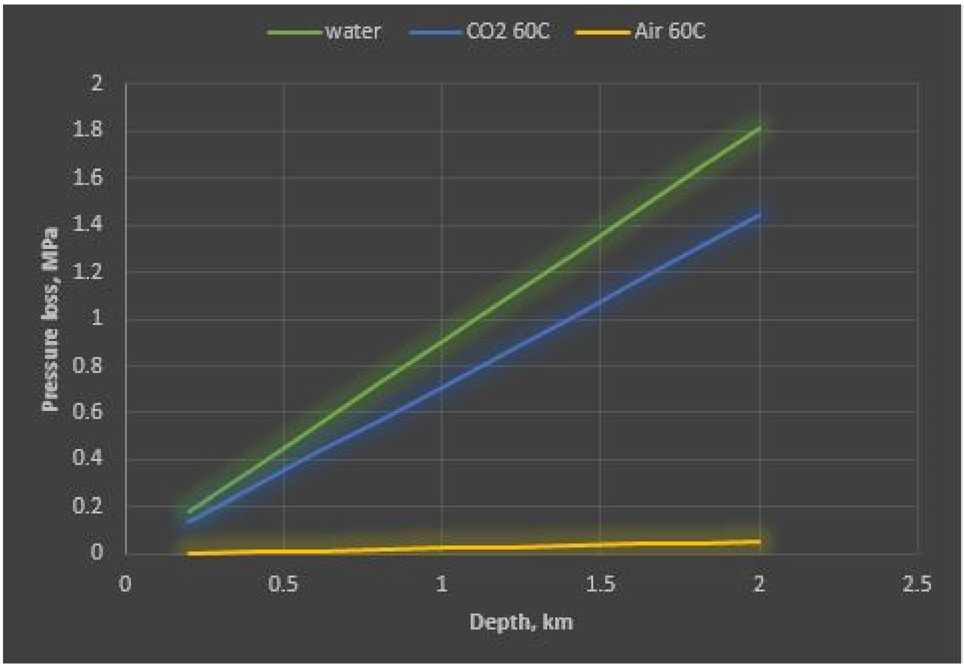



**Figure 9: Friction energy loss at 60 degree Celsius**

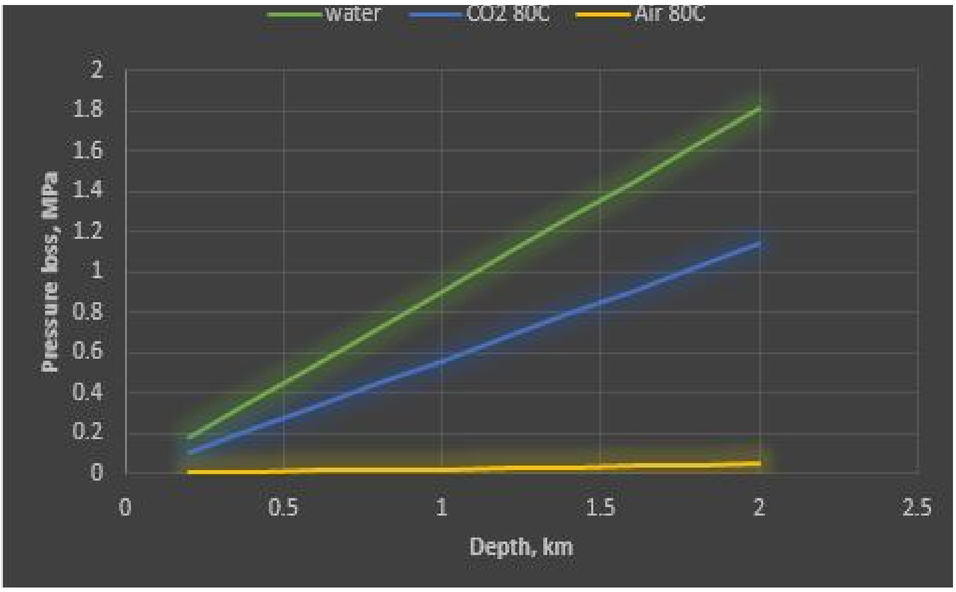



**Figure 10: Friction energy loss at 80 degree Celsius**

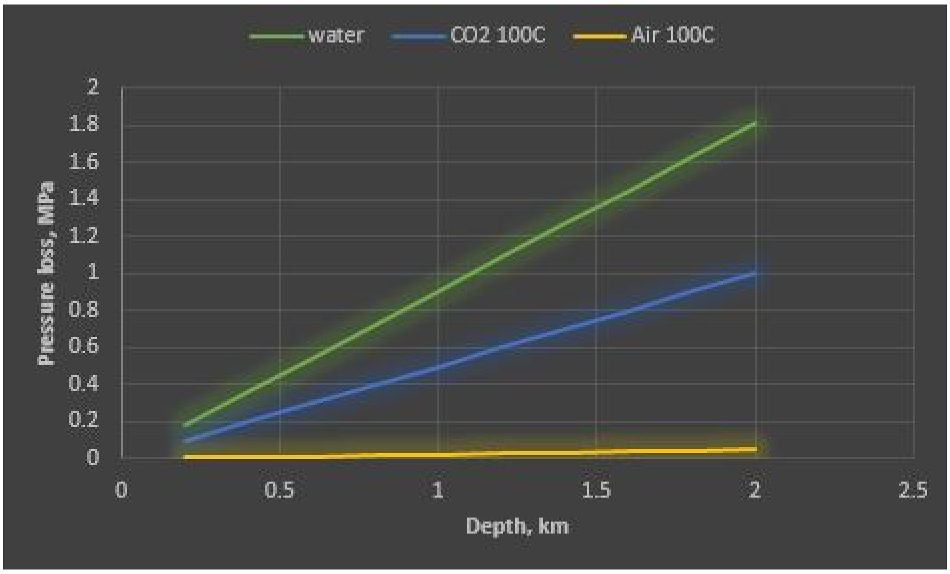



**Figure 11: Friction energy loss at 100 degree Celsius**

Friction pressure loss of air, water and CO2 is shown in **figure [7], [8] and [9].** Friction pressure loss of 1.8 MPa is exhibited by water when the coiled tubing length is of 2 km. At 100°C, 80°C and 60°C respectively, the friction pressure losses of CO2 is of 1.44 Mpa, 1.11 Mpa and 1.00 Mpa. Significantly lower pressure losses of 0.055Mpa, 0.052Mpa and 0.050Mpa are exhibited by air compared to that of CO2 and water at temperature of 100°C, 80°C and 60°C respectively.

Water exhibits friction factor of 2.3E-2. Lower friction factors of 1.94E-2, 1.915E-2 and 1.914E-2 are exhibited by CO2 fluid at temperature of at 100°C, 80°Cand 60°C respectively due to CO2 having low viscosity. 1.968E-2, 1.963E-2 and 1.960E-2 are the friction factors exhibited by air at temperature of 100°C, 80°C and 60°C respectively. However due to the flow speed of air and CO2 being higher, there is an increase in friction pressure loss.

As a result of an increase in pressure and a decrease in temperature, leads to an increase in CO2 density which decreases the flow rate, which in turn results in a decrease in friction pressure loss.

Inside the coiled tubing, the viscosity of onsite drilling fluid is larger due to the reusing of circulating drilling fluid system which is contaminated by additives and drilled cuttings in practice which requires measurements under real field drilling conditions.

In the annulus, the friction pressure is significantly greater than that of the one in the coiled tubing as there is a significant rise in viscosity of the fluid due to the powder like hard rock cuttings. For water drilling fluid, this occurrence is found to be true. Ideally in the annulus, compressible drilling fluid viscosity should be lower than that of the incompressibility of water as low viscosity is exhibited by compressible fluids. However, in the future, the accurate condition of air drilling fluid pressure and viscosity need to be further studied and experimented in field drilling tests and laboratory experiments.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

Energy delivery capabilities of air, water and CO2 drilling fluids for coiled tubing drilling are theoretically calculated and compared in this project. It is found that water being an incompressible drilling fluid, could only deliver hydraulic energy to the drilling system. Linearity is exhibited by the relationship between the outlet of the annulus at the surface and the inlet of the coiled tubing. The difference in kinetic energy between outlet and inlet is very small and negligible. Linear relationship is shown by the relationship between friction pressure energy loss of water with the coiled tubing length.

In comparison, it was discovered that air and CO2 are both being far more complex drilling fluid than water. Their compressibility allows for manipulation in the energy delivery mechanism. Storing and releasing of internal energy is done by absorbing heat, compression and expansion, which are achievable by air and CO2 due to their temperature, pressure, hydraulic power and thermodynamic properties. Its friction pressure loss and the total energy delivery to the drilling system are both nonlinear functions.

However, water and CO2 of the same mass flow rate and differential pressure are both surpassed by air drilling fluid in term of energy offered to the drilling system. More energy that air can store and supply when there are higher temperature and pressure. Air also has smaller friction energy loss than CO2 and water due to its lower viscosity. Moreover, energy utilization efficiency can be increased by air through absorption of heat energy produced in the drilling process and reusing it through further expansion in the annulus for increased flow rate in bringing the cuttings to the surface. Lifespan of coiled tubing can be extended through the controlled power delivery capability of air, which allows for low pressure in drilling operation. It is concluded that air is theoretically a much more powerful, more efficient energy delivery and utilization drilling fluid than water and SC-CO2.

## 5.2 Recommendation

Due to time limitations and financial constraints, the research cannot be expanded to include more different parameters to be investigated. However, it could be said that this project is a new area of research in UTP. In order to proceed with the further research, as long as the conditions are maintained. The types of drilling fluid can be alternated and the other software can be employed.

The recommendations for future work or improvement would be:

- Conducting coiled tubing fatigue analysis while circulating drilling fluids in various rates.
- Performing power output calculation from down-hole turbine to investigate the rate of penetration due to different drilling fluids.
- Comparing the results with different software to ensure highest accuracy of the calculation.
- Expand the type of $CO_2$ and air drilling fluids to other gases like pure nitrogen and then make a comparison studies among them.

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