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STRESS AT BOREHOLE DURING CARBON INJECTION

OLLIVIA LENYA ANAK SAGU

MECHANICAL ENGINEERING

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By,

OLLIVIA LENYA ANAK SAGU

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Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Stress at Borehole During Carbon Injection

By

Ollivia Lenya anak Sagu

A project dissertation submitted to the

Mechanical Engineering Department

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(MECHANICAL ENGINEERING)

Approved by,

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(DR WILLIAM PAO KING SOON)

Universiti Teknologi PETRONAS

TRONOH, PERAK

May 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted on 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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OLLIVIA LENYA ANAK SAGU

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ABSTRACT

This study aims to analyze the character of temperature of CO_2 along borehole in regards with different injection rate. It is to identify whether injection rate plays a role in determining the temperature changes along borehole. Secondly, the effect of temperature on breakdown pressure is studied. The temperature difference between CO_2 and surrounding will induce an amount of thermal stress along the borehole. The temperature difference of surrounding and CO_2 also plays an important role in the enthalpy of CO_2 along wellbore, hence, it will affect the pressure of CO_2 along wellbore. Finally, this study is concluded with a suggestion for safe range of injection rate.

Unlike a producing well, CO_2 injection well has more constraint. The injection pressure must not exceed the fracture pressure formation along wellbore to ensure the integrity of the wellbore. Temperature difference of CO_2 and surrounding might induced a lower breakdown pressure along the wellbore.

The scope of this study is stress along the wellbore. The wellbore is the connection of CO_2 from surface to the subsurface storage. Hence, the integrity of the wellbore is the one of the keys to ensure a safe injection program.

For this report, the methodologies are purely theoretical. Mathematical equations of CO_2 characteristic along wellbore is adapted from Luo and Bryant (2010). Next is the breakdown pressure identification. In order to identify pressure of CO_2 along wellbore, Span and Wagner (1994) Equation of State was used.

The result of this report helps to identify a safe environment and condition for CO_2 injection.

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CO_2 Carbon Dioxide

CCS Carbon Capture and Storage

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

It is estimated that one third of all CO_2 emissions are due to human activity come from fossil fuels used for electricity generation. Other industries such as oil refineries, fertilizer and cement plants also emit large amount of CO_2.

From Kane and Klein (2004), CO_2 is identified as a major greenhouse gas (GHG). Greenhouse gas is the main contributor in the world climate change. In the 21^{st} century, climate change is one of the primary environmental concerns.

Recognized by many observers as potential global threat, global warming poses to bring many negative impacts. The impacts include increasing global average temperature, rising sea levels and changes in precipitation, with consequences for low-lying inhabited areas, agriculture, biodiversity and human health. (Freund, 2006)

1.2 PROBLEM STATEMENT

1.2.1 PROBLEM IDENTIFICATION

Carbon dioxide is injected in its supercritical form. However, there is a possibility of pressure drop and temperature drop as the CO_2 travels from compression plant to the storage site. Hence, compressing will be necessary. Before compressing the CO_2, it is important to identify the stress along the borehole to ensure the integrity of the CO_2 storage. One thing to be taken into account is the heat transfer rate of the CO_2 to the surrounding.

CO_2 injection column has more constraint than the producing column; injection rates are constraint by the requirement not to exceed the fracture pressure of reservoir or the threshold of the seal rock.

1.2.2 SIGNIFICANT OF PROJECT

Malaysia has ratified Kyoto Protocol but is yet to embark in a carbon injection program. Thus, for safety factor, it is important to identify possible circumstances that might happen during any injection program.

1.3 OBJECTIVE AND SCOPE OF STUDY

The objective of this study is to identify effect of temperature along wellbore during carbon injection. Secondly, it is to identify a safe injection rate.

This project only covers the effect of CO_2 temperature and pressure on stress along wellbore area.

1.4 RELEVANCY OF THE PROJECT

The project is relevant to identify the basic design for a CO_2 injection wellbore. It can provide a method to identify safety guideline for any possible injection plan in Malaysia.

1.5 FEASIBILITY OF PROJECT WITHIN THE TIME SCOPE AND FRAME

The project is feasible within the 8 month period. This project is based on numerical assumptions/calculations.

CHAPTER 2

LITERATURE REVIEW

2.1 KYOTO PROTOCOL AND GLOBAL WARMING

Since 1992, the awareness towards global warming had set several countries to be on foot and beginning to make effort to address and mitigate the issue. To date, there are 7 key meetings to address global warming. (Westbrook, 2002)

In reference of Westbrook (2002), it began in Rio de Janeiro meeting, 1992.The conclusion of the meeting; included voluntary emission limitations plus setting up a series of follow up meeting of the Council of Parties (COP).

The following COP; COP 1 and COP 2 held in Berlin and Geneva respectively did not come up with any impactful outcomes. It was later in COP 3, held in Kyoto had led to Kyoto Protocol.

Kyoto Protocol major feature is the set of binding targets for reducing greenhouse gas (GHG) emissions. The mandatory emission limits were defined. Kyoto Protocol became an international agreement linked to the United Nations Framework Convention on climate change.

COP 4 was a key point whereby Clinton administration of United States of America signed the Kyoto Treaty but it was yet to be ratified. The following COP5 was a relatively non event. Emphasis was however, put on emission trading aspects. COP6 was considered to be a failure but it did not stop for next COP7. During COP 6, there was a follow on meeting between EU and USA to see if it could narrow its differences with regard of carbon emissions.

COP 7 did not have any major impact but it was considered by the supporters as a major triumph.

For many sustainable development and environmental advocates, the year 2012 will be the year to look forward for with the Rio +20. Ten years after Earth Summit in 002), there will be number of changes in technology and methods to reduce green house gas emissions.

It should be the aim for every engineer to produce unplugged energy. But until then, we must acknowledge our dependence on nature and try to minimize the negative impact on the environment.

2.2 CARBON CAPTURE AND SEQUESTRATION (CCS)

Carbon Capture and Sequestration (CCS) is one of technologies to abate anthropogenic CO_2 emissions, particularly from one huge source point such as power and chemical plant. In CCS, CO_2 is extracted from a gas stream, pressurized and then injected into suitable geological formation for long term storage. (Lawal, 2011)

In 2008, Kaarstad has stated that technologies of CCS have been proven to a certain extent but is still in its infancy. Lawal (2011) had further supported that the challenges in CCS are still lingering due to the fact that CCS is still commercially immature. Circumstances such as technology infancy, challenging economic threshold and public reservations and its technical viability pose uncertainties towards CCS.

Country like Canada regards the importance of studies in CO_2 capture, storage, transportation, storage engineering, the geosciences and monitoring, measurement and verification to evaluate the components of this technology and allow scale up to large demonstration. (Lakeman et al, 2008)

Malaysia ratified the Kyoto Protocol but has not yet started any carbon injection program. Potential candidate for CCS is identified in the M4, offshore Sarawak.

2.3 CARBON CAPTURE AND SEQUESTRATION RISKS

Paterson et al (2010) had stated that CO_2 wells are different from oil, water and gas wells, because large density changes due to transient thermal effects can decouple the surface pressure from downhole pressure. This means the wellhead pressure can decline while the reservoir pressure builds up and vice versa.

Cold CO_2 will cause stress reduction in the injection layer. Once the temperature front reaches a relatively large area around the wellbore, the stress reduction will produce a negative volumetric strain which get transferred to the surface. The most important effect of cold CO_2 injection is the fracture pressure. When the formation is cooled, it will encounter a reduction in total stress, hence lowering the fracture propagation pressure. This will result onto the reduction of pressure differential available for injection and the injectivity. (Goodarzi, 2010)

During carbon injection, temperature difference between carbon dioxide and surrounding causes pressure difference.

Garnham and Tucker (2012) had identified the 50 risks of CO_2 end-to-end injection. They had addressed the concerns of public, technical issues and stakeholder concerns into the risks. One of the major risk concerns is the safety offshore during CO_2 injection. Due to the different character of CO_2 from other hydrocarbons; heavier than air and does not require a source of ignition to be deadly, it raises questions about the possible risk it may pose.

In addition, the topside of the facilities will be exposed to very low temperatures in the event of an emergency depressurization- this will make replacement and/or protection of existing pipe work and wellheads necessary.

The low temperature of CO_2 during injection is the root of the equipment risk, geological risk and safety risks. Thus it is important to understand the temperature characteristics of carbon dioxide during injection period and the propagation of its effect.

Jimenez and Chalaturnyk (2002) had stressed on the integrity of wellbore for CO_2 injection. Wellbore is the access between the surface and the storage and is the most preferable path for leakage outside the reservoir. The integrity of a wellbore system is affected by geomechanical, geochemical and hydrogeological processes that also influence the integrity of caprock.

2.4 WORLD CO_2 PILOT

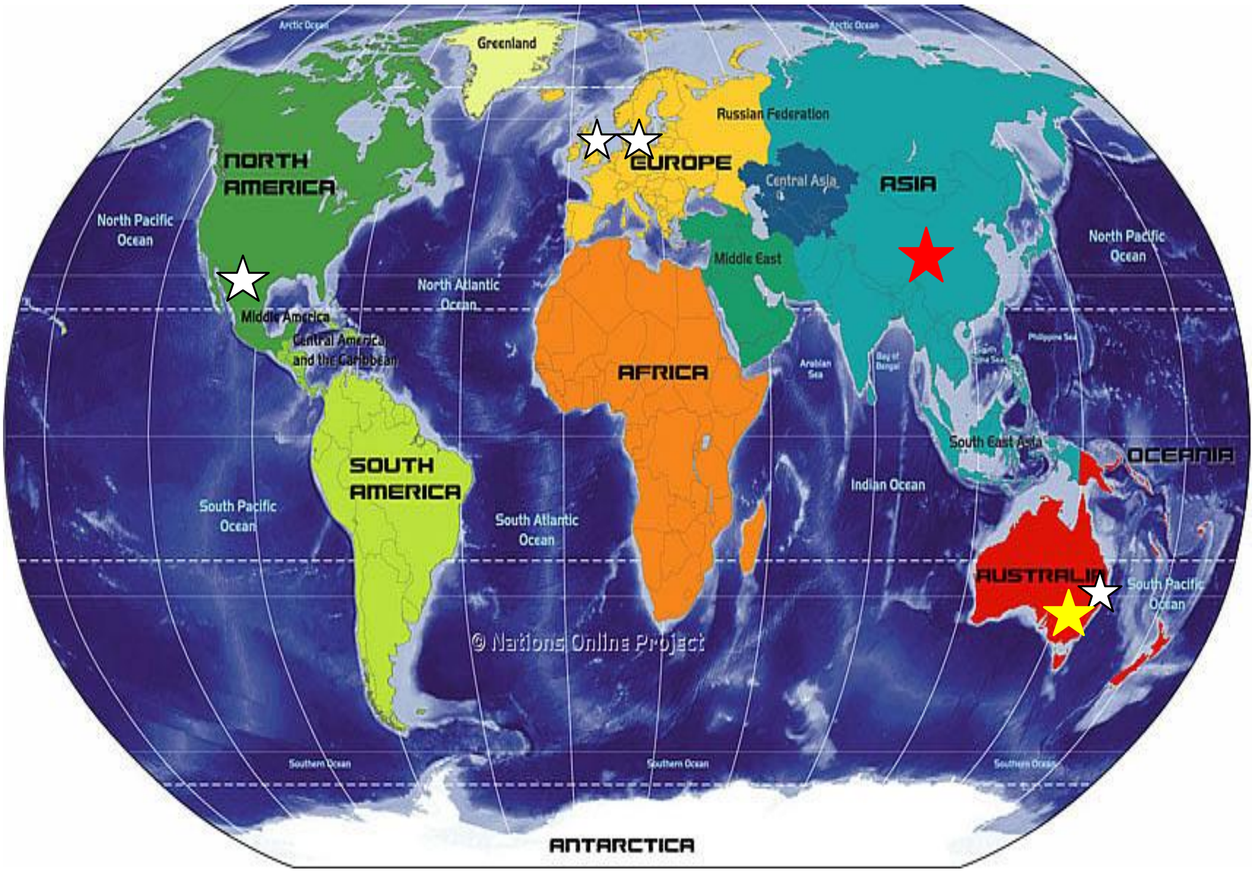

Figure 2.1 World Pilot CO_2 Project

In over 20 countries and 4 continents major research and demonstration efforts had begun.

Country	Company/ Entity	Project name	Date of run	Tons/y or tons total
Norway	Statoil	Sleipner (Largest aquifer storage)	Oct 1996 to present	1M (~12M)
Canada	EnCana and PTRC	Weyburn	2000 to present	1.2 M (10M)
Algeria	BP, Statoil, Sonatrach	In Salah	2004 to present	1.2M (6M)

Table 2.1 Large Active CCS Projects

Apart from the places listed above, there are more upcoming projects for both commercial and research purposes (Friedmann and Lawrence, 2009).Carbon injection projects are not merely limited for carbon storage; it also has a more alluring economic value in enhanced oil recovery (EOR) projects.

2.5 CO_2 CHARACTERISTICS

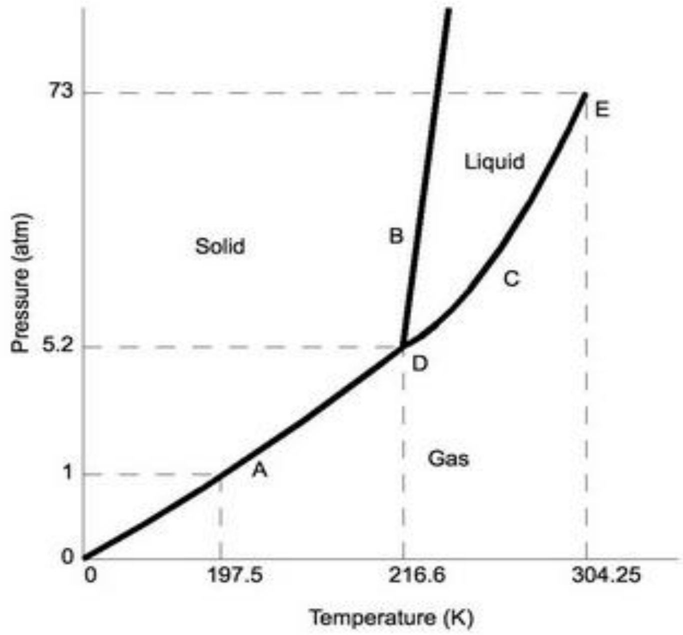

Figure 2.2 CO_2 Phase Diagram

CO_2 is a colourless and odourless gas. At ambient temperature and atmospheric pressure, it is slightly heavier than air. But above its critical temperature and pressure (31^{o}C and 74 bar), it has a similar property to a liquid which can be pumped and injected. (Scharf and Clemens, 2006) Uniquely, at the supercritical condition CO_2 also has characteristic of gas.

Scharf and Clemens (2006) had also listed characteristic of CO_2 in the underground:

- Has low ability to displace formation water. After injection, it rises to the top quickly and spreads out laterally in viscous fingers or channels.
- Dissolves faster but also less in water compared to oil.
- On average, 50kg of CO_2 can be dissolved in 1m^3 water under typical subsurface conditions.

- May react with rock minerals, depending on the mineralogy and rock texture, formation water composition, reservoir temperature and pressure, flow rates and timing of the reaction.

2.6 STORAGE

Quoted from Freund (2006); “For a geological formation to be suitable for storing CO_2, it must have sufficiently high permeability to permit injection with adequate capacity to warrant use for storage and a boundary (upper) seal that can contain the CO_2 for a very long time.”

There are 3 formations which are used to geologically store captured carbon dioxide; depleted oil and gas reservoirs, saline aquifers and unmineable coal bed seams. CO_2 is injected in the supercritical form into these formations. (Zahid et al, 2011)

2.6.1 DEPLETED OIL AND GAS RESERVOIR

Carbon are injected into certain formations such as depleted oil and gas reservoir, saline aquifers, enhanced oil recovery purposes and coal bed methane. (Zahid et al, 2010). Each formation and purposes of injection has both pros and cons.

Injection into depleted oil and gas reservoir is advantageous due to the high global capacity. The capacity can reach 140Gt and 40Gt for disused gas and oil fields respectively. The characteristics of the reservoirs are well known and familiar. Existing infrastructures of wells and pipeline can be used. (Zahid et al, 2010).This can save capital expenditure. It is undeniable that oil and gas reservoirs are proven containment over the geologic time (Zahid et al, 2010).

The challenges wait for injecting into oil and gas reservoirs are safety factors. It is a concern of leaking wells or improperly abandoned wells. Next, there are very few reservoirs in the world that are depleted.

A project example of injection into depleted oil and gas reservoir is C2O2 Otway Project in Australia. (Paterson et al, 2010)

In Malaysia, M4 carbonate field located offshore Sarawak has been identified as potential candidate for CO_2 injection site. The field has undergone a feasibility study to evaluate potential geological risk associated with CO_2 injection. (Mohd et al, 2012)

2.6.2 SALINE AQUIFER

Saline aquifer is the best potential CO_2 storage with 1000-10000Gt storage. The stored CO_2 is expected to be isolated from the near surfaces for thousands of years. The widespread presences of saline aquifer all over the world are an advantage. Safety concern is eliminated when it comes to offshore aquifers. (Zahid et al, 2010)

Deep aquifers contain fossil, high salinity connate water that is not fit for industrial and agricultural use or for human consumptions. Such aquifers are already used for the injection of hazardous and non hazardous liquid waste. The high pressures encountered in deep aquifers indicate they can withstand CO_2 injection. (Basbug et al, 2007)

Altundas et al (2010) had stated that saline aquifer sequestration has no tangible benefit but by far, it has the advantage of having the largest storage potential. Thibeau et al (2007) had earlier on support the motion of saline aquifer as potential and promising option for worldwide CO_2 storage capacity.

There is lack of characterization experience for saline aquifers. In addition, the absence of financial incentive is not encouraging more of saline aquifer injection.

However, there are a number of projects ongoing. For example, InSalah Project in Algeria; Sleipner in Norway; Gorgon in Australia; Ketzin in Germany and US DOE Regional Parties hip Program Projects.

2.6.3 ENHANCED OIL RECOVERY

It is economically attractive, produces additional oil. This made feasible because CO_2 injections are commercially done nowadays. Any undue risk will not involve humans and the environment.

The weaknesses in injecting CO_2 for enhanced oil recovery (EOR) are cheaper CO_2 can be obtained naturally, global storage capacity may be limited and for today's blowdown reservoir operations need to store CO_2 under pressure.

Other than as EOR method, CO_2 is injected into a gas field to maintain pressure in field. Subsequently it will help to increase and/or maintain gas production. (Freund, 2006)

It is estimated more than 80% of the oil reservoirs worldwide will be suitable for CO_2 injection based on oil-recovery criteria alone.CO_2 injection projects have focused on oil with densities between 29 and 48 ^{o} API (855 to 711 kg/m^3) and reservoir depths from 760 to 3700m. (Scharf and Clemens, 2006)

Bachu and Stewart (2002) argument added that, the total amount of CO_2 that be sequestered ultimately in EOR operations is very small compared with CO_2 sources.

Carpenter (2012) believed that EOR is the early entrant into CCS projects. EOR provides an opportunity to address both climate and energy security.

Ongoing projects are in Weyburn, Wasson and Salt Creek in North America.

2.6.4 COAL BED STORAGE

By injecting CO_2 into coal bed, it will produce methane, CH_4; making it economically attractive. Currently, there is identified coal deposit present worldwide.

However, unmineable coal seams are likely to be hundreds of meter deep, hence less permeability and this limited the capacity of CO_2 stored.

Other than that, the coal seams must be recognized as being unmineable, otherwise the stored CO_2 might release by subsequent mining, thereby negating the purpose of the original injection. The CO_2 is absorbed into the coal matrix to displace methane, providing a good by product. (Freund, 2006)

Qinshui Basin in China is an ongoing project to get methane from unmineable coal seams by carbon injection.

2.7 TRAPPING MECHANISMS

In CO_2 sequestration literatures, there are four trapping mechanisms identified. They are; solubility trapping, residual trapping, structural trapping and mineralization.

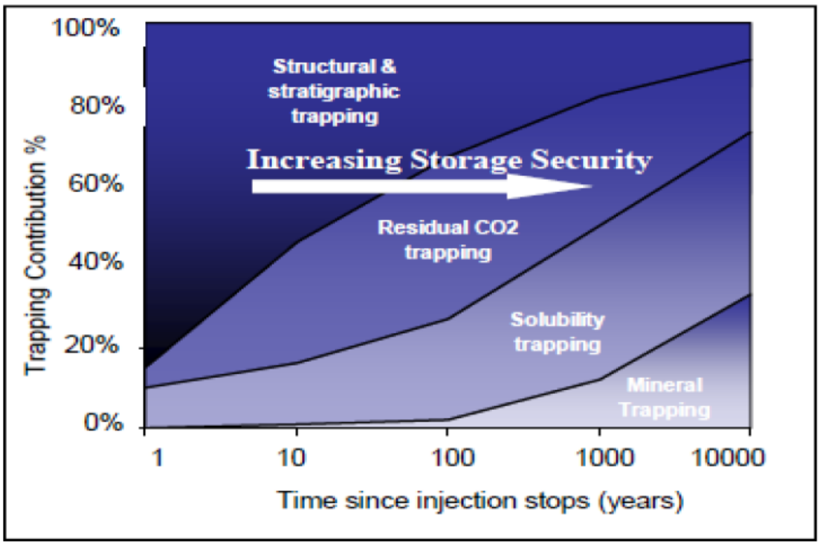

Figure 2.3 Trapping Mechanisms Containment through Time

Trapping mechanisms in saline aquifer takes time to secure the storage of CO_2. The immediate effect of trapping is by structural trapping, followed by residual trapping, solubility trapping and finally the mineral trapping.

2.7.1 SOLUBILITY TRAPPING

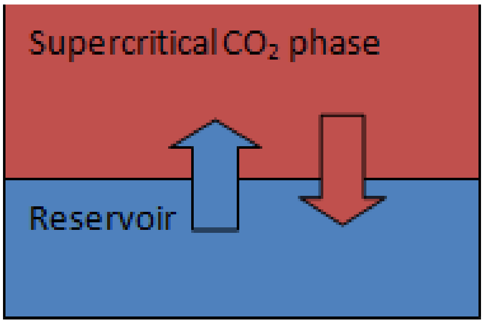

Figure 2.4 Solubility Trapping Mechanism

In solubility trapping, CO_2 is trapped in brine, which is essentially the impetus for CO_2 storage in a saline aquifer. (Tran et al, 2010).Hangx (2009) described solubility trapping occur when CO_2 is stored as a dissolved phase in reservoir pore fluid.

2.7.2 RESIDUAL TRAPPING

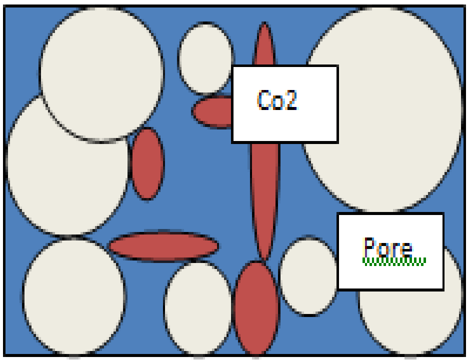

Figure 2.5 Residual Trapping Mechanisms

Residual trapping takes place through capillary effects and is important to keep the CO_2 gas immobile and away from caprock. (Tran et al, 2010) It is in the form of supercritical bubble filling the pore space of the formation. This is due to capillary effect. (Hangx, 2009)

2.7.3 MINERALIZATION

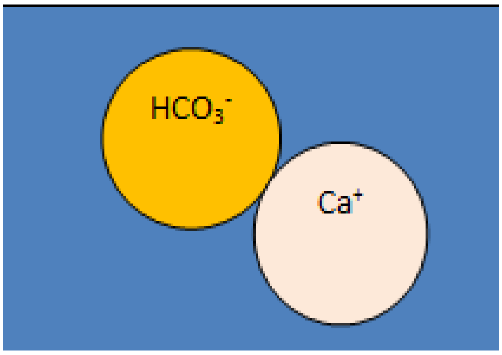

Figure 2.6 Mineralization Trapping Mechanism

Mineralization process is a process whereby the CO_2 that is injected into a geological formation dissolves into the formation water, reacts with the in situ minerals and ions, ad precipitates as carbonate minerals. Basic processes are CO_2 dissolution into the formation water, CO_2 speciation into HCO_3^- and H^+ (the latter acidizes water) and mineralization. CO_2 mineralization is the result of chemical reactions between HCO_3^- and the other ions, which precipitate new carbonate mineral. (Thibeau et al, 2007)

2.7.4 STRUCTURAL TRAPPING

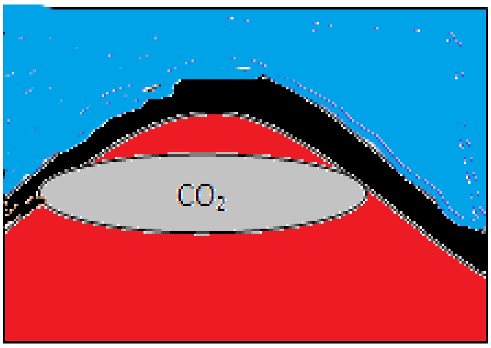

Figure 2.7 Structural Trapping Mechanism

Structural trapping involves the storage of CO_2 gas in a geological structure in the form of free gas or supercritical fluid. (Tran et al, 2010)

2.8 GEOLOGICAL RISKS

Under most subsurface conditions of temperature and pressure, CO_2 is buoyant relative to groundwater. If (sub-) vertical pathways are available, CO_2 will tend to flow upward and, depending on geologic conditions, may eventually reach potable groundwater aquifers or even the land surface. Leakage of CO_2 may also occur along wellbores, including pre-existing and improperly abandoned wells, or wells drilled in connection with the CO_2 storage operations. Escape of CO_2 from a primary geological storage reservoir and potential hazards associated with its discharge at the land surface raise concerns of health, environment and efficiency of sequestration in the first place. (Karsten, 2008)

Hawkes et al (2005) also stressed that the key for successful long term storage of CO_2 is the hydraulic integrity of both the geological formations that bound it and the wellbores that penetrate it.

Therefore, geological risk at sequestration site must be identified to avoid unwanted results.

2.8.1 PRESSURE CHANGE IN FAULT PLANE

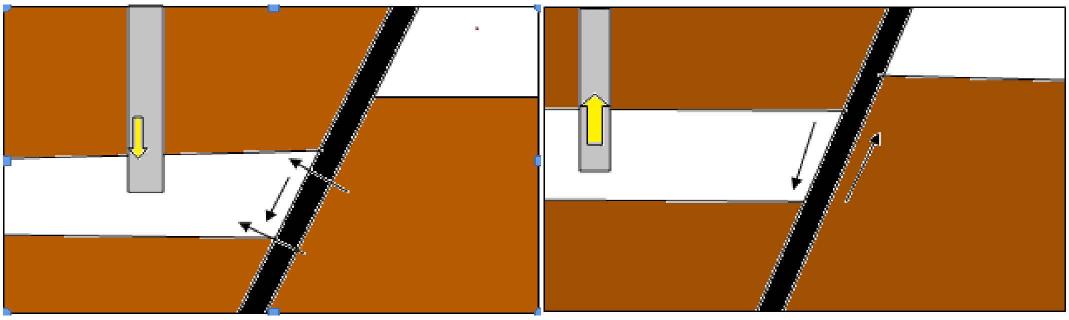

Figure 2.8 Fault Reactivation

Slip is induced when the maximum shear stress acting in the fault plane exceeds the shear strength of the fault. (Hawkes et al, 2005)

2.8.2 HYDRAULIC PRESSURE

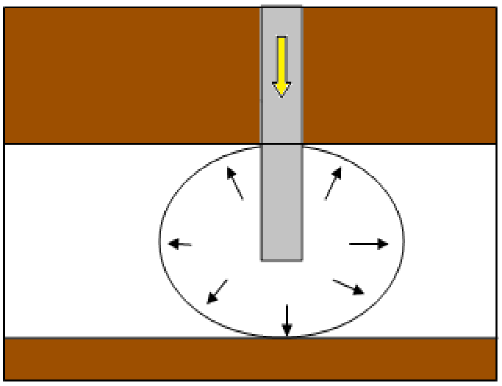

Figure 2.9 Mechanisms of Hydraulic Pressure

Injection of CO_2 has to be implemented at bottomhole pressure much lower than the breakdown pressure of the overlying caprock; failure to do so may end up fracturing the caprock that seals the formation in which the CO_2 has been injected. (Achanta et al, 2012)

Hydraulic fractures are induced by high injection pressure and low injection fluid temperatures. It is not a significant risk to the bounding seal integrity if the fractures are contained entirely in the reservoir. (Hawkes et al, 2005)

2.8.3 COMPRESSIONS AND OVERBURDEN

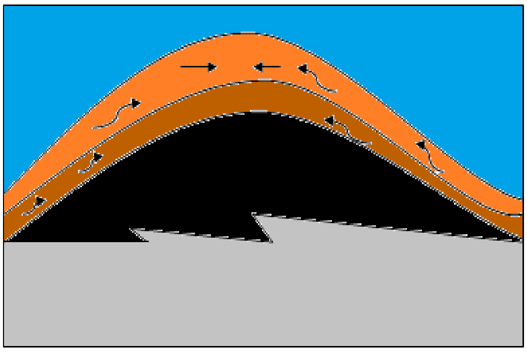

Figure 2.10 Compression Mechanisms

Changes in pore pressure will induce either expansion or contraction in the reservoir. As the volume changes, it can induce displacements in a significant proportion of the rock mass overlying the reservoir. If it is downwards, it will show overburden reaction. If it is upwards, it will show compression reaction. Compression reaction is the ideal situation to be made as assumption during analysis. Compression and/or overburden will later on lead to induced shear failure especially in an anticlinal or domed reservoir. (Hawkes et al, 2005)

CHAPTER 3

METHODOLOGIES

3.1 OBJECTIVES WITH ASSOCIATED METHODOLOGIES

In order to find solutions to the set of objectives listed in, a set of methodologies are outlines in table 3.1 to achieve these objectives.

Objectives	Methodologies
1) Analyze temperature characteristics along borehole.	Identify mathematical model suitable to analyze temperature. Using Microsoft Excel to simulate the characteristic.
2) Examine the effect of temperature on breakdown pressure.	Numerical model to analyze effect of thermal stress on breakdown pressure.
3) Identify pressure of CO_2 along borehole.	Using Span and Wagner's (1994) PVT equation.
4) Suggest safe injection rate	Identify breakdown pressure and CO_2 pressure along borehole.

Table 3.1 Objectives with Associated Methodologies

3.2 TEMPERATURE MODEL

Firstly, the equation to determine the temperature of CO_2 along the borehole is searched.

Luo and Bryant (2010) derived the equation:

$$T(z) = \left(T_{wh} - T_O - \frac{g}{c_p}\frac{R}{2\beta} + \frac{GR}{2\beta}\right)e^{\frac{-2\beta z}{R}} + \frac{g}{c_p}\frac{R}{2\beta} - \frac{GR}{2\beta} + T_O + Gz \quad \text{... Eq. 1}$$

Whereby, T_{wh} is wellhead temperature and T_o is the surrounding temperature. R is the well radius; G is the geothermal gradient and z, depth.

The equation describes the temperature of CO_2 along the wellbore when there is non-zero heat transfer.

$$\beta = \frac{UA}{c_P \dot{m}} \ \ldots \quad \text{Eq. 2}$$

The β is a ratio of heat from the borehole over heat from the CO_2 injection. From the equation, it is observed that the injection rate of CO_2, $\dot{m}$ influences the heat transfer ratio. The higher the injection rate, the lower is the heat transfer ratio.

Not to forget, temperature of surrounding also varies at different depth.

$$T\ surrounding = T_O + Gz \ \ldots \qquad \text{Eq. 3}$$

3.3 BREAKDOWN PRESSURE MATHEMATICAL MODEL

For fracture initiation to begin,

$$P_b = 3S_{hmin} - S_{Hmax} - P_p - \Delta\sigma^T \quad \ldots \qquad \text{Eq. 4}$$

The definition of thermo-elastic stress is:

$$\Delta\sigma^T = \frac{\alpha_T E \Delta T}{1-v} \ \ldots \qquad \text{Eq. 5}$$

From the definition, it is observed that the temperature difference between surrounding and CO_2 are the only operating function of thermo-elastic stress.

From **Eq. 4**,

$$\Delta T = Tsurr - T_{CO2} \ldots \text{Eq. 6}$$

It shows that for the wellbore to experience thermo-elastic effect and lower breakdown pressure, the surrounding temperature must be greater than the injected CO_2 fluid.

3.4 PRESSURE OF CO_2 ALONG WELLBORE

Using equation:

$$H = C_p(T_{surr} - T_{CO2}) \dots \qquad \text{Eq. 7}$$

Pressure of CO_2 is a property that depends on temperature and enthalpy of CO_2. Thus, identifying the phase of CO_2 at a particular temperature is crucial. Since temperature along borehole is already identified, it will be more convenient to identify the enthalpy change along the borehole.

Luo and Bryant (2010) had stated that the heat capacity of CO_2 along wellbore does not change drastically. It is assumed that the heat capacity to be at constant at the mean value of 2500J/kg.K.

Using Span and Wagner's PVT(1994), the range of pressure of CO_2 along wellbore can be identified.

3.5 VALUES USED FOR CALCULATION

For this project, values are selected to observe two situation of CO_2 injection. For the first case, the CO_2 temperature is lower than the surrounding temperature. For the second case, the temperature of CO_2 is higher than the surrounding temperature.

The values used are as followed:

No.	Properties	Value	Unit
1.	CO_2 Temperature	15 & 30	^oC
2.	Surrounding Temperature	20	^oC
3.	Geothermal Gradient	0.03	$^oC/m$
4.	Injection Rate 1	2,000	kg/day
5.	Injection Rate 2	20,000	kg/day
6.	Injection Rate 3	200,000	kg/day
7.	Thermo-elasticity Coefficient, α_T	$1.5x10^{-5}$	K^{-1}
8.	Heat transfer Coefficient, U	20	$W/m^2.K$
9.	Wellbore Radius, r	0.1	M
10.	CO_2 Heat Capacity, C_p	2500	J/kg.K

Table 3.2 Properties Values

3.6 GANTT CHART

To ensure aptness in completing this project, a schedule in form of Gantt Chart is prepared. The Gantt Chart spreads throughout the two semesters of conducting Final Year Project.

No	Detail week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	Selecting FYP Topic														
2.	Preliminary research work														
	Re-enact previous works results														
	Identify problems and extension of scope of study														
	Literature review write up														
3.	Proposal defense														
4.	Project work continues														
5.	Submission of interim draft														
6.	Submission of interim report														

Table 3.3 FYP1 Gantt Chart

No	Detail week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1.	Project work continues															
2.	Submission of Progress Report															
3.	Project work continues															
4.	Pre-SEDEX															
5.	Submission of															

	Draft Report															
6.	Submission of dissertation (Soft bound)															
7.	Submission of Technical Paper															
8.	Oral Presentation															
9.	Submission of Project Dissertation (Hard bound)															

Table 3.4 FYP2 Gantt Chart

3.7 KEY MILESTONE

The key milestone is a way to keep track, goals and achieve project objectives throughout the 29 weeks of project.

Time	Activity
January,2012	Selection of FYP Title
February,2012	Simulating temperature model
March,2012	Proposal defense
June,2012	Simulating breakdown pressure
July, 2012	Simulating pressure of CO_2 along wellbore
August,2012	SEDEX, VIVA, Technical Report, Softbound Dissertation
September,2012	Hardbound Dissertation

Table 3.5 Key Milestones

CHAPTER 4

RESULTS AND DISCUSSION

4.1 TEMPERATURE DISTRIBUTION ALONG WELLBORE

When CO_2 is injected into relatively warmer surroundings, heat transfer occurs from the wellbore surroundings to the CO_2. This obeys the second rule of thermodynamic which describes the direction of heat transfer flow. The temperature characteristic is observed in Figure 4.1 below.

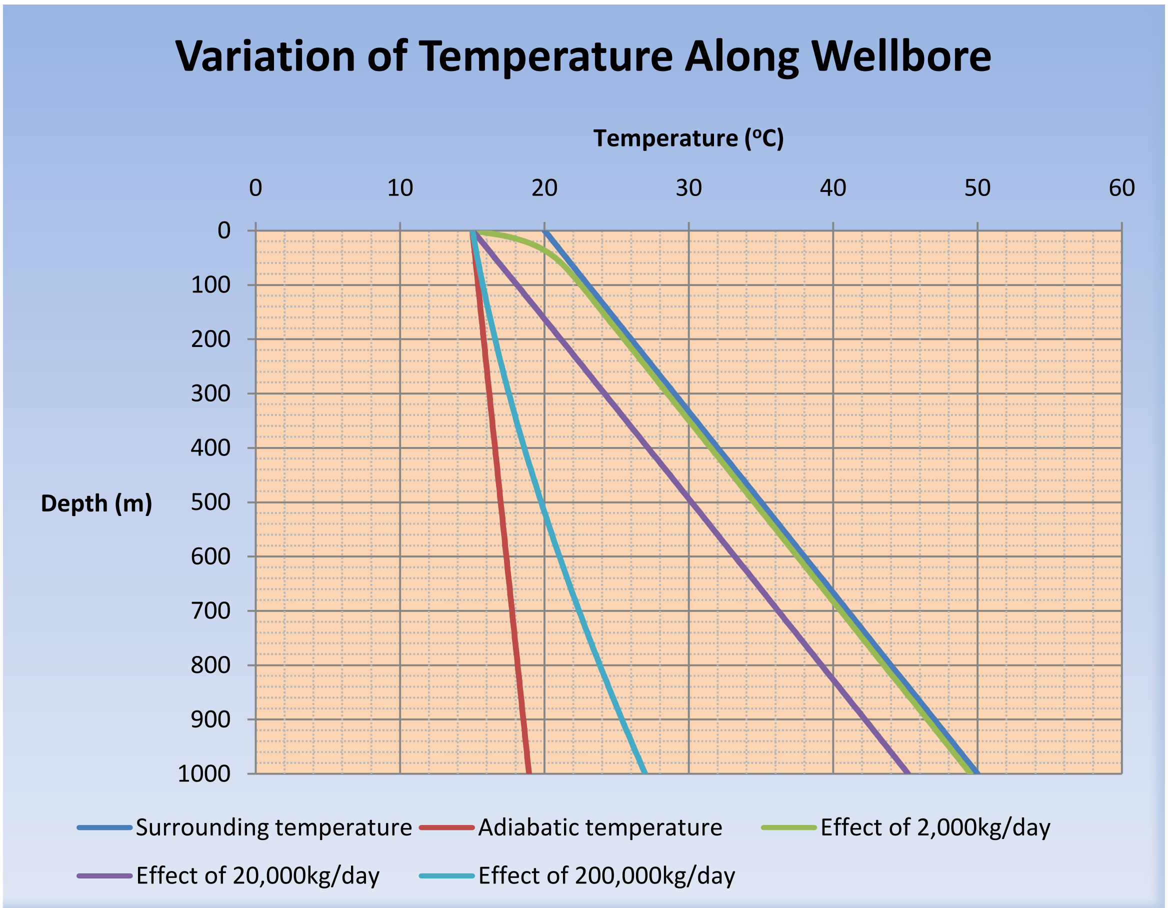

Figure 4.1 Variation of Temperature when 15^{o}C CO_2 is injected into Surrounding of 20^{o}C.

At 2,000kg/day, the heat transfer rate is higher than the injection rate of 20,000kg/day and 200,000kg/day. When the heat transfer rate is higher, the temperature of CO_2 will be closer to the temperature of surrounding. Thus, the temperature difference between surrounding and CO_2 will be less prominent.

As rate of injection increases to 20,000kg/day, the heat transfer rate decreases. The CO_2 temperature line slowly goes parallel with surrounding temperature but it does not reach surrounding temperature. At one point, the CO_2 temperature and surrounding temperature difference will be at constant.

For injection rate at 200,000kg/day, the heat transfer rate decreases. CO_2 temperature line does not get parallel with the surrounding temperature; instead it approaches towards adiabatic temperature.

In another case of CO_2 injected is warmer than the surrounding temperature, the temperature distribution is observed to be different.

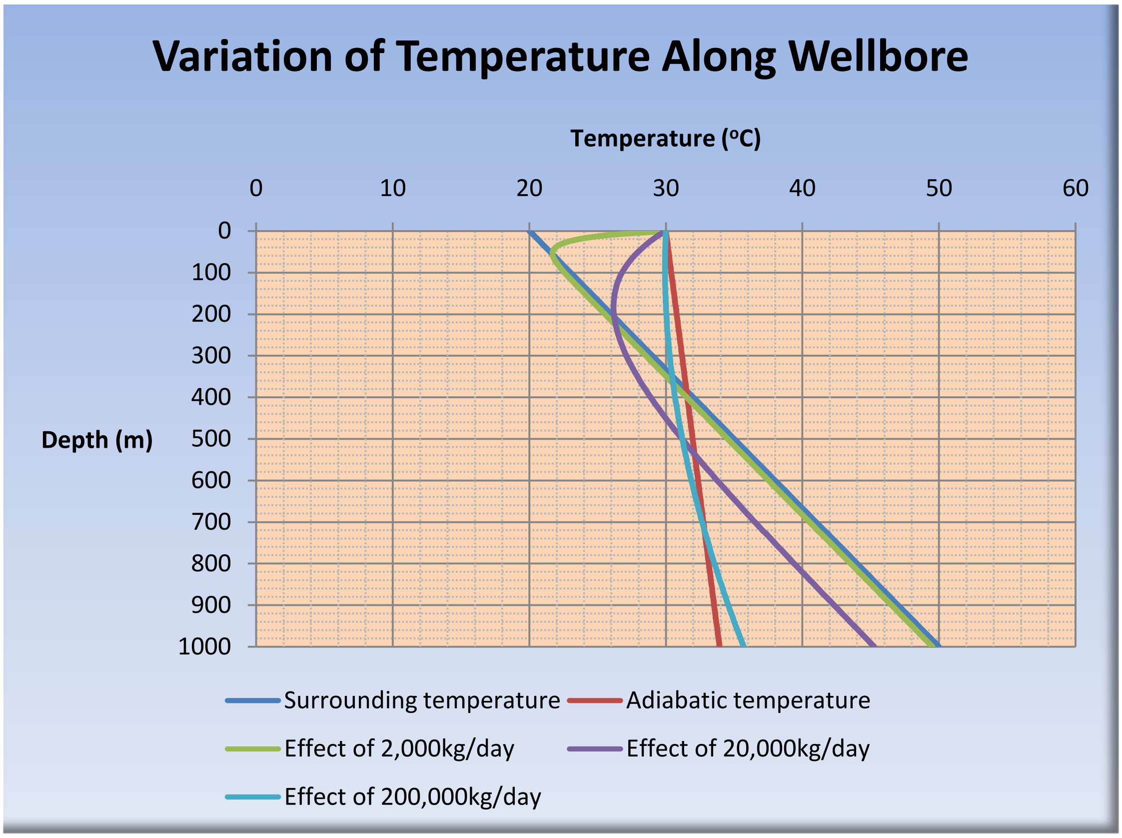

Figure 4.2 Variation of Temperature when 30°C CO_2 is injected into Surrounding of 20°C

For injection rate of 2,000kg/day, the temperature decreases steeply in the depth of 100m. After that, it is observed that the temperature of CO_2 parallel with surrounding temperature but with small temperature difference.

At 20,000kg/day, the temperature of CO_2 is equal to the temperature of surrounding at the depth of 200m. However, it increases temperature after passing through same temperature with CO_2 after 200m. The temperature of CO_2 formed a parallel line with surrounding temperature with a bigger temperature difference.

The CO_2 temperature distribution along borehole for injection rate at 200,000kg/day displays a trend of not having any similarity with the surrounding temperature trend line. Instead, it is almost similar to adiabatic temperature distribution. As CO_2 travels along the borehole, it is observed that not much changes for the CO_2 temperature. It slightly increases along the borehole. This creates a big temperature difference between CO_2 and the surrounding.

4.2 BREAKDOWN PRESSURE ALONG BOREHOLE

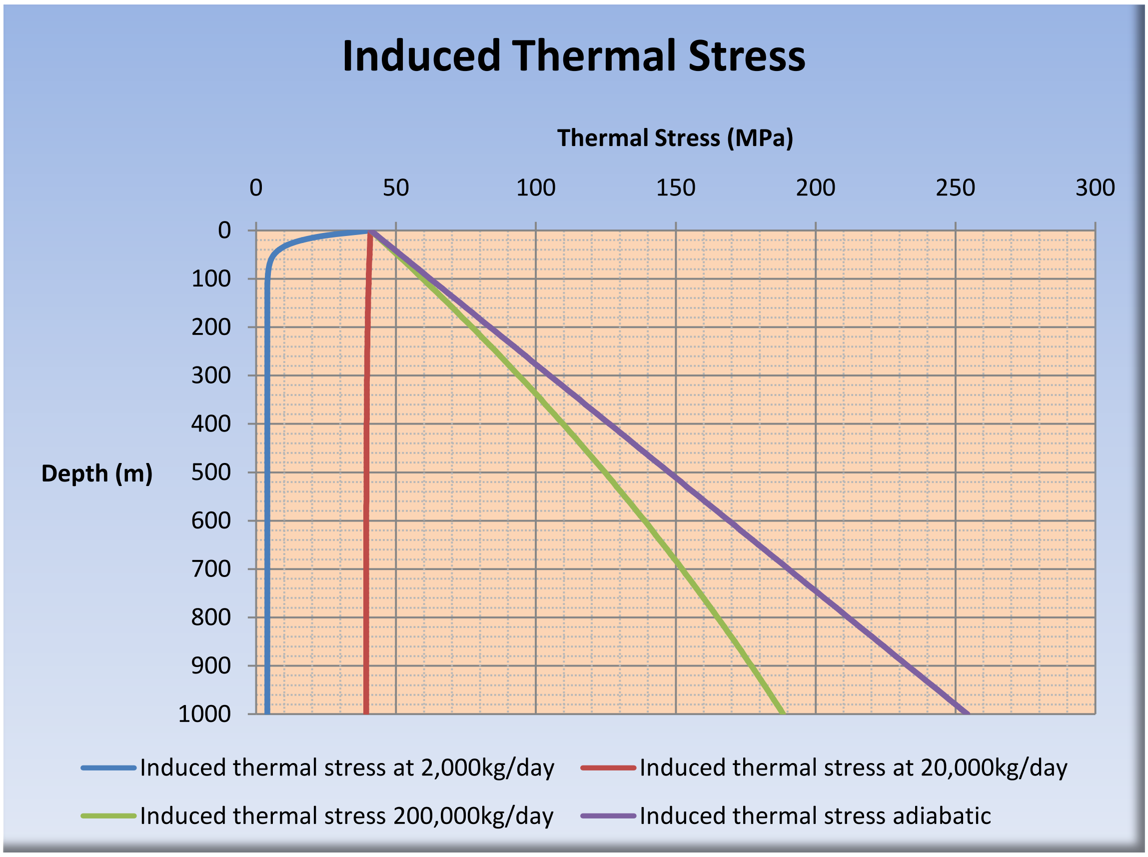

Figure 4.3 Induced Thermal Stress When CO_2 is 15^oC

Induced thermal stress depends on the temperature difference between surrounding and CO_2. The bigger the difference is, the higher the induced thermal stress is. Hence, it is observed that the biggest induced thermal stress is by 20,000kg/day rate. It approaches the adiabatic induced thermal stress.

The temperature difference of 20,000kg/day rate is almost constant along borehole. Thus, the induced thermal stress is constant along the borehole too.

For 2,000kg/day, the temperature difference is drastic at the first 100m depth of the well due to the high rate of heat exchange. Once equilibrium of heat was achieved, the temperature difference began to be constant along the borehole making the induced thermal stress constant.

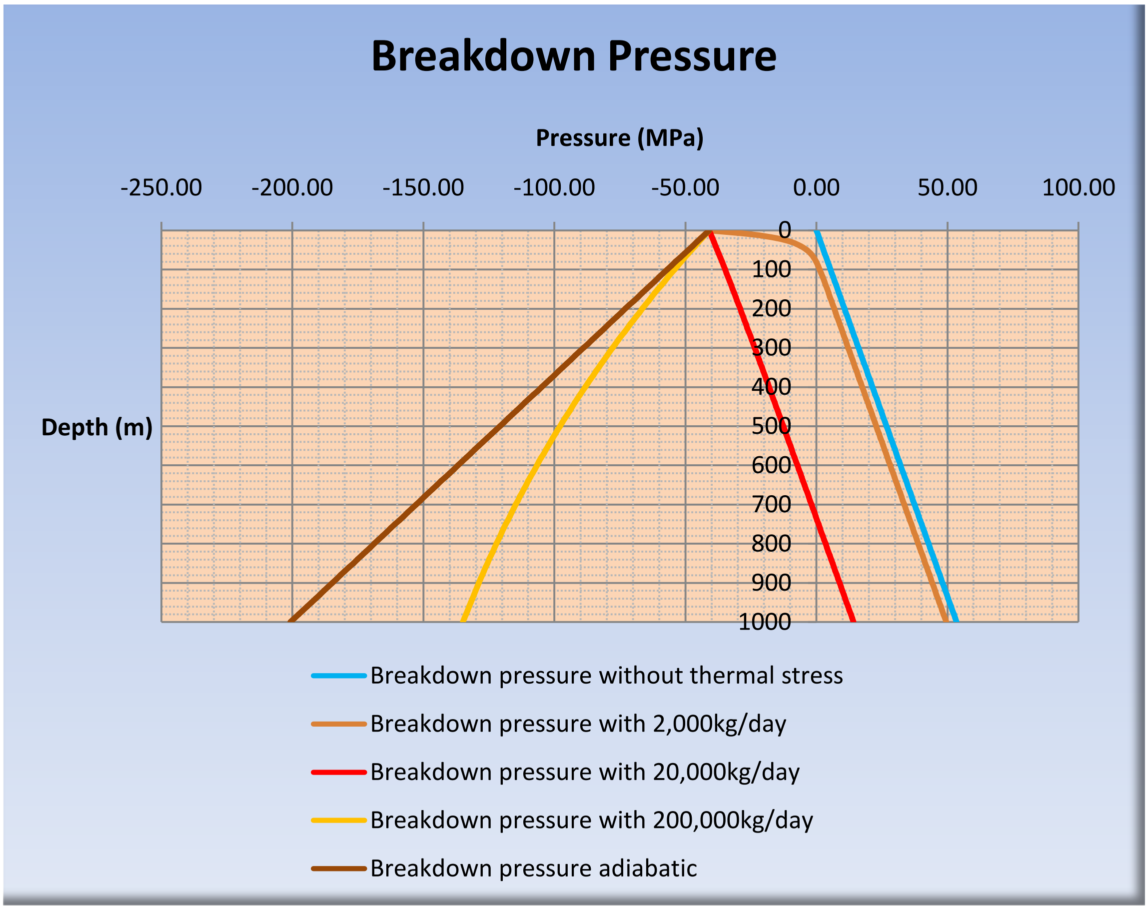

Figure 4.4 Breakdown Pressure when CO_2 is 15^{o}C

As induced thermal stress increases, the breakdown pressure along the wellbore decreases. A decreasing breakdown pressure will require less applied force to cause damage to the wellbore.

For adiabatic injection and injection at 200,00kg/day, the breakdown pressure is in the negative area. For geomechanics, a negative value represents a tension stress (unlike conventional negative stress value which represents compression stress).

Injection rate at 20,000kg/day is in the tension stress state at the length (from top) 700m of the borehole.

As for injection rate of 2,000kg, the formation in tension stress state before it reaches 100m depth.

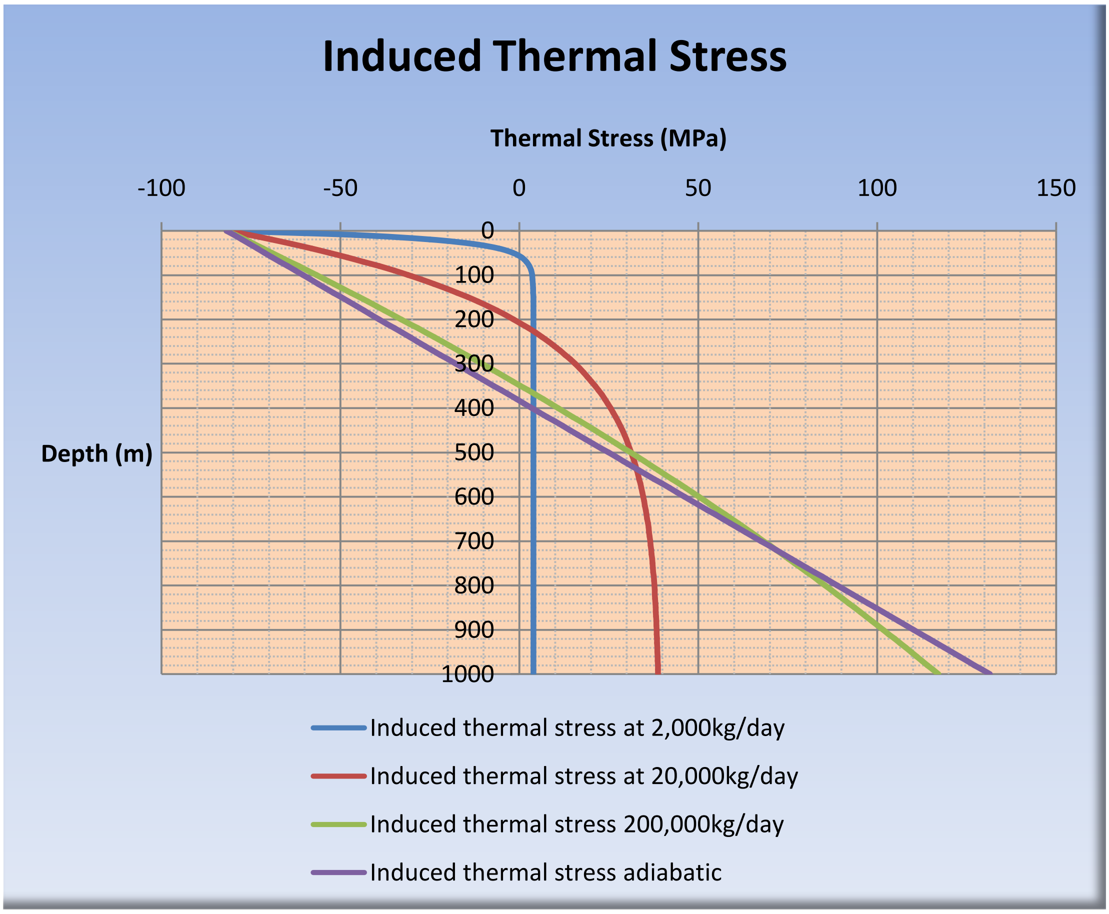

Figure 4.5 Induced Thermal Stress when CO_2 is 30^{o}C

The induced thermal stress is in the negative region for injection rate of 2,000kg/day at the few meters depth (before it reaches 100m). The negative value in induced thermal stress is due to the direction heat transfer. The heat transfers from the CO_2 to the surrounding. It reaches the positive region and continues to increase until it reaches the constant value of thermal stress along the wellbore.

Just like injection rate of 2,000kg/day, the injection rate at 20,000kg/day displays value in negative region. It also means that the direction of heat transfer is from CO_2 to the surrounding. At negative value of induced thermal stress will produce an increment in critical pressure for fracture initiation. At the depth of 200m, the induced stress gets into the positive induced stress region, whereby it will result into a decrease in the critical pressure for fracture initiation.

Again at injection rate of 200,000kg/day, it displays an almost similar trend line just like adiabatic injection. At the injection rate of 200,000kg/day, the induced thermal stress is in positive region until the depth of 350m. At the depth of 700m-800m, the induced thermal stress of 200,000kg/day injection rate is lower than of the adiabatic thermal stress.

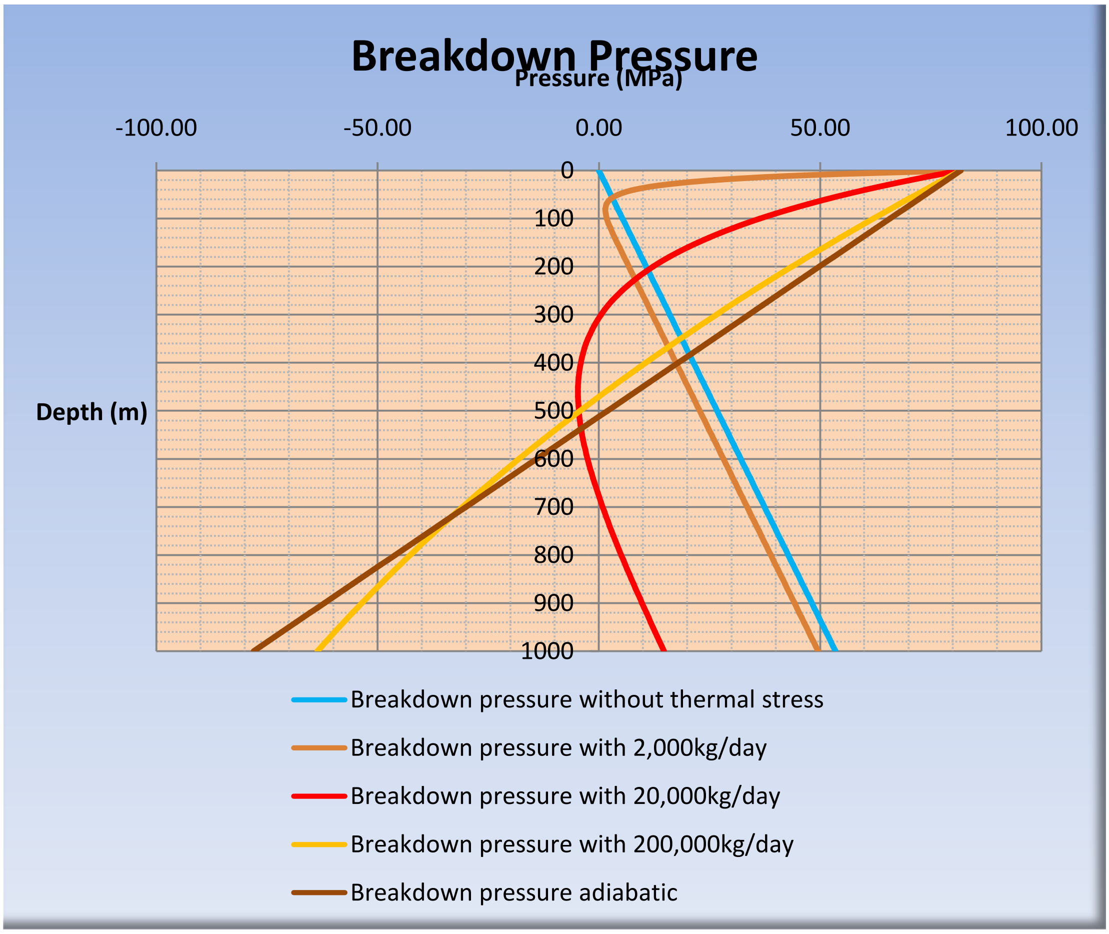

Figure 4.6 Breakdown Pressure when CO_2 is 30^{o}C

Breakdown pressure at 2,000kg/day is seen to be greater than breakdown pressure without thermal stress. It is at 80MPa instead of at 0MPa at the wellhead. It is indicated in the graph that the breakdown pressure continues to decrease at the top of

100m. And it decreases until is lower than the breakdown pressure before injection. It displays a trend line that is parallel to the original breakdown pressure but with a pressure difference.

Similar to 2,000kg/day; at 20,000kg/day, the breakdown pressure begins at the top with 80MPa and continues to decrease. But it the breakdown pressure only shows lower value than original breakdown pressure at the depth of 200m. From here it continues to decrease until the negative (tensile) region at the depth of 300m-700m. It became a compressive stress afterwards and continues to increase as it goes deeper. However, the breakdown pressure is still lower than the original breakdown pressure.

Injection rate at 200,000kg/day displays an almost similar trend to the adiabatic rate. The breakdown pressure at 200,000kg/day is lower than the original breakdown pressure at the depth of 350m and continues to decrease along the wellbore. The formation became to show tensile stress at the depth of 470m. It continues to be in tensile stress with greater magnitude along the borehole.

4.3 PRESSURE OF CO_2 ALONG WELLBORE

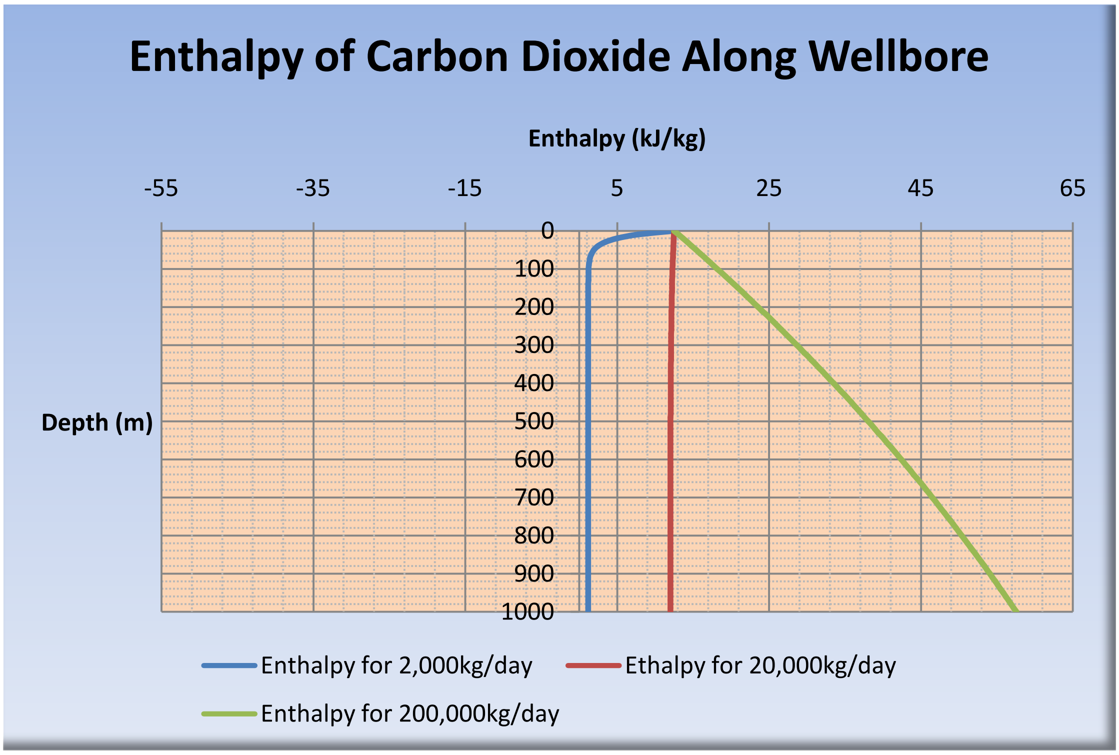

Figure 4.7 Enthalpy when CO_2 is 15^oC

At the rate of 2,000kg/day, the enthalpy of CO_2 as it is injected into warm surrounding is a positive value. A positive enthalpy indicates heat gain from the surrounding to the CO_2. At the depth of 100m, the enthalpy rate begins to be constant along the wellbore.

When CO_2 is injected into warm surrounding at the rate of 20,000kg/day, the enthalpy is found to be almost constant along the wellbore from the top until the bottom.

As for the rate at 200,000kg/day, the CO_2 is observed to display an increasing value of enthalpy along the wellbore. This is due to the increasing temperature difference of surrounding and CO_2 along the wellbore.

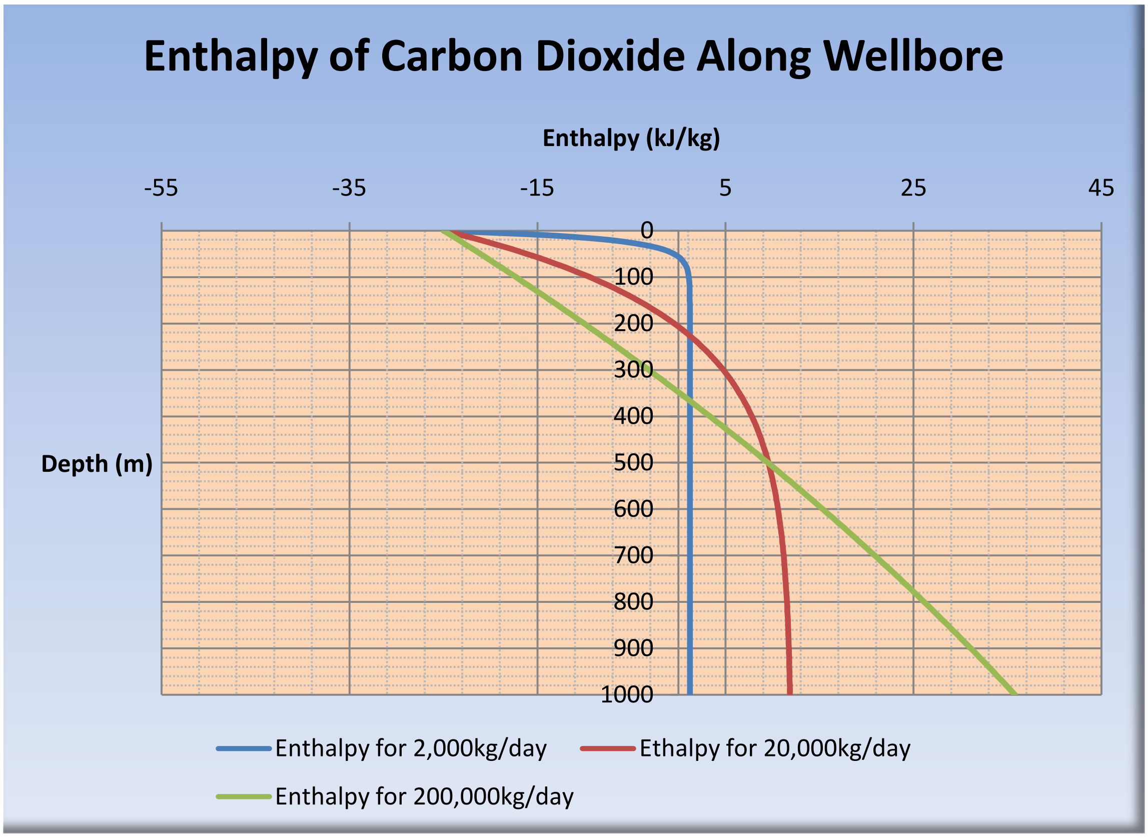

Figure 4.8 Enthalpy when CO_2 is $30^{o}C$

All three injection rate displays a negative enthalpy at the top of the wellbore. It indicates heat loss to surrounding.

For 2,000kg/day, the enthalpy is at negative for the depth before 100m. It shows that along this depth, heat from CO_2 is transferred to the surroundings. The enthalpy became positive and is constant along the borehole, indicating that the heat of surrounding and CO_2 is at equilibrium state.

At the first 200m of the wellbore, injection rate 20,000kg/day is still dissipating heat to the surrounding. However unlike the earlier injection rate, it does not have a constant enthalpy value as it travels along the borehole. The enthalpy slowly increases along the borehole.

An almost linear line is observed for the enthalpy of injection rate at 200,000kg/day. At this rate, heat is dissipated until the depth of 350m, before it gain heat from the surrounding.

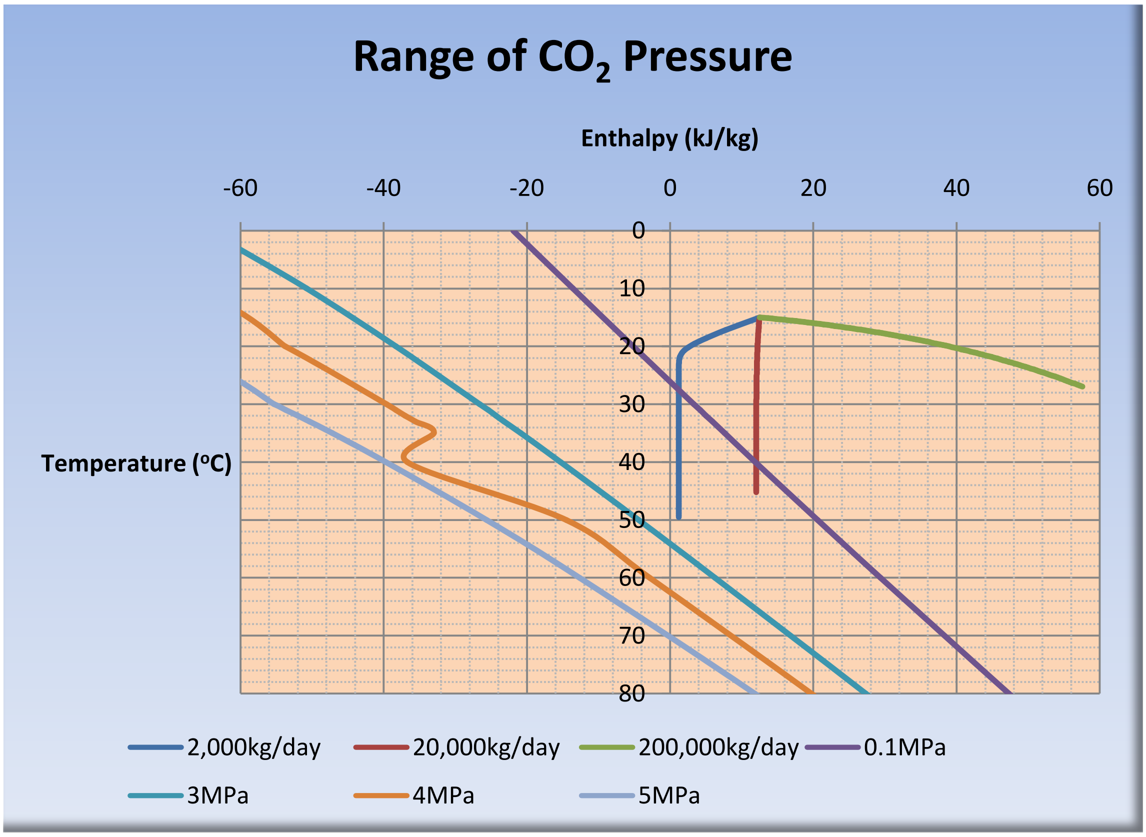

Figure 4.9 Range of CO_2 Pressure when CO_2 is $15^{o}C$

Range of CO_2 pressure depends on the enthalpy of CO_2 and temperature of CO_2 along wellbore. Although at certain interval of injection along the borehole, the temperature of CO_2 is constant the surrounding temperature keeps on increasing along the depth. Thus, there will be a change in enthalpy of CO_2.

Luo and Bryant (2010) had stated that the heat capacity of CO_2 along the wellbore is constant. Thus, the calculation of enthalpy is done with CO_2 mean heat capacity of 2,500 J/kg.K.

When temperature of CO_2 is lower than of surrounding, the pressure range of CO_2 at injection rate of 2,000kg/day is observed to be lower at 0.1 MPa and gradually increases to be more than 0.1MPa but less than 3MPa.

At 20,000kg/day, the pressure range is observed to be less than0.1MPa. It gradually increases towards 0.1MPa but does not deviate very much further from 0.1MPa range.

For 200,000kg/day, the pressure range of CO_2 is observed to be less than 0.1MPa. This might be due to the rate of heat transfer. Whereby, the higher the injection rate is, the smaller is the coefficient of heat transfer ratio. Thus, the temperature difference between surrounding and CO_2 is not a big gap. This will make the density of CO_2 along the borehole constant.

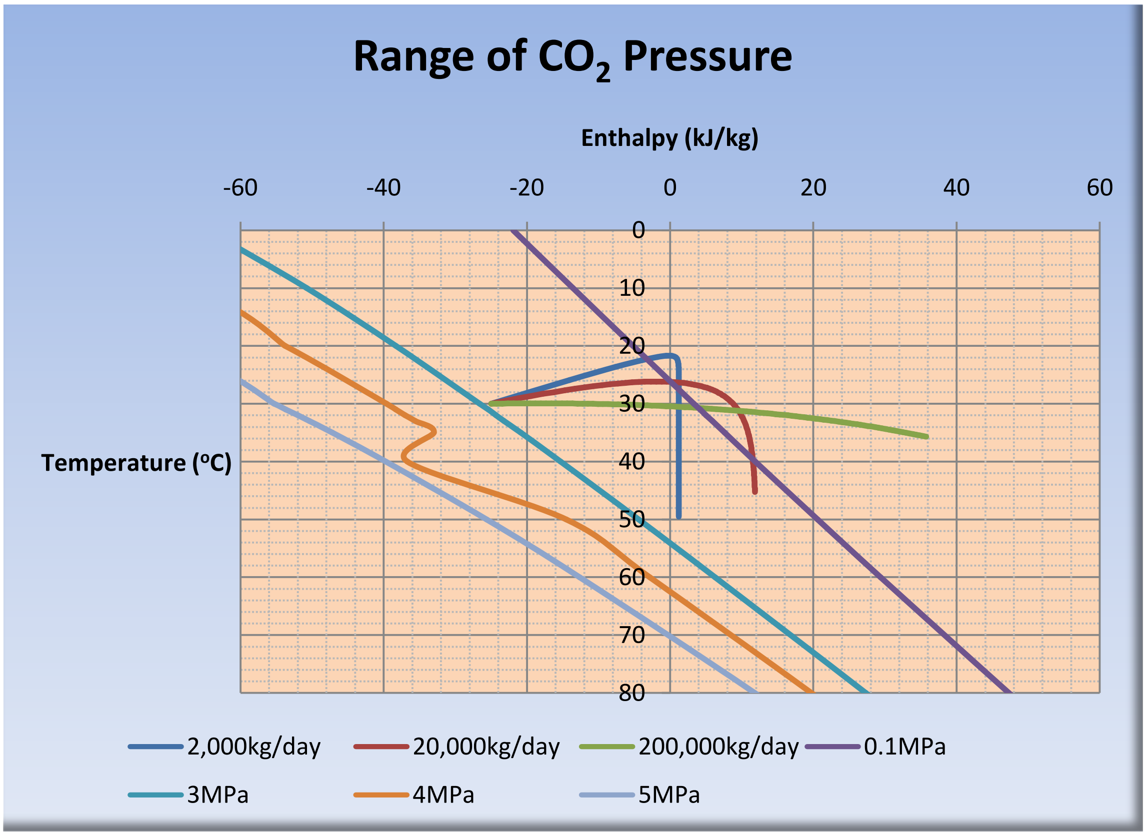

Figure 4.10 Range of CO_2 when CO_2 is 30^{o}C

When CO_2 is injected at a temperature that is higher than the surrounding, the pressure is higher at the wellhead. As it continues down the borehole, the pressure decreases.

At 2,000kg/day, the wellhead pressure is at 3MPa. It gradually decreases to the pressure of 0.1MPa. Along the wellbore, it continues to have a constant enthalpy but increasing temperature. After decreasing pressure, it will eventually increases in pressure.

When CO_2 is injected at the rate of 20,000kg/day, the pressure decreases from 3MPa and moves to 0.1MPa. Almost similar to the previous injection rate, the enthalpy rate will eventually be almost at constant rate but with increasing temperature, it will increase in pressure too.

During injection at the rate of 200,000kg/day, the pressure gradually decreases. The temperature is almost constant (for 200,000kg/day injection rate displays an almost adiabatic characteristic) but the enthalpy changes due to change in surrounding temperature.

4.4 SAFE INJECTION RATE

Injection must be done with CO_2 temperature higher than surrounding temperature to avoid breakdown of formation from the very top of the wellbore. Using warmer CO_2 will avoid breakdown at the top of wellbore. However, the ability to inject is limited to the amount of injection rate. For a deeper wellbore length, it is better to inject at higher rate.

These situations, supports the statement by Donatus (2011), quoted from Bachu (2005), "Cold sedimentary basin (low surface temperature and/or low geothermal gradient) are more favourable for the storage than hot sedimentary basin (high surface temperature and/or high geothermal gradients) because CO_2 attains higher density at shallower depths."

A safe injection rate will depend on the depth of the targeted reservoir or saline aquifer. The risk that must be taken into account of high injection rate is the pressure of CO_2 along the wellbore. As observed earlier on, the as injection rate increases, the pressure decreases. Paterson et al (2010) had stated due to transient effects, surface pressure can decouple from downhole pressure. Meaning that, the wellhead pressure can increase while the reservoir pressure decreases and vice versa due to the large density changes.

The earlier works by Luo and Bryant (2010) had suggested that density of CO_2 along wellbore to be constant along the wellbore (at the value of 800kg/m^3). However, this clashes with other literature that; Paterson (2010) and Donatus (2011); density changes due to transient temperature changes along wellbore. Thus, the other method to know the pressure of CO_2 along wellbore is to know the enthalpy and the temperature of CO_2 along the wellbore.

Hence, after knowing that the pressure of CO_2 decreases along wellbore, it is safe to say that CO_2 alone will not fracture the formation along the borehole. It will require extra forces like the injection pressure from the wellhead. It must be reminded that, as the wellbore gets deeper, it will require more amount of work to overcome the hydrostatic pressure along the borehole and pore pressure at the bottom of the wellbore (to ensure storage of CO_2). A deeper borehole will certainly increase the cost of injecting CO_2.

It is possible to inject CO_2 into storage with the rate of hundreds of ton given that the CO_2 is injected at a higher temperature than of surrounding. To avoid fracture along borehole, it is better to target a shallow reservoir. Thus, a safe injection rate will be depending on the depth of the storage.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 RELEVANCY TO THE OBJECTIVES

It can be concluded that the injection rate plays a key role in temperature characteristics. As the result, the effect of thermo-elastic stress due to temperature difference will influence the breakdown pressure along the wellbore. The temperature also plays an important role in determining the pressure/state of CO_2 along the borehole.

Temperature of CO_2 injection borehole depends on the rate of injection and surrounding temperature of the well. At temperature higher than surrounding, CO_2 does not display a decrease in breakdown pressure. Instead, the breakdown pressure only decreases at certain depth depending on the rate of injection. This can assist in selecting the right storage formation depth to avoid damages at the wellbore and the storage system too.

It is important to determine the pressure of CO_2 along wellbore to avoid the injection pressure to exceed the breakdown pressure of formation along wellbore. An increase in injection pressure is required when the injection is done in the range of hundred thousand kilogram/day is possible will require more injection pressure because of the decreasing pressure of CO_2 along wellbore. It is important to ensure that the pressure of CO_2 is higher than pore pressure to allow injection and storage. The objectives are achieved in this study.

The integrity of wellbore during CO_2 injection is important because wellbore is also a potential leakage point for CO_2. It is crucial because, to store CO_2 in saline aquifer and/or reservoirs, it has to travel along the wellbore. Failure of identifying the integrity of wellbore will affect the efficiency of carbon capture and storage. This could lead to questions of cost and risk public confidence of carbon capture and sequestration technology to mitigate global warming.

Key takeaway:

- CO_2 must be injected at temperature higher than surrounding temperature.
- CO_2 must be injected into cool basin/reservoir.
- A safe and economical injection rate depends on the depth of the reservoir/storage.

5.2 SUGGESTED FUTURE WORKS

The result of the study had only shown characteristics of breakdown pressure on an ideal isotropic area. Wellbore may have cut through many different environments as it is drilled through. There are more factors to be considered such anisotropy along wellbore, pre-existed fractures along the wellbore and also possibilities of fault reactivation along the wellbore.

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