COMPUTATIONAL FLUID DYNAMIC MODELLING OF CO2 LEAKAGE IN ABANDON WELL

by

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CERTIFICATION OF ORIGINALITY

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

(Abdul Haziq bin Abdul Rahman)

ABSTRACT

Greenhouse gas emission (GHG) has become serious threat to the environment nowadays. In order to reduce the gas emission to the atmosphere, carbon dioxide is injected to the underground formation for carbon sequestration process. The stored CO_2 might have a potential to leakage from the storage through the wellbore, due to poor cementation and high concentration of CO_2. The permeability and integrity of the cement plug playing the key factor in preventing the CO_2 leakage. The purpose of this research is to discover the potential of CO_2 leakage from abandon well, by analyzing the reaction of CO_2 and effect on Portland cement permeability. The process will be simulated using Computational Fluid Dynamics, a software tool that has been used to analyses the fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena by solving the mathematical equations which govern these processes using a numerical process.

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CHAPTER 1: INTRODUCTION

1.1 Project Background

Carbon dioxide is constantly being exchanged among the atmosphere, ocean, and land surface as it is both produced and absorbed by many microorganisms, plants, and animals. However, emissions and removal of CO_2 by these natural processes tend to balance. Since the Industrial Revolution began around 1750, human activities have contributed substantially to climate change by adding CO_2 and other heat-trapping gases to the atmosphere.

Carbon dioxide is the primary greenhouse gas (GHG) emitted in atmosphere along with methane nitrous oxide and other fluorinate gases. GHG is the atmospheric gases that contribute to the greenhouse effect by absorbing infrared radiation produced by solar warming of the Earth surface and lead to climate change such as global warming. Carbon dioxide is the largest portion in GHG as in 2011; CO_2 formed 84% of the total greenhouse gas emission concentration in United States [2].

In order to reduce the GHG emission from industrial activity, an agreement called Kyoto Protocol has been created by United Nations (UN). Kyoto Protocol stated that all participated parties or countries must ensure that their total anthropogenic carbon dioxide equivalent emission of the greenhouse gases do not exceed their assigned amount, calculated pursuant to their emission limitation and reduction commitments in accordance with the provision of this, with a view to reducing their overall emissions such gases by at least 5.2% below 1990 level in commitment period of 2008 to 2013[1].

Our reliance on fossil fuels emit carbon dioxide is projected to increase between now and 2030. This have pushed energy industry, state and federal government and other interested parties to search for effective method to reduce emission while maintaining natural resources as a fuel source [3]. One of the portfolio proposed is carbon sequestration or carbon capture and storage (CCS) project.

Carbon sequestration can be defined as the ‘process of capturing CO_2 emissions, which would otherwise be released into atmosphere and permanently storing them in geologic formation, including oil and gas reservoir, unmineable coal seams and deep saline formation [3].

Carbon capture and storage project or carbon sequestration is one of the alternatives selected to reduce the emissions of CO_2 which started commercially since 2008. As at September 2012, CCS institute identified 75 large-scale integrated projects (LSIPs) around the world. It is reported that this large-scale project can capture and store at least 800,000 tonnes of CO_2 annually for a coal-based power plant and 400,000 tonnes of CO_2 annually for other emission-intensive industrial facilities [4].

Apart from being stored in the geological formation to save environment, CO_2 has been injected into depleted oil and gas reservoir as tertiary oil recovery method, or also known as Enhanced Oil Recovery (EOR). During EOR, CO_2 injected into the reservoir for gas flooding to increase the reservoir pressure and reduce the hydrocarbon viscosity. By using this technique, a typical EOR can recover 30-60% of the original reservoir oil and gas can be restored. In the context of carbon sequestration, EOR is one of the methods used to store the CO_2 in underground formation, also known as Carbon Sequestration with Enhanced Oil Recovery (CSEOR) and Carbon Sequestration with Enhanced Gas Recovery (CSEGR) for gas reservoirs.

However, the reliability of EOR based carbon sequestration has been a major concern due to a potential CO_2 leakage from the underground storage, particularly through the wellbore and injection pipe. For a successful carbon sequestration project, the storage unit must be leak free, to the atmosphere or other geological formation in order to meet the safety regulation and their goal as GHG gas emission reduction storage. For instance, the Environment Protection Agency (EPA) in the United Stated has stated that their goal is to be able to account for 99% of the injected CO_2 in the storage [5].

Wellbore integrity is a main challenge to prove the reliability and safety of CO_2 storage within geological formation. Numerous researches have been done to identify the leakage of carbon sequestration technique for oil and gas well. In this project, a numerical simulation based software Computational Fluid Dynamics (CFD) will be used to simulate the CO_2 in carbon sequestration storage to identify the potential leakage in abandon well.

1.2 Problem Statement

Implementation of CO_2 sequestration in geological formation requires a proper assessment on the risk of CO_2 leakage, as the leakage of CO_2 from the storage will bring negative impact on safety and environment. There is possibility that CO_2 could leak back to the surface through the faults or formation rock, however this is very unlikely [3]. In contrary, the major concern of carbon sequestration leakage is the leakage through the wellbore that has been drilled for exploration and production of oil and gas and subsequently abandoned. Abandoned well are typically sealed with cement plug to block vertical migration of fluid. Regulations require that any porous zone or covered to prevent cross flow between geological formation in abandon well [7]. As for poor plugging and plug cementing, it is very significant that leakage will occur. Permeability and integrity of the cement plug will be the key factor in preventing the leakage from carbon sequestration storage.

Current abandonment practices require that cement plug must be a minimum of 30 meters in length (or 60 meters for plug deeper than 1500 meters) and extend of a minimum 15 meters above and below the porous zone being plugged [5]. For a well that has a production casing the abandonment is more customized, but all non-saline water sources must be protected and hydraulic isolation must existed between porous zones. The three main type of abandon cased well plug cementing which are: 1) bridge plug set above perforation with cement on top of the plug, 2) squeeze cement in the perforation, 3) cement plug across perforation. All this method however, have a common requirement to have at least 8 meters of cement inside casing which is pressure tested to 7000 kPa. The casing strings are cut 1 meter to 2 meter below the below the ground level and a steel plate is welded to prevent any access to the casing strings [5,7]. Figure 1 shows the diagram abandoned cased well.

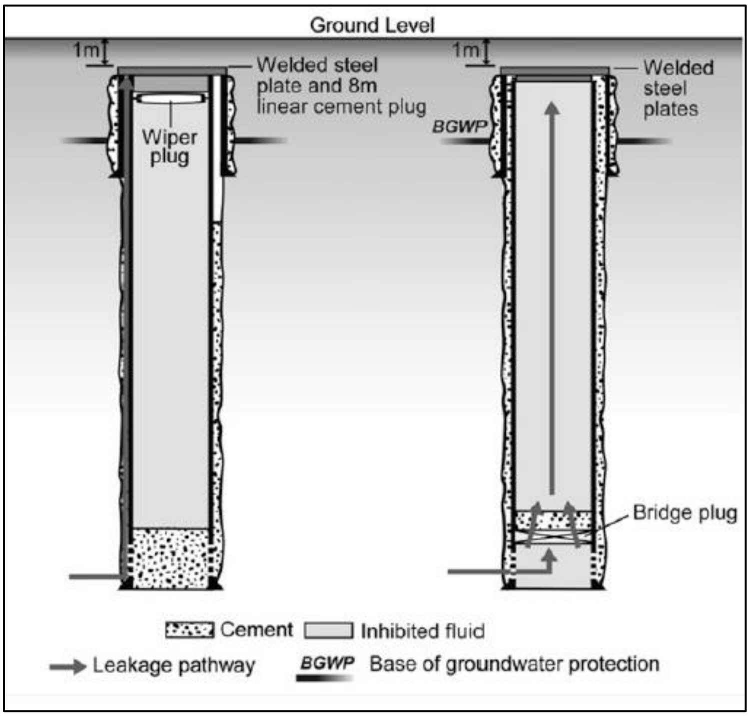

Figure 1: Typical abandonment of cased and completed well [7]

1.2.1 Potential CO_2 Leakage in Wellbore System

CO_2 that has been injected or stored in underground formation can migrate or driven upward due to buoyancy and pressure different. There are several possible pathways for CO_2 to escape in the well system. As for cased and completed abandon well, cement plug will be set over the producing interval or using bridge plug. Leakage can occur through the interfaces between different material, particularly between outside cement and casing (Figure 2a), and between plug and inside casing (Figure 2b). Leakage also can occur through cement plug steel casing (Figure 2c), through the casing (Figure 2d), through cement or fractured cement (Figure 2e) and interface between cement and formation rock [5, 6]. In this project, the potential of CO2 leakage through the cement plug only will be evaluated.

All the potential leakage stated can occur if CO_2 can penetrate through the cement or cement plug in the well. To prevent the leakage, the cement must be able to maintain low permeability over lengthy exposure to CO_2 in the reservoir condition [4]. The common used cement in industry is Portland cement. The physical and chemical reaction between CO_2 and Portland cement over long period exposure being the main role in determining leakage from carbon sequestration storage.

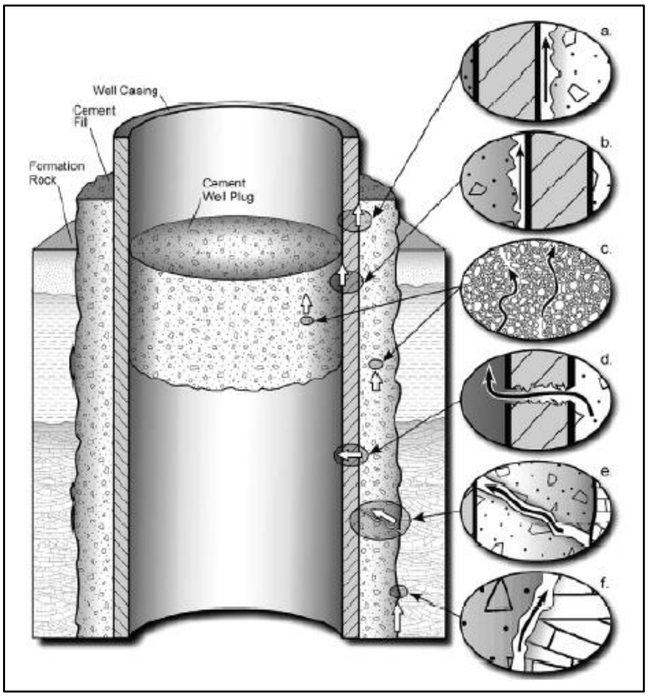

Figure 2: Potential leakage paths for CO_2 in well system a) between outside cement and casing b) between outside cement and casing c) through cement plug steel casing d) through the casing e) through cement or fractured cement f) interface between cement and formation rock [6]

In the presence of high concentration of carbon dioxide, it may cause an acidic environment within the wellbore. The reaction between CO_2 and cement can weakened the strength of cement and increase the porosity and permeability. The Portland cement is unstable in CO_2 rich environment and can degrade upon the CO_2 exposure in the presence of water [7, 8].

In order to determine the potential CO_2 leakage in abandon well, the effect of reaction between high concentration CO_2 and Portland cement to permeability of the cement will be simulated using Computational Fluid Dynamics (CFD) modeling. Computational Fluid Dynamics is simulation software that predicts the fluid flow, mass transfer, heat transfer, chemical reaction and related phenomena by solving numerically the mathematical equations that govern this process. The application of CFD in determining CO_2 leakage represented a step forward in evaluating potential leakage and toward a comprehensive model that includes complexities and detailed presentation of data and result.

1.3 Objective

1. To simulate the CO_2 leakage modeling through core plug within the abandon well using Computational Fluid Dynamic (CFD) simulation.

2. To evaluate the reaction of supercritical CO_2 exposure to Portland cement and effect of permeability, velocity, pressure and temperature to the penetration of CO_2

1.4 Scope of Works

1. Analyze and evaluate the potential of CO_2 leakage through cin sequestration storage area from literature study.

2. Construct CFD model for potential leakage through cement plug and conduct simulation to determine the penetration rate of CO_2.

3. Evaluate the effect of carbon dioxide concentration to permeability of Portland cement.

1.5 Relevancy of the project

Carbon sequestration or Carbon Capture and Storage project is an alternative to reduce the carbon dioxide emission in the atmosphere. Associated to enhanced oil recovery, carbon sequestration also being a part in oil and gas industry. Leakages of CO_2 from storage to wellbore are dangerous to environment and safety awareness as well as not justify the carbon sequestration project cost and its objective.

Hence, simulation of CO_2 leakage in abandon well using CFD can be used to monitor the process, determine the leakage phenomena and assist in preventing the leakage from occur.

1.6 Feasibility of the project

The project is feasible as it can finished within two semester (FYP1 & FYP2) timeframe and the availability of licensed Computational Fluid Dynamic software provide in Universiti Teknologi PETRONAS. As for the simulation, Computational Fluid Dynamic software is proven viable to simulate fluid flow and chemical reaction in various condition, in this case the reaction of CO_2 and Portland cement.

1.7 Limitation of the project

There are several limitations for this project. The project only limit to evaluation of potential CO_2 leakage through cement plug only as to run simulation for complete model require lot simulation time which is not feasible to final year project.In addition, the data used were obtain from secondary sources in literature as the accuracy of the data depended on the publish material.

CHAPTER 2: LITERATURE REVIEW

2.1 Well Abandonment Practices

Modern regulatory standard require specific provisions for plugging and documenting oil and natural gas wells before they are abandoned. Plugging and abandonment (P&A) regulations vary to some degree among reservoir in different geography but the main regulations prescribe the depth intervals which must be cemented as well as the materials that are allowable in plugging practices [16].

A well is plugged by setting mechanical or cement plugs in the wellbore at specific intervals to prevent fluid flow. The plugging process usually requires a workover rig and cement pumped into the wellbore. As for well with CO_2 flooding, the reservoir pressure is increased due to the injection of fluid for CO_2 recovery. The high pressure and CO_2 concentration in the reservoir may create a chance that the formation fluid will bypass the plugging material and migrate uphole [16].

2.1.1 Abandonment Method

According to the report from Watson and Bachu (2008) [7,18], there are three general zonal abandonment methods for cased well. The methods are:

1. Bridge plug capped with cement above perforation with 8 meters of cement (**Figure 3**)
2. Cement plug set across perforation. (**Figure 4**)
3. Retainer and cement squeeze into perforation. (**Figure 5**)

The most commonly method used is using the bridge plug that capped above perforation. It is anticipated that the bridge plug abandonment method will have a shorter life than other method due to mechanical failure, change of reservoir pressure due to injection of CO_2, acid gas or water or the change in fluid chemistry below the bridge plug. [17]

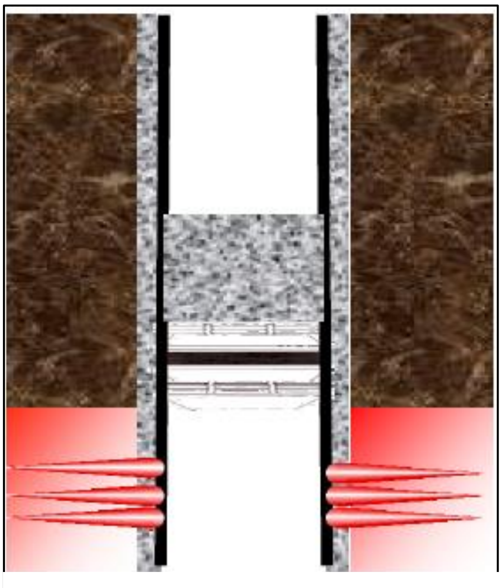

Figure 3: Bridge plug capped with 8 meters of cement [18]

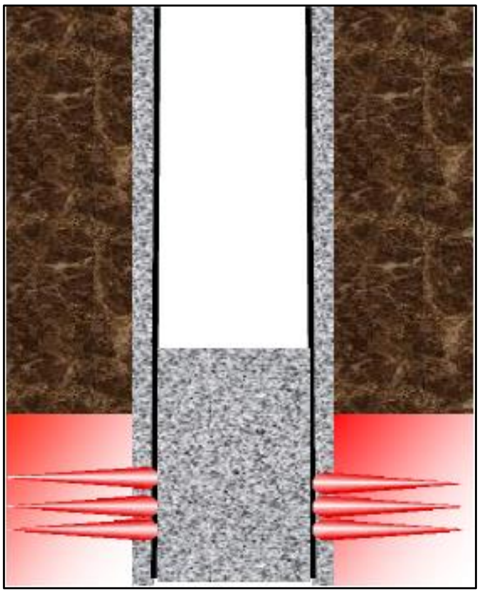

Figure 4: Cement plug set across perforation [18]

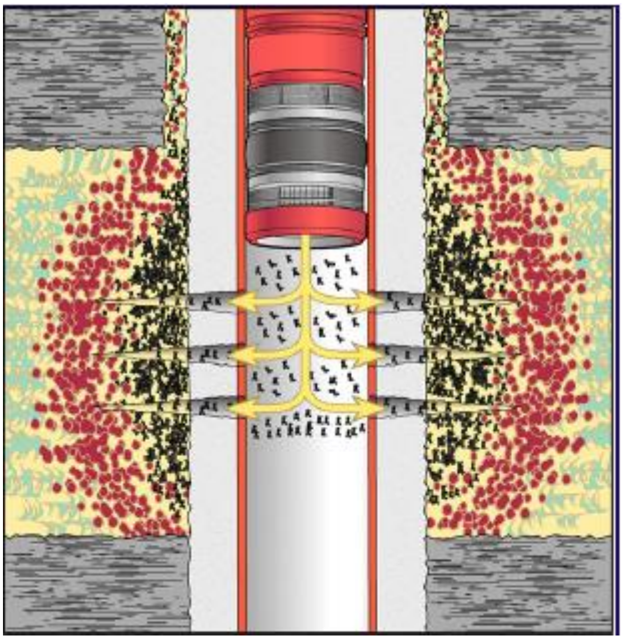

Figure 5: Cement squeeze with retainer into perforation [18]

2.1.2 SCVF and GM Testing

After plugging, the well will be checked for Surface Casing Vent Flow (SCVF) and Gas Migration (GM) inside the wellbore. SCVF is commonly encountered in oil and gas industry and is variously referred to as sustained casing pressure, annular gas pressure, casing vent flow or annular gas flow. Regulation requires that all wells drilled and cased be tested for SCVF within 60 days of drilling rig release before the final abandonment. Well that have positive SCVF and exhibit gas flow rate greater than 300 m^3/d, have liquid hydrocarbon flow, have saline water flow, or have stabilised build up pressure greater than 9.8 kPa/m to the depth of the surface casing shoe, must be repaired immediately[7]. As for GM, the test is required for several identified area, which the test consist of boring small hole in the soil to a minimum depth of 50 cm in a test pattern radiating out from the wellbore to test any migration of gas in the soil around the wellbore. After completing SCVF and GM test, the well will be cut and capped [7]. The wellhead is excavated 1m below grade and cut off. Caps are then welded on the production and surface casing, as shown in **Figure 6**.

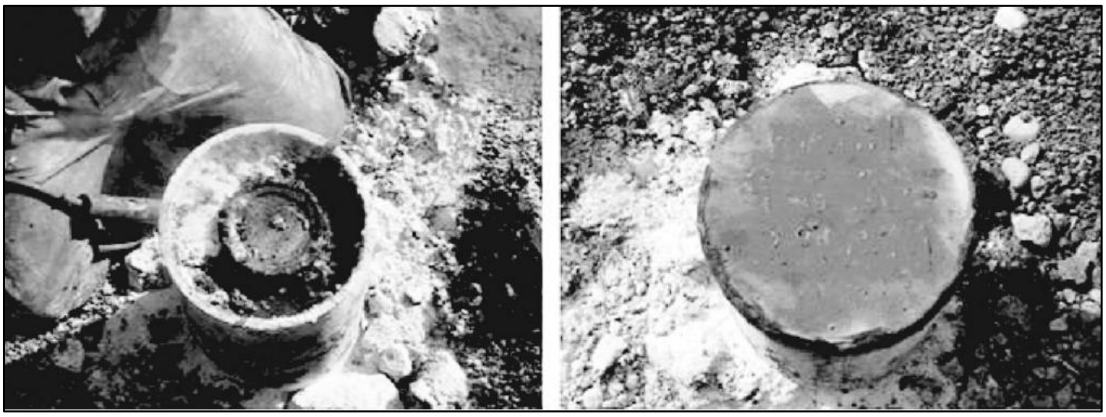

Figure 6: Wellbore cut and capped on production casing and surface casing [7]

2.2 Cement and Plug

Cement has been commonly used to plugging and seals the abandon well, while drilling mud, bentonite and mechanical plug are also used to frequently in conjunction with cement [16]. The type of cement that widely used is Portland cement.

A basic and widely used plugging material is formulated as slurry of water and Portland cement that is compositionally managed in terms of gallons (gal) of water or pounds (lb) of additives per 94-lb sack (sk) of cement. With the advances in well drilling technology and the types of wells being drilled and completed, the cementing technology has improved to allow for cementing of horizontal wells, high-pressure wells, high temperature wells, low-temperature wells, CO_2 wells, and other specialty applications. Those same cement technologies can be used in the plugging of abandoned wells [16].

The American Petroleum Institute (API) first developed a classification system for oilfield cements in 1952. The API cements are all Portland cement-based with similar ingredients but are mixed in different proportions. The different classifications are ground to a different fineness and have different water requirements for mixing. **Table 1** summarizes the different API classifications of cement. When using the API cement for cementing a well or for plugging, various additives such as retarder and accelerator are blended into the cement for specific purposes.

API Classification	Depths (Ft)	Water Requirement (gal / sk)	Slurry Density (lb / gal)	Description
Class A	0 to 6,000	5.2	15.6	Common or regular cement
Class B	0 to 6,000	5.2	15.6	Moderate to high sulfate resistance.
Class C	0 to 6,000	6.3	14.8	High-Early Cement. Fine grind, good availability
Class D	6,000 to 10,000	4.3	Varies	For Moderate Temperature and Pressure. Coarse grind plus retarder
Class E	10,000 to 14,000	4.3	Varies	High pressure, high temperature. All depths with retarders
Class F	10,000 to 16,000	4.3	Varies	Use for extremely high temperature and pressure
Class G & H	0 to 8,000	G -5.0 H – 4.3	G - 15.8 H – 16.4	Basic cement. Used at all depths with retarders.

Table 1: API Cement classification [16]

2.2.1 Reaction between CO_2 and Portland cement

Several studies have been conducted to determine the effect of CO_2 on the quality of cement used in the wellbore construction. Most of the studies indicate that cement will not withstand CO_2 attack and will fail to provide the seal in casing annulus when CO_2 is introduced. The inclusion of additives such as bentonite which increase the free water ration increase the potential for cement break down in the presence of CO_2 [8].

When CO_2 is in contact with regular Portland cement the latter is not chemically stable. CO_2 gas in water will reach equilibrium with water through the following reaction:

$CO_2 + H_2O = HCO_3^- + H+ = CO32^- + 2H^+$

Regular Portland cement contain $CO(OH)_2$ which will react with CO_2 when water is present and form solid calcium carbonate through the following chemical reaction;

$Ca(OH)_2 + CO_3^{2-} + 2H^+ = CaCO_3 + 2H_2O$

This process is called cement carbonation. Even if this process does alter the composition of the cement it leads to lower porosity in the cement since calcium carbonate has higher molar volume ($36.9cm^3$) than $Ca(OH)_2$ ($33.6cm^3$) [11,5]. From a cement sheath integrity perspective, this reaction will actually improve the cement properties and therefore the carbonation is a self-healing mechanism in the carbonate.

In a CO_2 sequestration project the available supply of CO_2 around the wellbore will continue the carbonation process as long as $Ca(OH)_2$ is present in the cement. However the calcium carbonate is also soluble with respect to CO_2 even though it is more stable than $Ca(OH)_2$. Experiments by Kutchko et al. [8], showed that when all $Ca(OH)_2$ is reacted in the carbonation process the pH will drop significantly. When the pH drops more of the CO_2 will react with water and form HCO_{3-}. The abundance of HCO_{3-} will react with the calcium carbonate and form calcium (II) carbonate which is soluble in water and can move out of the cement matrix through diffusion [8]. The final reaction that occurs is calcium silicate hydrate reacting with H_2CO_3 and forms calcium carbonate ($CaCO_3$) according to the following chemical reaction;

$3 H_2CO_3 + Ca_3Si_2O_7 * 4H_2O = 3 CaCO_3 + 2 SiO_2 * H_2O + 3 H_2O$

The volume of calcium silicate hydrate is larger than that of calcium carbonate and this reaction will increase the porosity of the cement closest to the reservoir formation containing CO_2. Barlet-Gouedard et al. [10], tested a Portland cement API class G in both CO_2 saturated water and supercritical CO_2 at 90°C. For wet supercritical CO_2 conditions the rate of the alteration front can be calculated based on;

Depth of CO_2 alteration front (mm) = 0.26 x (time in hours) $^{1/2}$

The carbonation process will have penetrated 10 mm into the sample after 60 days or 100 mm after 17 years (**Figure 7**). Kutchko et al. [9], performed similar experiments on a class H Portland cement slurry at 50°C with a CO_2 saturated brine. The results for CO_2 supercritical brine at 50°C showed a slower alteration front within the cement. The curve fit estimating alteration depth based on Kutchko et al. results for supercritical CO_2 is;

Depth of CO_2 alteration front (mm) = 0.016 x (time in days) $^{1/2}$

For example the carbonation process will have penetrated 10 mm after 1000 years and 100 mm after 100,000 years (**Figure 7**). One main difference between these experimental procedures, aside from cement type and temperature is that Barlet-Gouedarad et al. [10] used deionized water while Kutchko et al. [9] used 0.17 molar NaCl brine. Barlet-Gouedard et al performed additional experiments with a 4 molar NaCl brine to simulate downhole formation water conditions. It was observed that the carbonation rate was a 10th of the carbonation rate in the 2006 experiments and the results where more in agreement with Kutchko et al. and field experiments. The experiments clearly documented that salinity increase reduces the carbonation rate. Another difference between these experiments is that Kutchko et al. [9], used neat cement (API class H) while Barlet-Gouedard et al. [10], used cement blends. Kutchko et al. (2008) tested cement sample with bentonite additives. This sample showed a much higher degree of carbonation similar to Barlet-Gouedard et al. (2006). Another interesting observation is that any fracture or weakness in the cemented sample also showed a higher degree of carbonation.

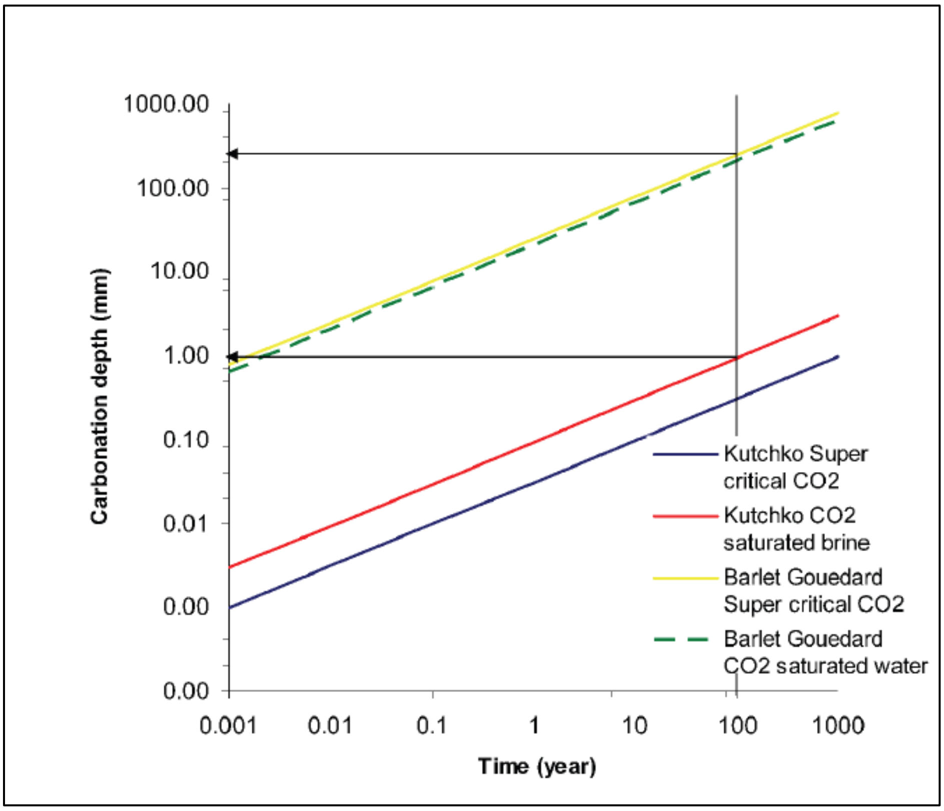

Figure 7: Carbonation depth estimated from laboratory test [5]

The laboratory studies of cement show that Portland cement is subjected to carbonation when H_2CO_3 is present. Even though the carbonation itself is not a process that is inherently bad for well cement since it reduces its permeability, the continuing source of H_2CO_3 will increase porosity and permeability of the cement. As indicated in **Figure 7**, the carbonation depth will be 1mm or 200 mm after 100 years dependant on the salt concentration of the brine. With only a 22 mm thick cement sheet outside the casing, the casing is not protected from CO_2 attacks [5].

CHAPTER 3: METHODOLOGY

The following methodology is a guideline system for solving the project problem by obeying the objectives mentioned earlier in this report, with specific components such as project activities, research methodology, key milestones, Gantt-chart and tools.

3.1 Project Activities

In order to develop the CFD model of CO_2 leakage in abandon well, work scopes and activities have been divided. First of all, the existing literature regarding the carbon sequestration and CO_2 leakage has been reviewed and evaluated.

The literature review consisted on the current practice of abandon well, which specified the method and procedure in the abandonment. Then, the literature regarding the cementing and plugging of abandon well has been reviewed and analyzed. The literature review also consisted of the chemical reaction of CO_2 with Portland based cement.

From the evaluation of the literature, the CFD model of CO_2 leakage in will be developed. The data and information gathered in the literature will be conveyed to the CFD model such as the defining parameters, boundary condition and geometry development. The physical and chemical reaction obtained from literature will be analyzed and applied to the model.

After configuring the model, sensitivity study of the parameters will be done. The model then will be validated with field data. Then, the simulation of CFD model continues until the convergence of the result. After obtaining the result the project continues with technical documentation and presentation of the project.

3.2 Research Methodology

The research methodology for CFD simulation is divided into four stages, from problem identification, pre-processing, solver, and post processing.

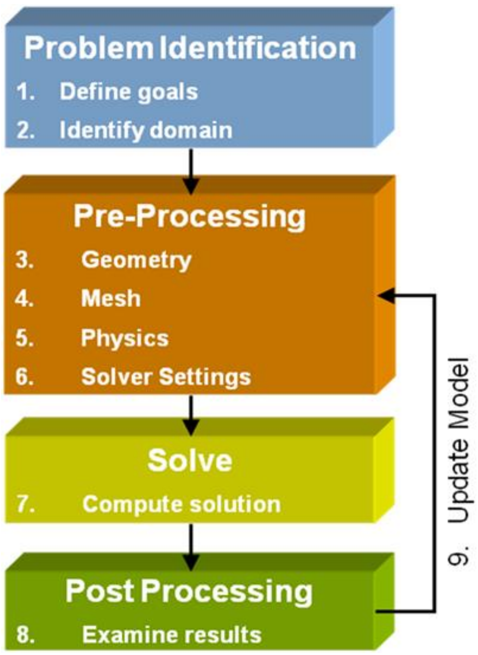

Figure 8 : Flow Chart of CFD Analysis

3.2.1 Problem Identification

First step is to define the problem and understand the purpose of the simulation. It is very important to understand as much as possible about the problem being formulate. At this stage, all necessary data required for simulation are collected including geometry details, fluid properties, flow specification and boundary and initial conditions.

3.2.2 Pre-processing Phase

Pre-processing phase in CFD includes the geometry development, meshing, physics and solver settings. The geometry model for CO_2 leakage well has been developed based on data from literature as shown in **Figure 9**. The development of the geometry was done by using 3D drawing software, ANSYS SpaceClaim.

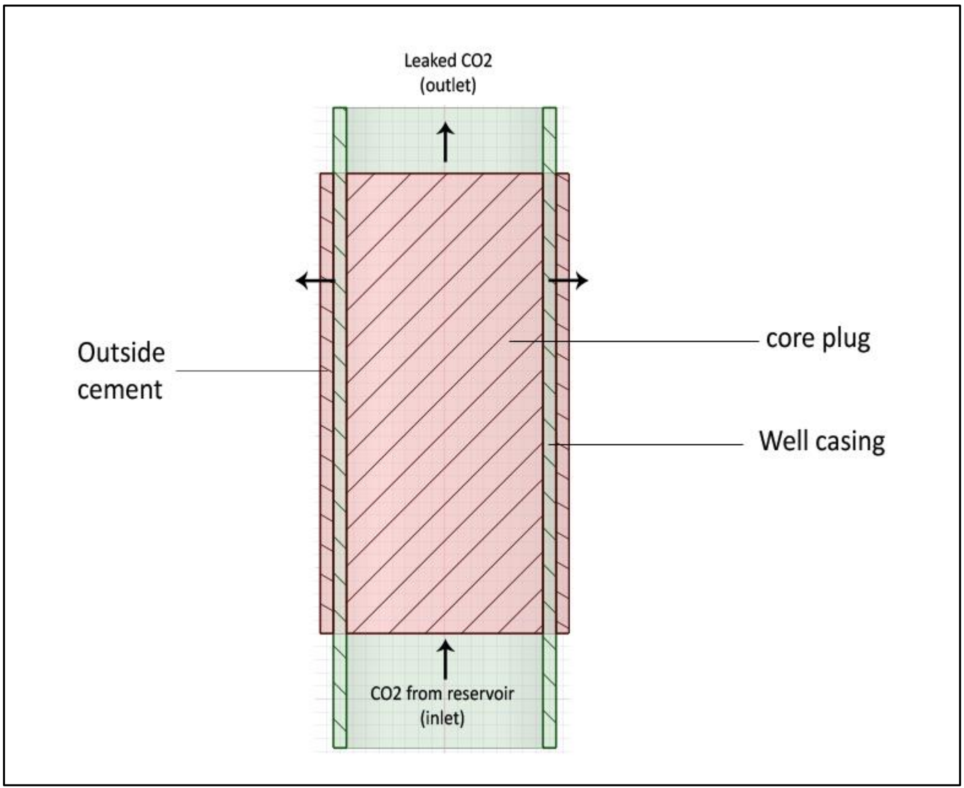

Figure 9: CO_2 Leakage in abandon well geometry model.

The process continues with meshing generation. . In this stage, the domain is discretized into a finite set of control volumes or cells. The discretised domain is called the "grid" or the "mesh". A sensitivity study will be done to obtain the optimum number of mesh for the simulation.

The completed mesh generation was then will be imported into the ANSYS CFX workbench for simulation. At this stage, physics such as the fluid properties and boundaries condition were specified, selection of turbulent model and prescribe operating conditions. Then solver control will be set up with convergence criteria and number of iteration for the simulation will be specified.

3.2.3 Solver

In this section, the CFD software performs iterative calculations to arrive at a solution to the numerical equations representing the flow. The simulation continues the domain until the convergence is reached.

3.2.4 Post Processing

Once a converged solution is obtained, the results are analyzed through variety of methods such as contour, plan, vector or line plots to check the satisfactory of the solution. If the result is unsatisfactory, the error needs to be identified. The steps of the CFD analysis are repeated several times with different types of model to choose the best flow model.

3.3 Key Milestone

- **Problem Simulation and Data Collection**
  - Identification of the problem and the objective of the project.
  - Gathering data from literature about CO_2 Leakage in Abandon Well
  - Gathering of field data required to run CFD simulation

- **Geometry and Mesh development**
  - Development of geometry model for CO_2 Leakage well
  - Generation of Mesh for the geometry

- **Sensitivity Study**
  - CFD simulations for different cement permeability
  - CFD sensitivity analysis for the defining parameters
  - Choosing for the best model of the CFD simulation

- **Validation of CFD Model with Field Data**
  - Run a CFD simulation on actual model with actual field data.
  - Analyses the output of the simulation.
  - Comparison between the CFD model and actual field data.

- **CFD Simulation and Result Analysis**
  - Carryout CFD calculations and iterations.
  - Result analysis.

- **Technical Documentation**
  - Preparing the Project Report.
  - Presentation of the Report.

3.4 Gantt Chart

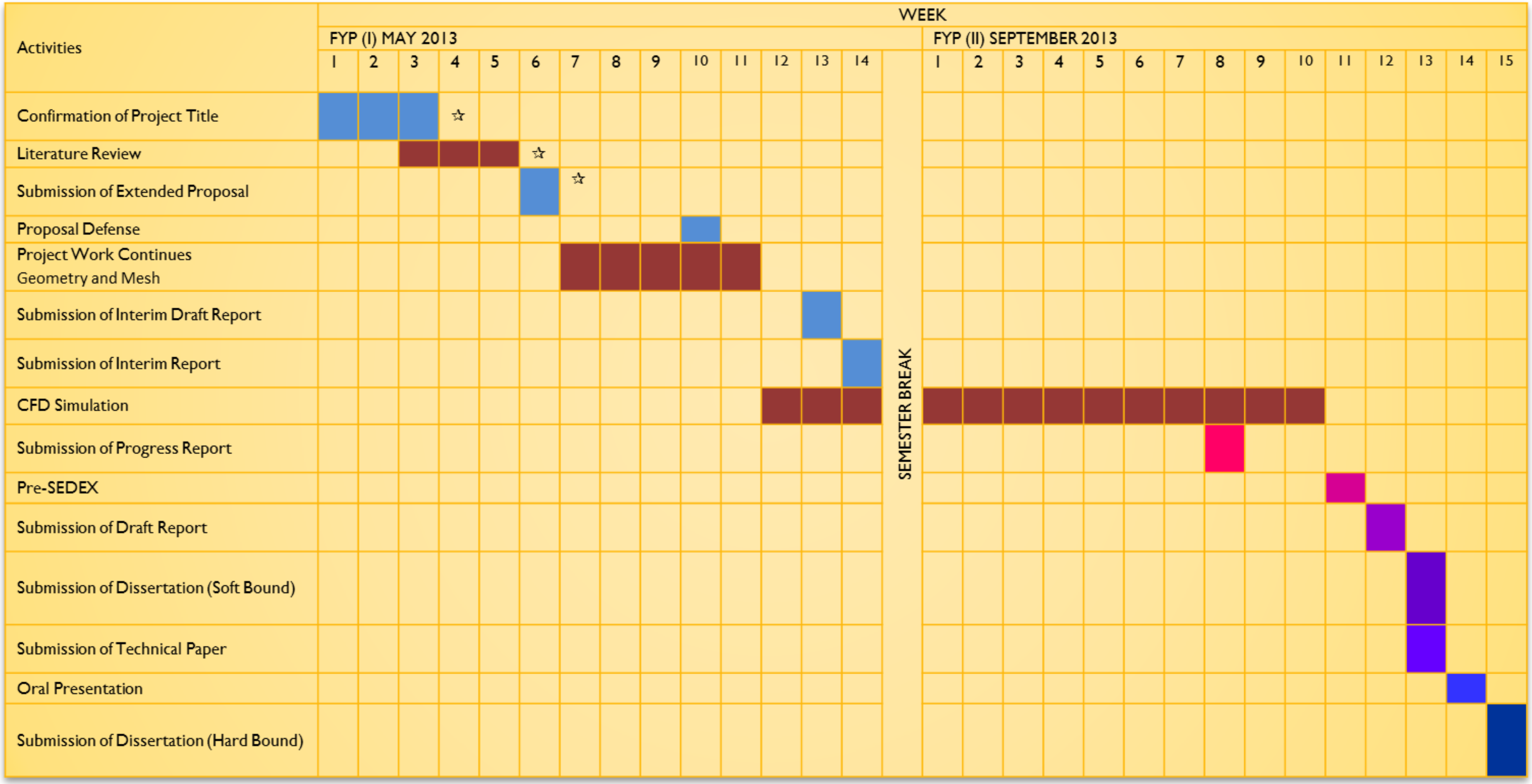

Table 2: Project Gantt Chart

3.5 Tools: Computational Fluid Dynamics

Computational fluid dynamics (CFD) is the science of predicting fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena by solving the mathematical equations which govern these processes using a numerical process. CFD is a branch of Fluid Mechanics that uses Numerical Methods and Algorithms to solve and analyze problem involving fluid flows. CFD provide detailed insight of fluid flow in simple and complex 3D geometries, complementing other process simulation tools such as iCON, HYSIS and PETROSIM. The result of CFD analyses provide a relevant engineering data used in conceptual studies of new designs, detailed product development, troubleshooting, and redesign. The advantages using CFD are reduced the total effort required in the laboratory, reducing the total cost required for experimentation and provide comprehensive flow visualization.

The CFD analysis is a mathematical tool capable of simulating a wide range of fluid flows by solving Navier-Stokes equations. There are three mains governing equation used in CFD analysis which are:

- **The continuity equation**

$$\frac{\partial p}{\partial t} + \nabla .(\rho U) = 0$$

- **The momentum equations**

$$\frac{\partial(\rho U)}{\partial t} + \nabla .(\rho U \otimes U) = -\nabla p + \nabla . \tau + S_M$$

- **The total energy equation**

$$\frac{\partial(\rho h_{tot})}{\partial t} = \nabla .(\lambda \nabla T) + \nabla .(U. \tau) + U. S_M + S_E$$

CFD is a methodology and there are several software that used to run CFD simulation which are ANSYS CFX (commercial), ANSYS Fluent (commercial), STAR CCM+ (commercial), TransAT (commercial), and OpenFoam (open source). For this case, we used ANSYS-CFX software to run the simulation. Typically, a CFD software package consists of three main groups of software, a pre-processor, a solver and post-processor.

i. Pre-processing

Pre-processing includes geometry and mesh generation, flow specification, and setting solver control parameters. Once the geometry has been generated and meshed, the fluid properties, flow models and solver control parameters are specified and boundary and initial conditions applied. These steps are usually carried out through a graphical interface.

ii. Solving the equations

All the data defined in the pre-processing step are fed into the solver program in the form of a data file. The solver is a specialized program that solves the numerical equations based on the data specified in the data file. The results obtained by the solver are written to a results file for examination using the post-processor software.

iii. Post-processing

In this software, the data obtained by the solver can be visualized and displayed using a variety of graphical methods such as contour, plane, vector and line plots. Calculations can also be made to obtain the values of scalar and vector variables, such as pressure and velocity, at different locations.

CHAPTER 4: RESULT AND DISCUSSION

4.1 Data Gathering

In this section of the report, the data gathering activities were conducted and documented. In order to develop the CFD model for CO_2 leakage in abandon well, several data are needed. The data that used in this project were obtained from journal and published literatures that simulate the condition of CO_2 in abandon well. As the data obtained from secondary sources, the accuracy of the data is depended on the published material.

Table 3 below show the data obtained for modeling of CO_2 leakage in abandon well:

Cement Properties		
Density	1.89 g/cm3	Rimmele et al [21]
Specific Heat Capacity	2100 J kg'C	Barlet-Gourdad et al [20]
Thermal Conductivity	1.2 W/m 'C	Barlet-Gourdad et al [20]
Porosity	0.33	Rimmele et al [10]
Permeability	1 e-19 m^2	Bachu and Bennion [19]
Heat Transfer coefficient	23.5 W/m2 -K	Rimmele et al [10]
Supercritical CO_2 properties		
Density	679.3 [kg m^-3]	Vesovic et al [22]
Molar Mass	44.01 [g mol^-1]	Vesovic et al [22]
Dynamic Viscosity	56.037e-6 [Pa s]	Vesovic et al [22]
Specific Heat Capacity	2.1262 [J kg^-1 K^-1]	Vesovic et al [22]
Thermal Conductivity	0.071410 [W m^-1 K^-1]	Vesovic et al [22]
Initial Condition		
Pressure	280 bar	Barlet-Gourdad et al [20]
Temperature	90ºC	Barlet-Gourdad et al [20]
CO_2 Inflow velocity	0.00001 m/s	Rimmele et al [10]

Table 3: Data for CO_2 leakage modeling

4.2 Data Analysis

Permeability

Parmeability data used in the project was obtained from Bachu and Bennion [19] which describe the parmeability profile of Portland cement in the presence of CO_2 fluid. The parmeability of Portland Cement initially is expected to be between 0.116µD to 0.232µD. The parmeability profile describe by Bachu and Bennion is:

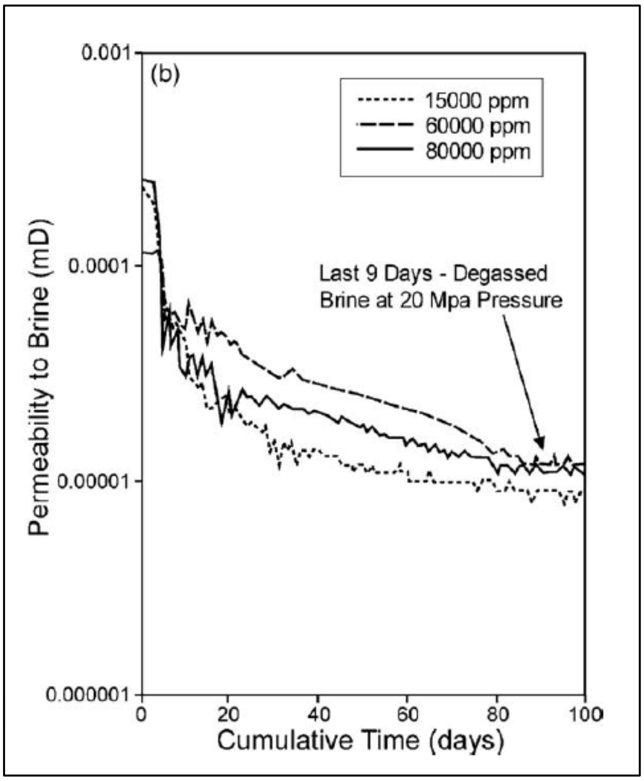

Figure 10: Parmeabiliy profile of Portland cement [21]

As there is no analytical expression can be used to describe the permeability profile, the average permeability (10e-05 mD) has been used as the assumption for overall permeability of the simulation.

4.3 Model Development

As the real geometry for CO_2 leakage model has a very high dimension, it will require a high number of meshes and long simulation time. So, a base case model has been created where only 25 mm of the cement plug will be simulated in order to evaluate the reaction between supercritical CO_2 with Portland cement.

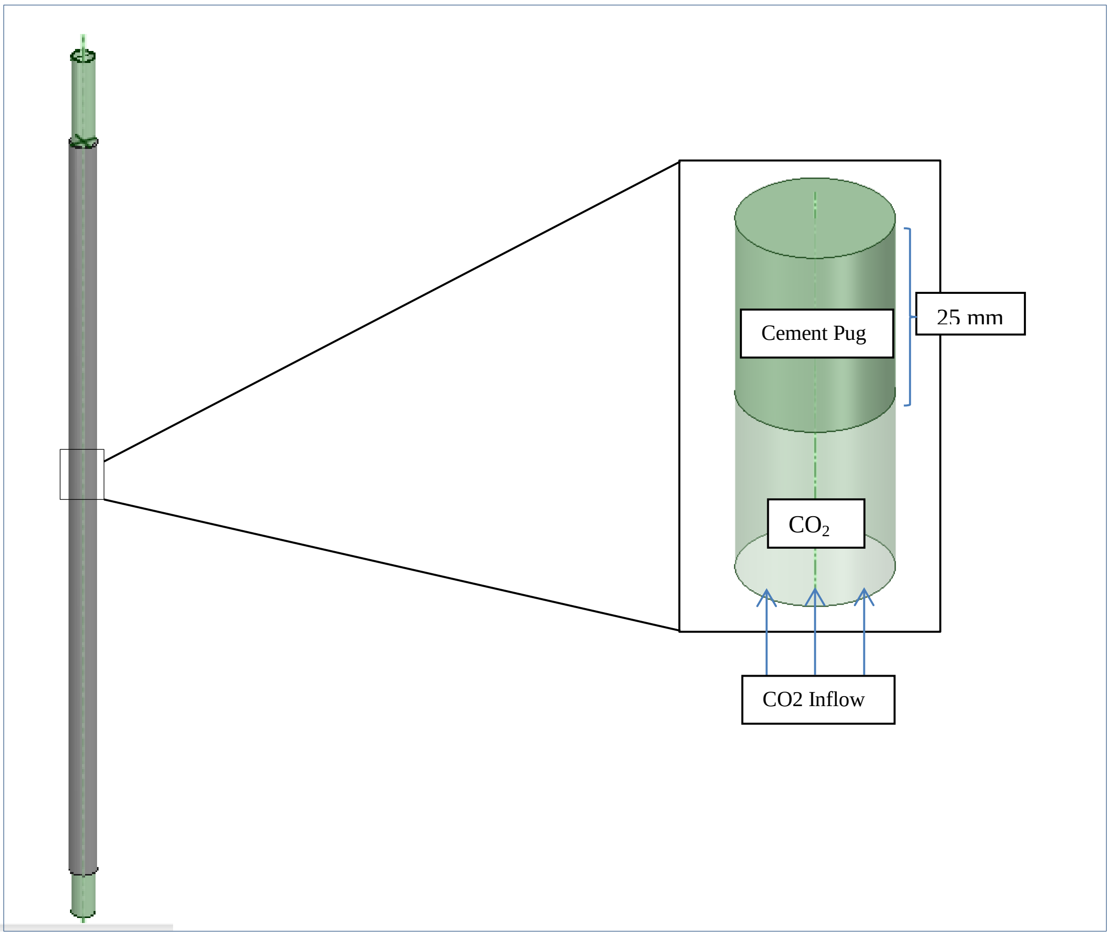

Figure 11: Geometry Development for Base Case Model

By using the base case model, the computational time of the simulation can be reduced and the model also can representing the whole cement plug to evaluate the reaction during CO_2 attack.

The modeling of CO_2 leakage in abandon well started with geometry development. The geometry for base case model is only a part of the r has been used as shown in **Figure 10** above. The geometry has been developed using ANSYS SpaceClaim Direct Modeler and ANSYS Design Modeler.

The completed geometry development then has been imported to CFX Meshing Generator for meshing development. **Figure 12** below shows the meshing generation for base case model. The number of meshes generated for this domain is 32674 nodes and 169496 elements.

Figure 12: Complete mesh generation for base case model

After completing mesh generation, the model has been taken into pre-processing stage, where physics of the model has been set. In pre-processing stage, the fluid physical properties, initial and boundary conditions and flow specification are set up. The physics set up is based on the data obtained in data gathering stage. The domain physics report is shown in **APPPENDIX 1.**

4.4 Base Case Model Analysis

The configuration for base case model is as shown in data gathering. The model has been simulated for simulation time 50 days, 100 days, 300 days, 500 days, and 1000 days using transient analysis. Figure 13 below shows the CO_2 volume fraction result for the model.

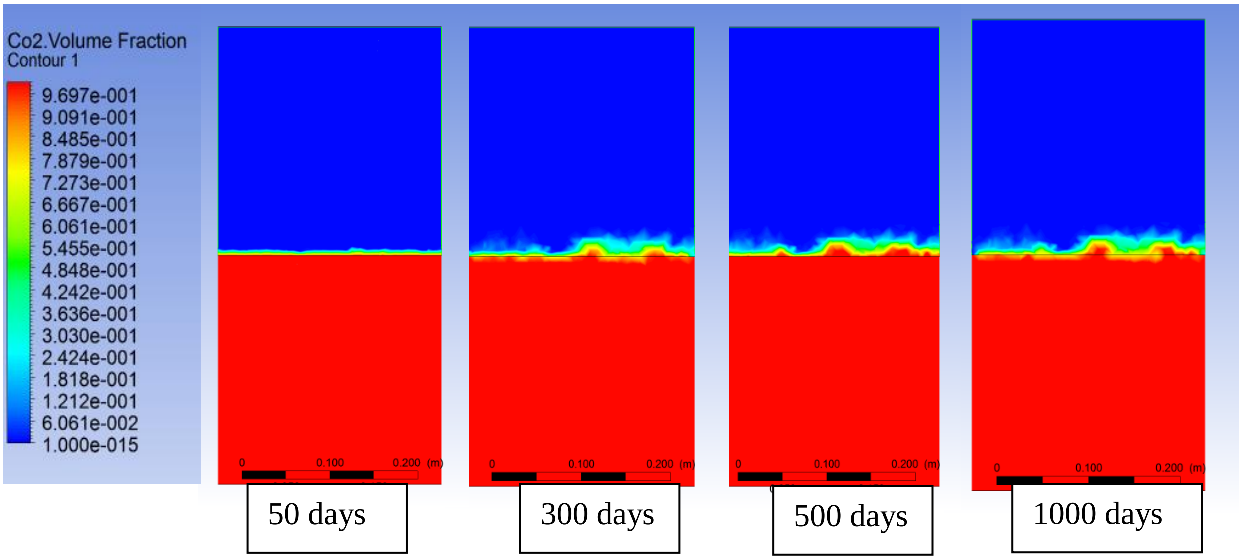

Figure 13: Volume fraction of CO_2 for base case model

To determine the depth of CO_2penetration, polyline and streamline data has been used in CFD post processing. The average highest points where CO_2 exist have been taken as the CO_2 penetration depth. Table 4 shows the penetration depth of base case model.

Table 4: Depth of Penetration for base case

Day	Depth of penetration (mm)
50	10
100	13
300	18
500	22
1000	28

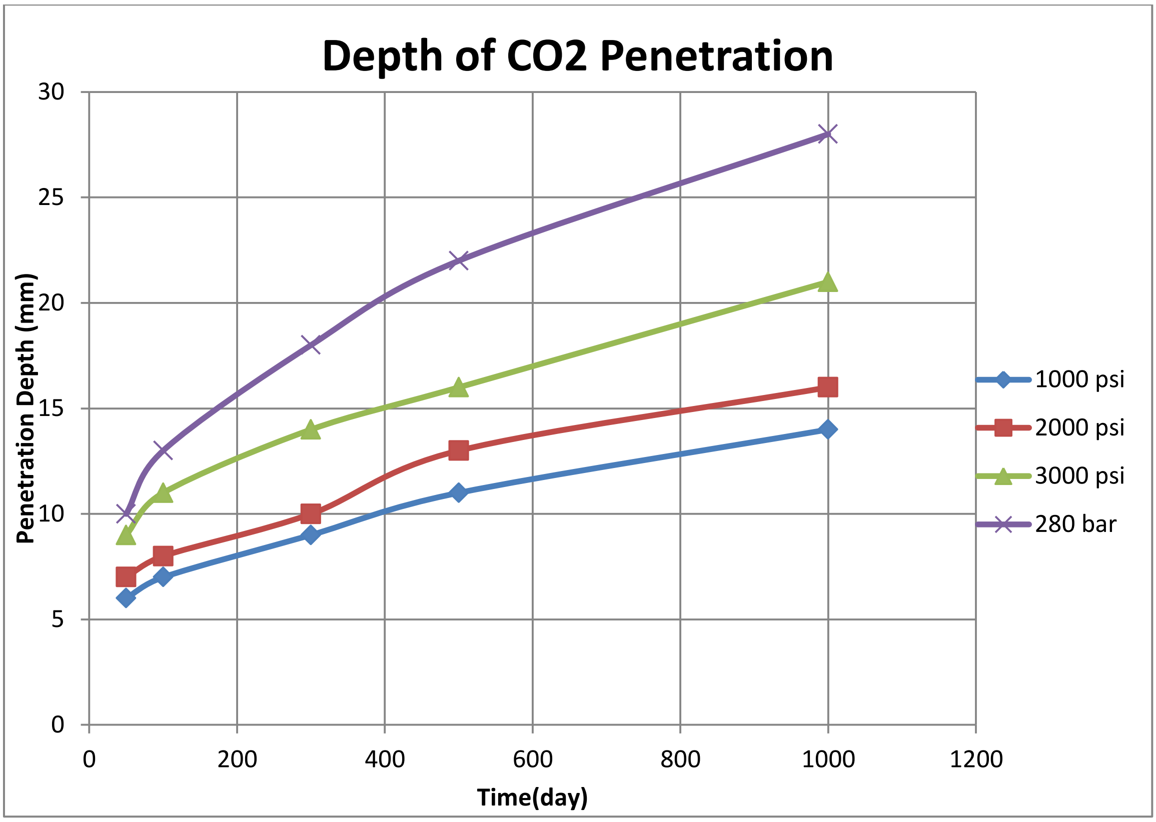

Figure 14: Depth of penetration for base case model

Based on the result, the base case model has a penetration depth of 28 mm in 1000 days simulation time. The model shows that the CO_2penetration depth is higher as the time increase. The penetration from 100 days to 500 days has a constant increment but it decrease at 1000 day penetration.

To predict the potential of CO_2leakage, the simulation result has been plotted into logarithmic with yearly timescale. The logarithmic plot of the penetration depth is shown in figure below.

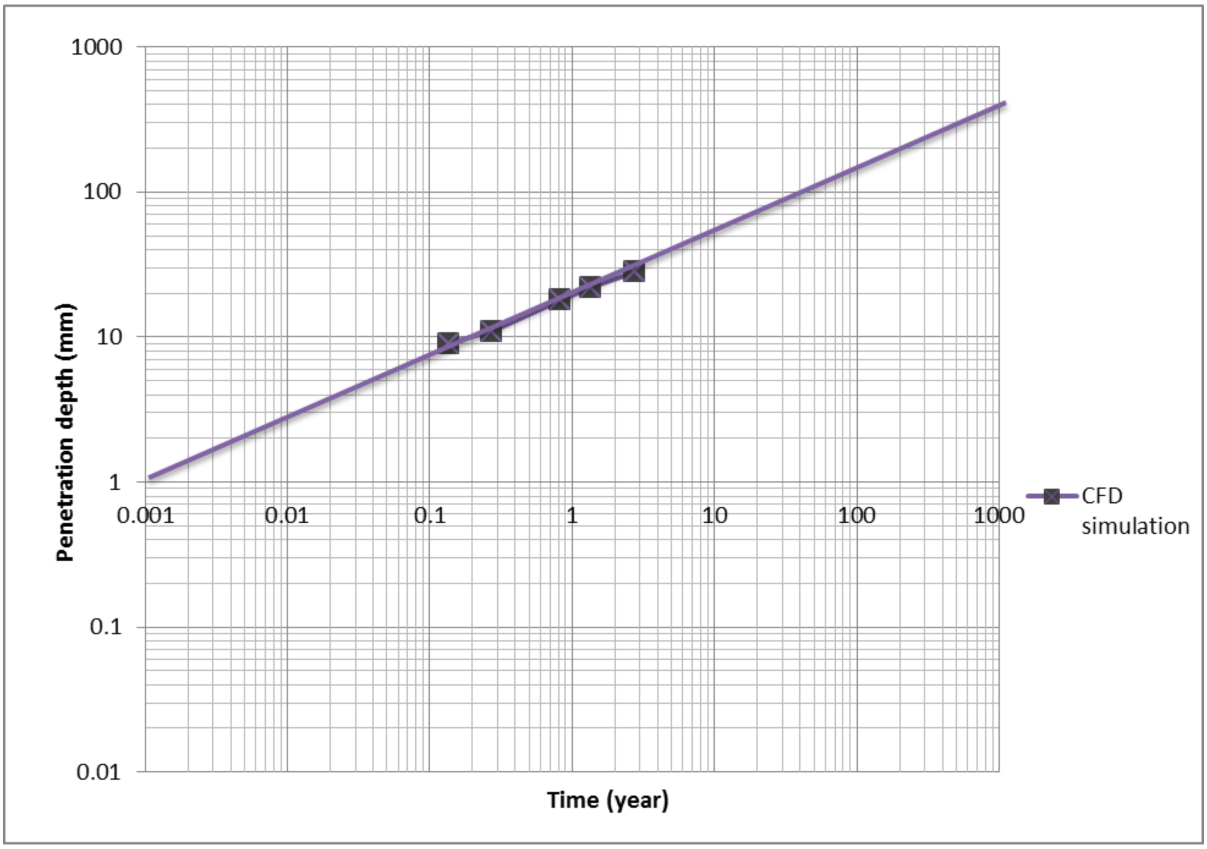

Figure 15: Logarithmic plot of CO_2 penetration

Based on the logarithmic plot, it is shown that the penetration depth increased exponentially. The rate of CO_2 penetration depth can be calculated as:

Depth of CO2 penetration = 20.05 x (time in years) $^{0.43}$

Based on the penetration rate, the CO_2 attack is expected to be around 54 mm in ten years and 150 mm in 100 years.

4.5 Comparison with Laboratory Experiment data

The result for run conducted with CFD model and reported laboratory experiment data obtained from literature are presented in Figure 17. The CFD is being compared with experiment data from Barlet Gouedard supercritical CO_2 and saturated data [20] and Kutchko saturated brine [5].

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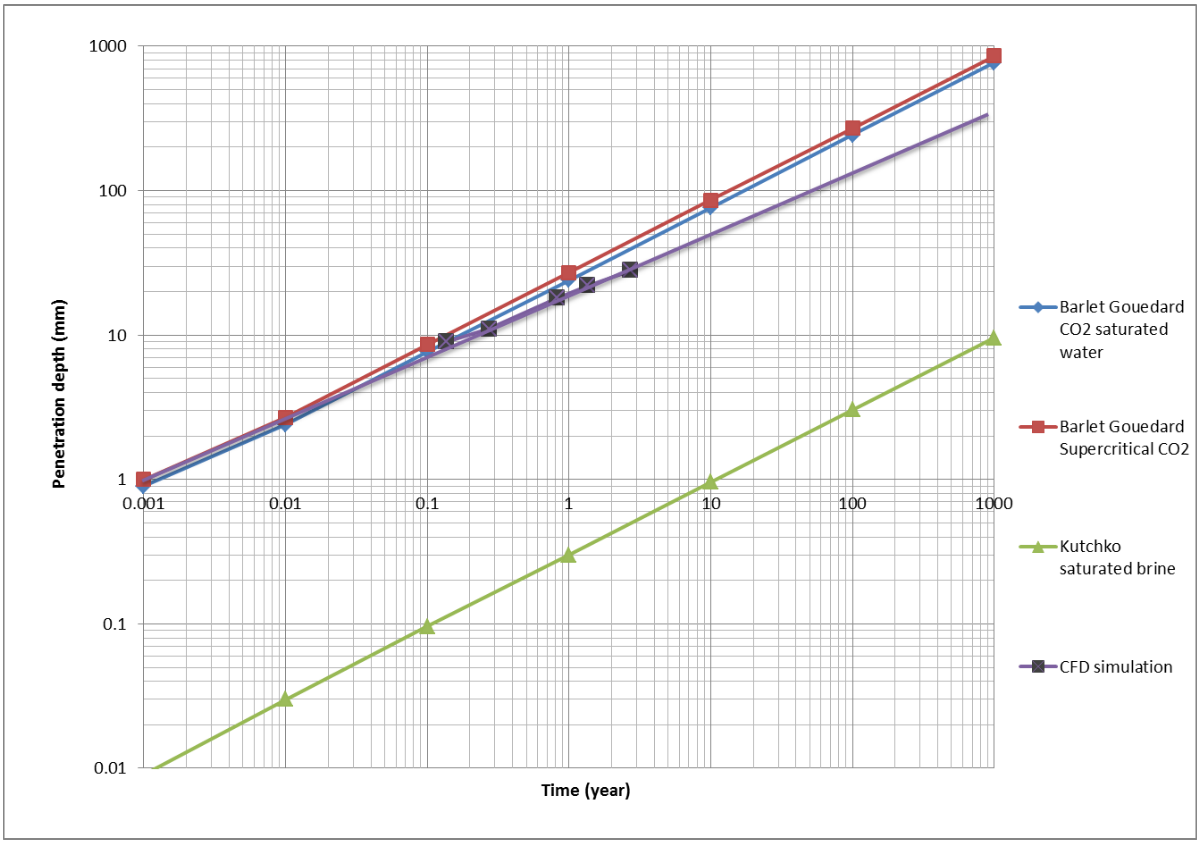

Figure 16: Comparison of CFD run with laboratory data

The laboratory data and result from this study shows a good agreement in the early stage, but the CFD model prediction deviated from laboratory measurement as the time increase. The deviation of result is probably due to following reason

- The use of addictive and cement blends such as bentonite in the experiment
- The use of saturated brine in the experiment
- The difference in model size and dimension

4.6 Sensitivity Analysis

The model has been tested with parametric analysis to test the effect of cement permeability, inflow velocity, pressure and temperature to the depth of CO_2 penetration.

4.6.1 Sensitivity analysis: Permeability

For permeability test, the model has been run using base case model with different range of permeability. The permeability used in analysis is 1e-17 m^2, 1e-18 m^2, 1e-19 m^2, and 1e-20m^2.

The CO_2 volume fraction for different permeability at 300 day is shown in Figure 18. The depth of CO_2 penetration is shown in Table 5 and Figure 19.

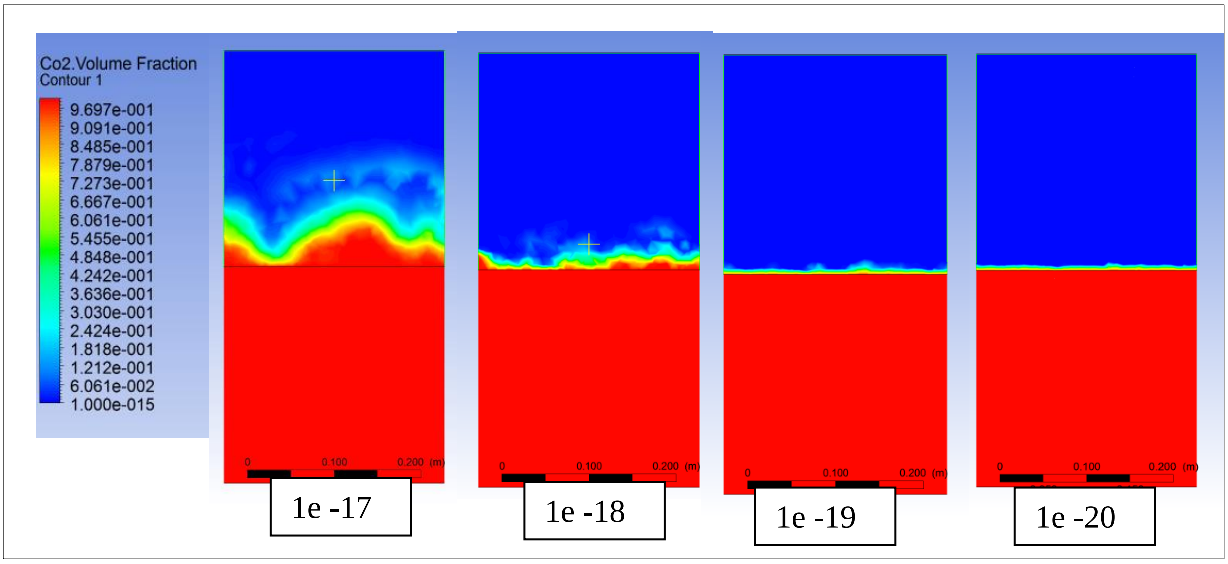

Figure 17: CO_2 volume fraction at 300 days

Table 5: Depth of penetration for different permeability

Day	Depth of CO_2 Penetration (mm)			
	1e-17 m^2	1e-18m^2	1e-19 m^2	1e-20m^2
50	55	18	7	3
100	74	20	8	4
300	102	21	10	6
500	123	26	13	8
1000	152	38	16	12

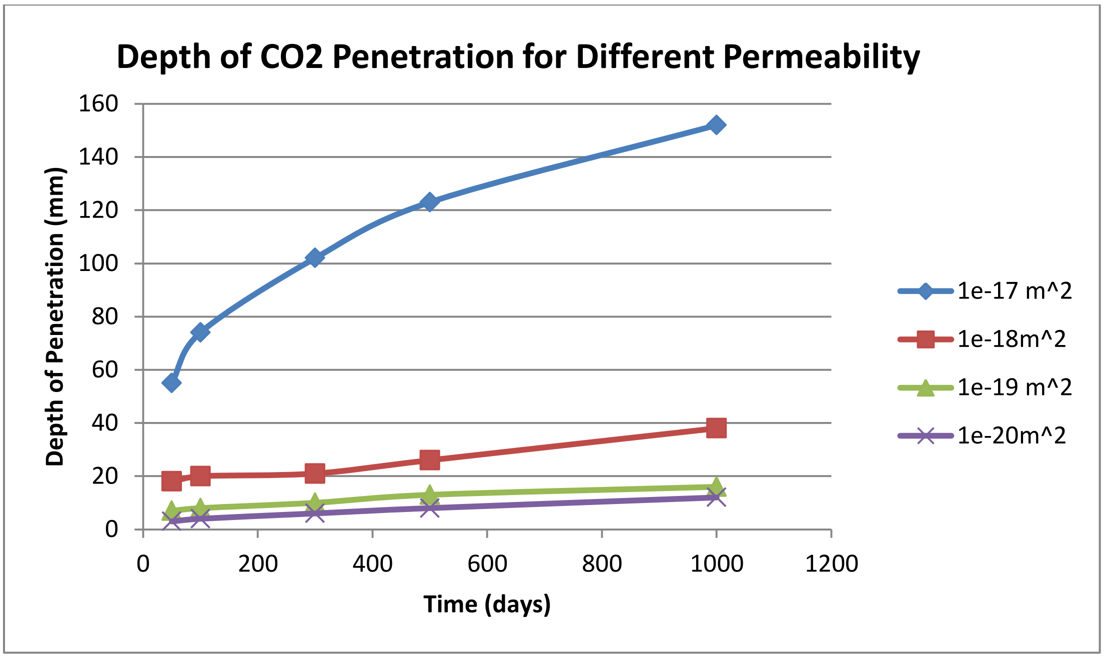

Figure 18: Depth of CO_2 Penetration for Different Permeability

The result shows the CFD simulation run for base case model with alteration of different permeability. From the result, we can see that permeability have a vital effect to depth of CO_2 penetration. The high permeability cement will produce a higher depth of CO_2 penetration. As for high permeability cement at 1e-17m^2, the depth of CO_2 penetration is 152 mm in 1000 days, which is taking more than 20 years for cement with 1e-19 m^2. The result showing that small changes in permeability has a great effect in the CO_2 penetration depth. Thus, in evaluating the potential of CO_2 leakage, the changes of cement permeability must be carefully observed.

4.6.2 Sensitivity analysis: CO_2 Inflow Velocity

For inflow velocity analysis, the model uses the base case model with different range of CO_2 inflow velocity. The velocity of CO_2 used in the analysis is 0.0001 m/s, 0.1 m/s, 1 m/s, and 3 m/s. The result for the simulation is shown in figures below.

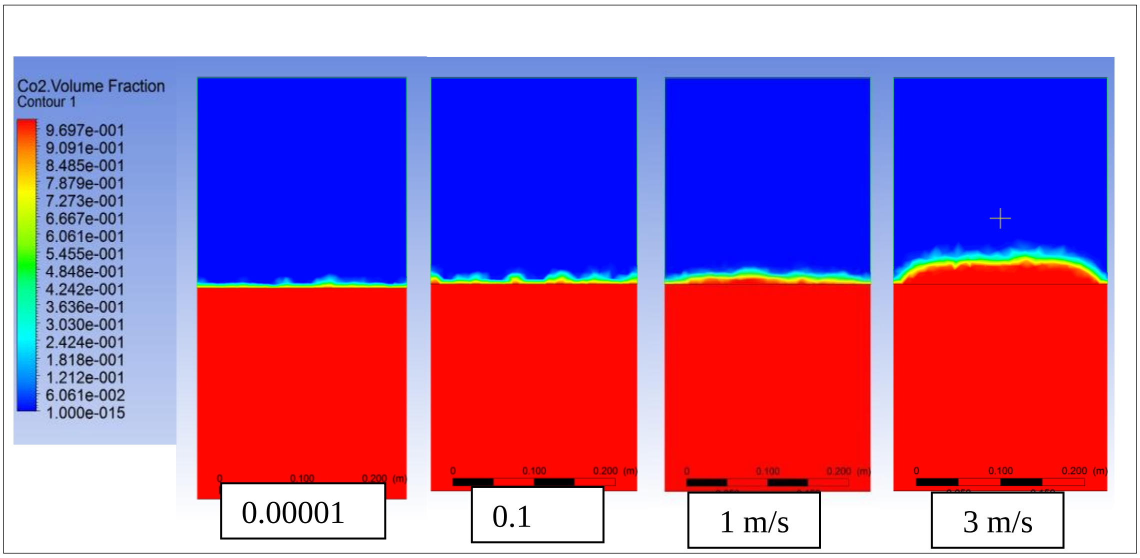

Figure 19: CO_2 Volume Fraction for different inflow velocity

Table 6: Depth of CO2 Penetration for different inflow velocity

Day	Depth of CO_2 Penetration (mm)			
	0.00001 m/s	0.1 m/s	1 m/s	3 m/s
50	7	9	13	18
100	8	15	17	26
300	10	20	28	48
500	13	28	38	60
1000	16	43	55	82

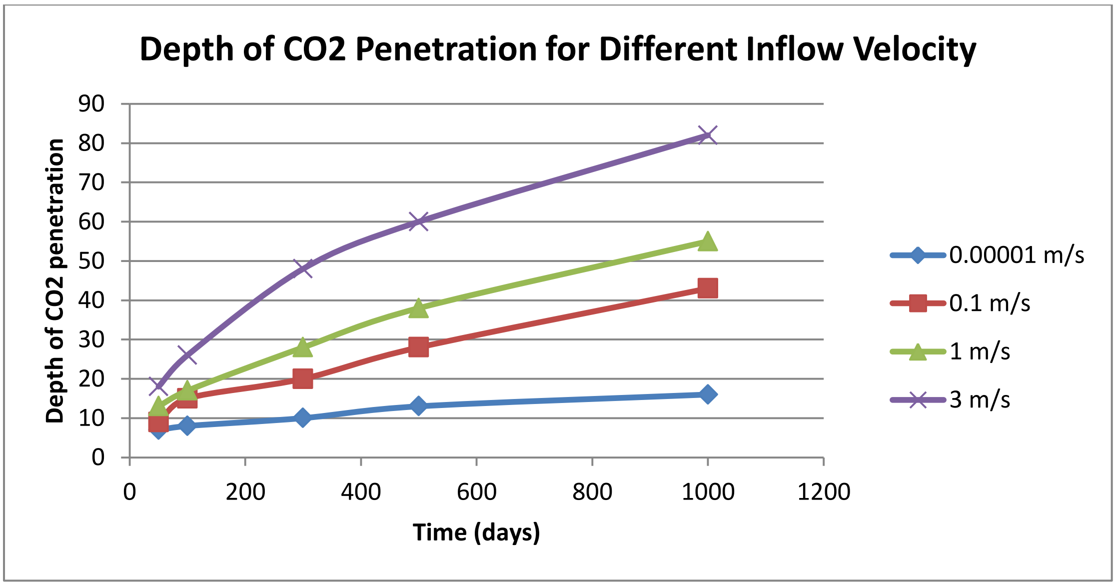

Figure 20: Depth of CO_2 Penetration for different inflow velocity

The result shows the CFD simulation run for base case model with alteration of different inflow permeability. The result shows that the CO_2 with higher inflow velocity exhibit a higher depth of penetration. At the early stage, there are not much different of CO_2 penetration depth between these inflow velocities. The depth of CO_2 penetration of each case deviates as the time increase, as for 1000 days simulation, the gap of penetration between different inflow velocities is higher. Thus, it also concludes that CO_2 inflow has vital effect to depth of penetration.

4.6.3 Sensitivity Analysis : Pressure

The following sensitivity analysis is to analyse the effect of pressure to depth of CO_2 penetration. The model uses the base case analysis with different range of pressure that is 1000 psi, 2000 psi, 3000 psi, 4061psi (280 bar).

Figures 21, Figures 22 and Table 7 show the result of the simulation.

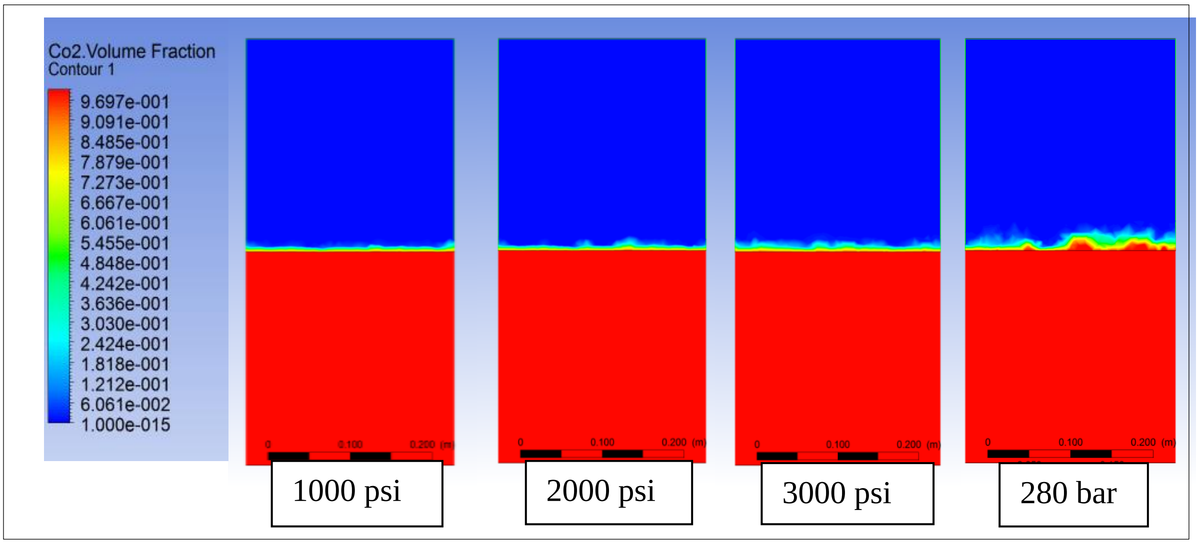

Figure 21: CO_2 Volume Fraction for different pressure

Table 7: CO_2 Penetration depth for different pressure

Day	Depth of CO_2 penetration (mm)			
	1000 psi	2000 psi	3000 psi	280 bar
50	6	7	9	10
100	7	8	11	13
300	9	10	14	18
500	11	13	16	22
1000	14	16	21	28

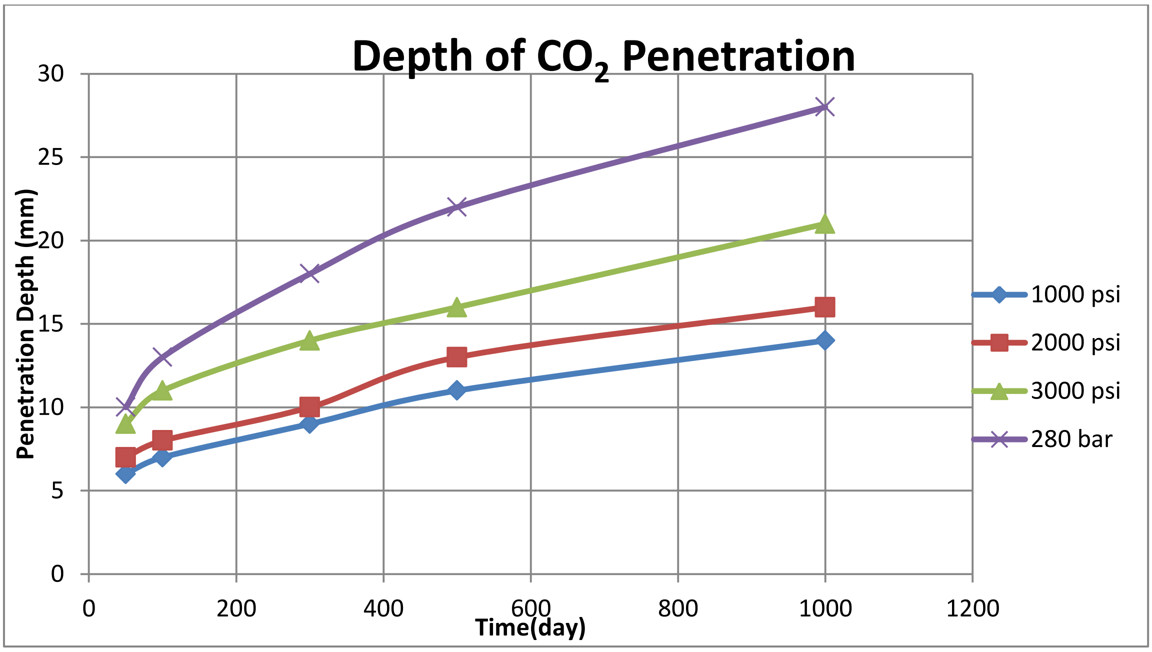

Figure 22: CO_2 Penetration depth for different pressure

The sensitivity analysis of different pressure shows that a higher pressure will create a higher penetration depth. The deviation of CO_2 penetration between different pressure however are smaller compared to permeability and inflow velocity analysis. The depth of penetration of 1000 psi pressure is 14 mm at 1000 days while depth of penetration of 3000 psi is 21 mm, showing that the pressure alteration has smaller impact to depth of CO_2 penetration.

4.6.4 Sensitivity Analysis: Temperature

Sensitivity analysis of temperature has been done by altering the temperature to 70ºC, 90ºC, 120ºC and 150ºC. Figure 23 and Table 8 below shows the result of the simulation.

Table 8: Depth of CO_2 Penetration

Day	Depth of CO_2 penetration (mm)			
	70 Celcius	90 Celcius	120 Celcius	150 Celcius
50	6	7	8	9
100	7	8	10	13
300	9	10	12	15
500	11	13	15	16
1000	14	16	18	20

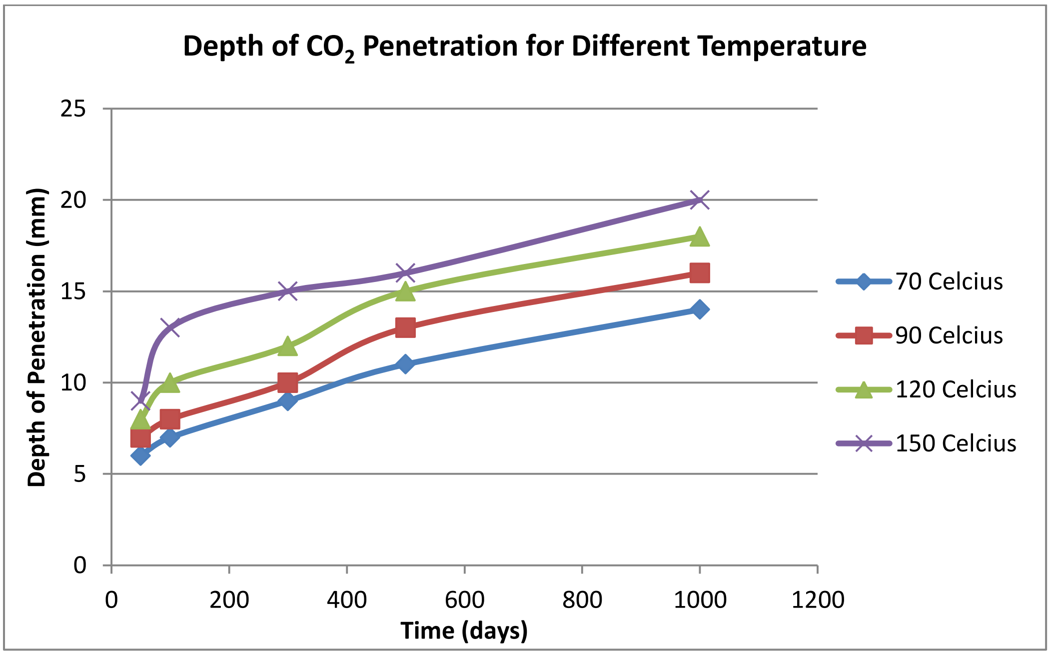

Figure 23: Depth of CO_2 Penetration

The result shows the CFD simulation run for base case model with alteration of different temperature. Based on the result, it shows that the higher cement temperature will allows more depth of CO_2 penetration. The different however, is not very significant between different temperature and gave the least impact to the depth of penetration.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

A CFD model to evaluate the reaction of supercritical CO_2 and Portland cement has been created. The base case model has been validated with experimental work. The comparison between CFD modelling and laboratory experiments show that the CFD model has a good agreement with laboratory experiments but deviated at higher stage due to several factor such as different in cement blending.

The result for base case model shows that CO_2 attack is expected to be around 150 mm in 100 years, which is still in safe range from leakage to happen. For CO_2 to penetrate along 8 meters of cement plug, it will take more than 10000 years, which we can conclude that there will be no leakage through cement plug. The leakage also may happen from outside cement, which has only 22 mm thickness and CO_2 may travel between the interface of casing and cement.

However, as shown in the sensitivity study, any changes in permeability of the cement will enhance the CO_2 penetration attack and the leakage may happen. The effect of inflow velocity also can enhance the penetration of CO_2 into cement plug.

In sensitivity analysis, the effect of permeability, inflow velocity, pressure and temperature has been tested. All of the parameters tested have an impact to the depth of CO_2 penetration. For permeability test, a higher permeability exhibits a very significant improvement to the CO_2 penetration. Inflow velocity also plays a vital role as higher inflow velocity will result to a higher penetration impact. Pressure alterations also have an impact to the CO_2 penetration but smaller compared to velocity, while temperature has the very lease impact of all parameter.

As conclusion, the project has met the objective to evaluate the potential of CO_2 leakage through cement plug in abandon well. The sensitivity analysis to test the effect of permeability, pressure, velocity and temperature to the reaction between supercritical CO_2 and Portland cement has been done.

5.1 Recommendation

There are few recommendation suggested for future work.

1) Simulation of CO_2 leakage for model with real geometry, including casing and 8 meters cement plug
2) Assessment of changes in permeability of cement plug due to CO_2 attack
3) CFD simulation for a longer timescale to evaluate the leakage potential

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APPENDIX 1

Domain Physics for Fluid Flow CFX_001

Domain - CO2	
Type	Fluid
Location	Co2
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
supercritical CO2	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Non Buoyant
Domain Motion	Stationary
Reference Pressure	2.8000e+02 [bar]
Heat Transfer Model	Thermal Energy
Homogeneous Model	On
Turbulence Model	Laminar
Homogeneous Model	On
Domain - Cement	
Type	Porous
Location	Cement
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
supercritical CO2	
Fluid Definition	Material Library
Morphology	Continuous Fluid

Settings	
Buoyancy Model	Non Buoyant
Domain Motion	Stationary
Reference Pressure	2.8000e+02 [bar]
Heat Transfer Model	Thermal Energy
Homogeneous Model	On
Include Pressure Transient Term	On
Turbulence Model	Laminar
Homogeneous Model	On
Domain Interface - Default Fluid Porous Interface	
Boundary List1	Default Fluid Porous Interface Side 1
Boundary List2	Default Fluid Porous Interface Side 2
Interface Type	Fluid Porous
Settings	
Interface Models	General Connection
Mass And Momentum	Conservative Interface Flux
Mesh Connection	GGI

Table 4. Boundary Physics for Fluid Flow CFX_001

Domain	Boundaries	
CO2	**Boundary - inflow**	
	Type	INLET
	Location	inflow
	Settings	
	Flow Regime	Subsonic
	Heat Transfer	Static Temperature
	Static Temperature	9.0000e+01 [C]
	Mass And Momentum	Cartesian Velocity Components
	U	0.0000e+00 [m s^-1]
	V	1.0000e-05 [m s^-1]
	W	0.0000e+00 [m s^-1]
	Fluid	AIR
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Fluid	Co2
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Boundary - Default Fluid Porous Interface Side 1	
	Type	INTERFACE
	Location	FI
	Settings	
	Heat Transfer	Conservative Interface Flux
	Mass And Momentum	Conservative Interface Flux
	Boundary - opening	
	Type	OPENING
	Location	Opening

	Settings	
	Flow Direction	Normal to Boundary Condition
	Flow Regime	Subsonic
	Heat Transfer	Opening Temperature
	Opening Temperature	9.0000e+01 [C]
	Mass And Momentum	Opening Pressure and Direction
	Relative Pressure	2.8000e+02 [bar]
	Fluid	AIR
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Fluid	Co2
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
Cement	**Boundary - Default Fluid Porous Interface Side 2**	
	Type	INTERFACE
	Location	SI
	Settings	
	Heat Transfer	Conservative Interface Flux
	Mass And Momentum	Conservative Interface Flux
	Boundary - wall cement	
	Type	WALL
	Location	F15.14, F17.14
	Settings	
	Heat Transfer	Adiabatic
	Mass And Momentum	No Slip Wall
	Wall Contact Model	Use Volume Fraction