The Study of Flow Dynamics in Long Pipeline for the Transport of Carbon Dioxide (CO_2)

by

Muhammad Syafiq Bin Afandi

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons.)
(Mechanical Engineering)

MAY 2013

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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

(MUHAMMAD SYAFIQ BIN AFANDI)

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

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TRONOH, PERAK
MAY 2013

ABSTRACT

Carbon dioxide (CO_2) capture and storage (CCS) is usually considered as a chain consisting three separate elements; capture, transport and storage of the CO_2. The capture and the storage are the two most studied parts of the CCS chain; however, the transport also gives the important roles in this system. For this study, the title of the project is to study the dynamics of the flow in the long pipeline for the transport of CO_2.

The dynamics flow of the CO_2 transport in a long pipeline was studied and analyzed. At first, before the study is carried out, the author thinks of the uncertainties that will arise in the transport of CO_2. Some of the uncertainties that might occur are the effect of the flow, the pressure drop and the changes of the temperature but for this research, the author will do the study of the effect of the flow and the changes in the velocity and the pressure in long pipeline of the CO_2 transport.

For the completion of this study, the author used two main methods which is using the research methodology and construction of the pipeline model using the Computational Fluid Dynamics (CFD) software. The research is carried out for the project's concept understanding. The research had been done by reading the technical articles, and the previous related research from various author. Later the model is constructed using the CFD software.

As expected, for a very long and open ended pipeline, the pressure will drop as the length of the pipeline increases. Besides that the bending angle of the pipe also give impact to the flow of the CO_2; the greater the bending angle of the pipeline, the higher the CO_2 flow pressure will loss. In addition, in the bending pipeline, there will be a back flow occurred to the CO_2 flow

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ABBREVIATION AND NOMENCLATURE

CCS	: Carbon Capture and Storage
CFD	: Computational Fluid Dynamics
CO_2	: Carbon Dioxide
d	: inner diameter of the pipeline
EOR	: Enhanced oil recovery
kPa	: kilopascal
MMscfd	: Million standard cubic feet per day
P	: pressure
Psia	: pound square inch absolute
q	: volume flow
v	: velocity

CHAPTER 1

PROJECT BACKGROUND

1.1 Background Study

Carbon Dioxide (CO_2) emission, capture, injection and transport are the important activities in oil and gas industries. According to Dooley et al. (2009), in their research, the CO_2 formation is from the processes of the producing of the hydrocarbon and fossil fuels. From the research done by Wu et al. (2010), CO_2 can come from the power plant or from the industrial facility. The purpose of capturing and transporting of the CO_2 is for storage and also for the storage. [Wu et al. 2010]

As the oil and gas industry grows, the technologies used changed. The previous or old equipment are not efficient to be used anymore and some of them cannot be operated. Thus engineers in this field had come out the idea to invent new technologies for this field. Carbon dioxide (CO_2) transport also included in the introducing of the new technology.

Normally for the CO_2 transport is dependent on the pressure. Aspelund and Jordal (2007) said that, the higher the transport pressure, the thicker the pipe will be. Besides that, the author has to consider that another factor that will lead to result of the study which the geographical factor such as the topography of the earth, and the environmental factors and also the distance of the CO_2 source to the CO_2 storage. [Brunsvold et al. 2011]

From this statement, the author included the transport pressure parameter as one of the parameters used in this study like the mixing process of the CO_2 gas and liquid at the supercritical condition.

1.2 Problem Statement

Due to the growth of this new technology, it introduces uncertainties that imply risk where the need to evaluate the effect of the total system reliability arises. There are many uncertainties that will arise such as the effect of the flow, the pressure drop and the temperature drop/increase, but for this research, only the flow studied was on the dynamics of CO_2 in a long pipeline by using the CFD ANSYS FLUENT. As the topic had been chosen, the author defined some of the problems that might be related with the CO_2 flow. The problems are:

1. For long pipeline especially in CO_2 transport, pressure of the flow inside the pipeline may varies with respective distance from the pipeline inlet and the type and the size of the pipeline.
2. The velocity of the flow may varies with respective distance from the pipeline inlet and the type and the size of the pipeline.
3. How different shape and the geometry of the pipeline do affected the changes in the CO_2 flow velocity and its pressure.

For better understanding and comprehension, the author read the related technical articles and previous technical research papers in the literature readings and findings.

1.3 Objective

The objective of this research is to simulate the flow of the CO_2 transport in a long pipeline and also to determine the effects that might occur during this process. The three operating parameters or variables being investigated are:

1. The effect of the flow of the carbon dioxide in long pipeline
2. The pressure profile of the carbon dioxide along the pipeline and
3. The mixing process of the CO_2 gas and liquid at the supercritical condition.

1.4 Scope of Study

In this study, the author had divided the scope of study into 2 parts which is for the first semester of the research, the main subjects under investigation were:

i. *The pressure wave propagation of CO_2 in the pipeline*
ii. *The effect of the mixing process of the CO_2 gas and liquid at the supercritical phase*
iii. *The flow of the CO_2 gas in the pipeline*

Meanwhile, for the second semester of the research, the author had done:

i. *Simulate the flow dynamics of the flow of CO_2 using the ANSYS FLUENT CFD*
ii. *Summarize and conclude the findings*

CHAPTER 2

LITERATURE REVIEW

2.1 Carbon Dioxide Capture and Storage (CCS)

Carbon Dioxide Capture and Storage (CCS) usually considered as a chain consisting three separate elements; capture, transport and storage (Aspelund et al., 2007). In addition from this article also, they stated that capture and storage are the most two studied part in CCS chain since the transport being considered the least technical challenging. However studies performed on transport have focused more on connection with storage than on the connection with capture.

Many studies of CCS had been done over the years and had been presented in the literatures. A through overview regarding the transport of CO_2 is given in Wu et al (2010). Transport is the intermediate stage of CCS that connects sources and storage site. Commercially CO_2 is transported by tanks, ships and pipelines. Small-scale offshore transport prefers tanks and the relatively small needs of onshore transport limit the development of ship transport. Thus, for large-scale and long-distance transport of CO_2, pipelines are the most economical way.

2.2 Supercritical Phase of the CO_2 Transport

As been stated by Aspelund and Jordal (2007), in transporting CO_2 especially in pipeline, CO_2 will be transported at supercritical pressure, most likely in the range of 80-150 bar. The CO_2 must be compressed to a pressure high enough to overcome the frictional and static pressure drops. Furthermore the CO_2 should be delivered at a pressure higher that the critical pressure to avoid two-phase flow; the liquid slugs in the pipeline and the liquids in the injection compressor. It is supported from the

Pipeline International website article at which the study had been done by Downie, and co-workers (2010) stated that in the supercritical mode, captured CO_2 has to be compressed to a pressure above the critical pressure.

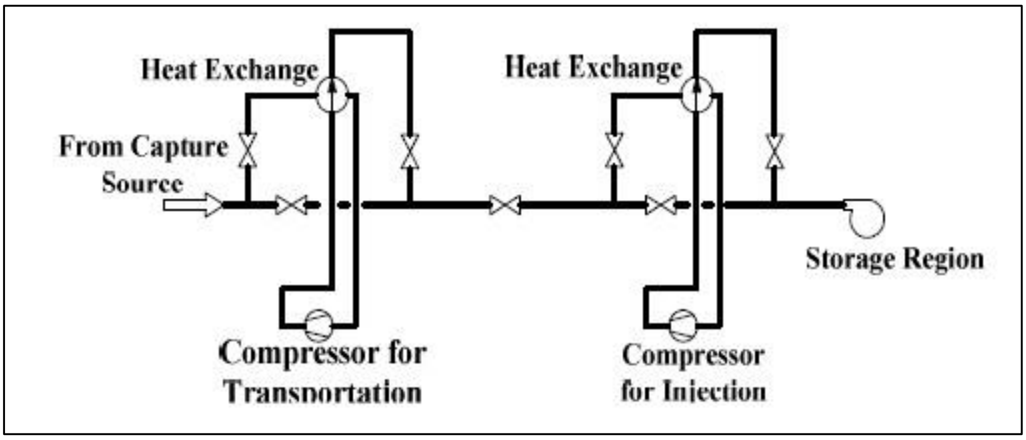

Figure 1: Operating Process of CO2 Pipeline Transportation by Supercritical Phase. [Wu, et al (2010)]

In addition to understand about the system especially in the supercritical phase transportation, Wu et al (2010) had explained how this process works in the Figure 1. During transport, CO_2 states above critical points and is boosted by compressors. Before boost, CO_2 must be changed from supercritical phase into vapor phase to ensure safety of compressors. This regasification is achieved by heat exchange. Other that vapor phase, supercritical phase transportation needs to set a minimum operating pressure to ensure it dense phase

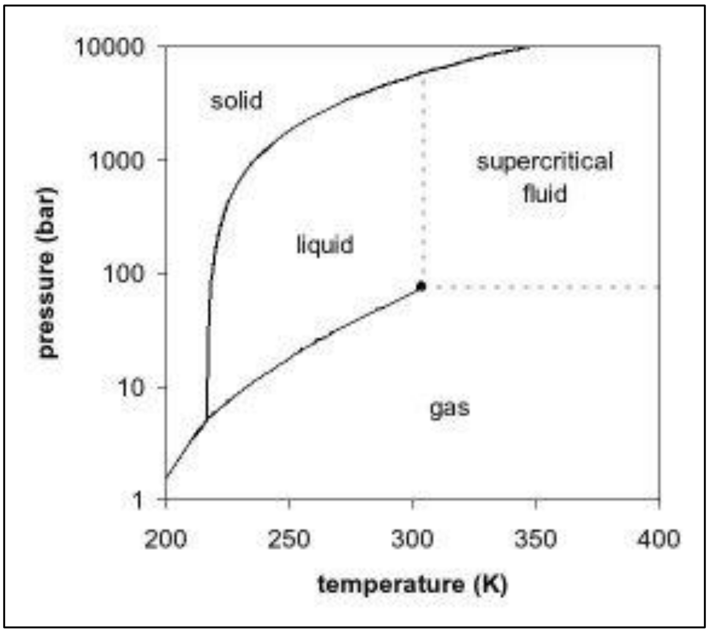

Figure 2: Carbon dioxide in supercritical fluid above its critical point of 301.1 K and 73.8 bar. [Supercritical fluid, (2008)]

As been shown in the Figure 2, the pressure-temperature phase diagram of the carbon dioxide. The carbon dioxide is in supercritical point of 301.1K and 73.8 bar which it was retrieved from the New World Encyclopedia website on 22nd April 2013. A supercritical fluid is any substance at a temperature and pressure above its thermodynamic critical point. It has the exclusive capability to diffuse through solids like gas, and dissolve materials like a liquid

2.3 Depressurization in the long pipeline

Clausen et all. (2012) had carried out a study regarding the result of the depressurization that might occur in transporting the CO_2 in an onshore pipeline which is initially in supercritical condition. From their findings, it is stated that the depressurization of the flow will be occur although due to the small changes or difference of the flow.

2.4 Modelling the pipeline

Klinkby et all. (2011) stated in their findings that some of the parameters are very important in modelling the pipeline. Before any modelling or simulation is constructed the parameters or initial input that should be considered and noted are the mass flow rate, pressure, temperature and holdup (volume fraction of liquid or dense phase if above the critical pressure/temperature) in the pipeline and well. However all those inputs did not show the actual steady state conditions, thus in order to reach the steady state conditions, it will take some simulation time.

Meanwhile from the findings of Patchigolla and Oakey (2013), they explained about the latest or the current technology of the large scale and long distance CO_2 transport. This technology is call Enhanced Oil Recovery (EOR).at which the CO_2 is displaced the oil in the underground reservoirs and thus improve the oil yield. In the same study they also said all the existing large-scale CO_2 pipelines are designed for dense phase/ supercritical phase pressure above 7.38 MPa. The typical optional intervals for temperature and pressure of the CO_2 are 15-30 ^{o}C and 10-15 MPa respectively. It is difficult to maintain with this design due to the special properties of the CO_2 and normal pressure loss in pipeline and in order to do that, the pressure the CO_2 has to be regularly recompressed along the route.

In addition of the research done by Patchigolla and Oakey (2013), it is difficult to predict the CO_2 flow due to the compressibility and density of CO_2 which is strong, non-linear dependence on the pressure and temperature. At the critical point of CO_2 which is at 7.38 MPa and 31 ^{o}C, even a small change of temperature or pressure will affect a large change in density. Besides that, the presence of the impurities of the CO2 will affect the CO2 physical properties and then give impact on the pipeline designed operation.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

The methodology for conducting this research project is exploration and discovery. Since some of the concepts of this project are not something new, a few researches had been done from the previous expertise in this field. With that, the literature reading can be done to get more understanding to this research.

3.2 Mathematical Modeling and Simulations

Since this project is about the transporting CO_2 in a long pipeline; due to restriction in conducting the research at the site, the author generated a mathematical model that was found in the literature review. After that, from the mathematical modeling, the research proceeded to the simulation part. For this part, the simulation was performed using the Computational Fluid Dynamics (CFD) Software like the ANSYS FLUENT CFD. The Figure 3 shows how the modeling and the simulation was executed.

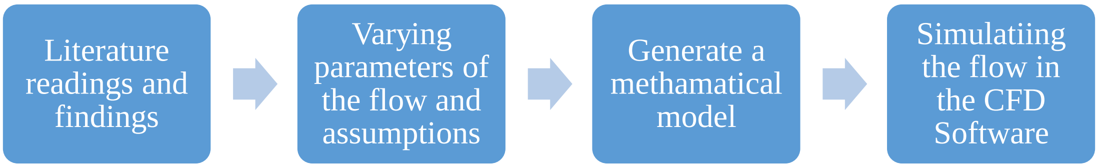

Figure 3: The graphical flow diagram on how the research was done

It starts from the literature readings and findings. Later, the author had defined the parameters involved in the study and determine the assumptions that related with the study. After that, the mathematical model was generated, then will lead to the simulation of the dynamics flow of the transport of CO_2 using the CFD Software (ANSYS FLUENT).

3.3 Project Flow Chart

Several steps had been done for the completion of the project which were:

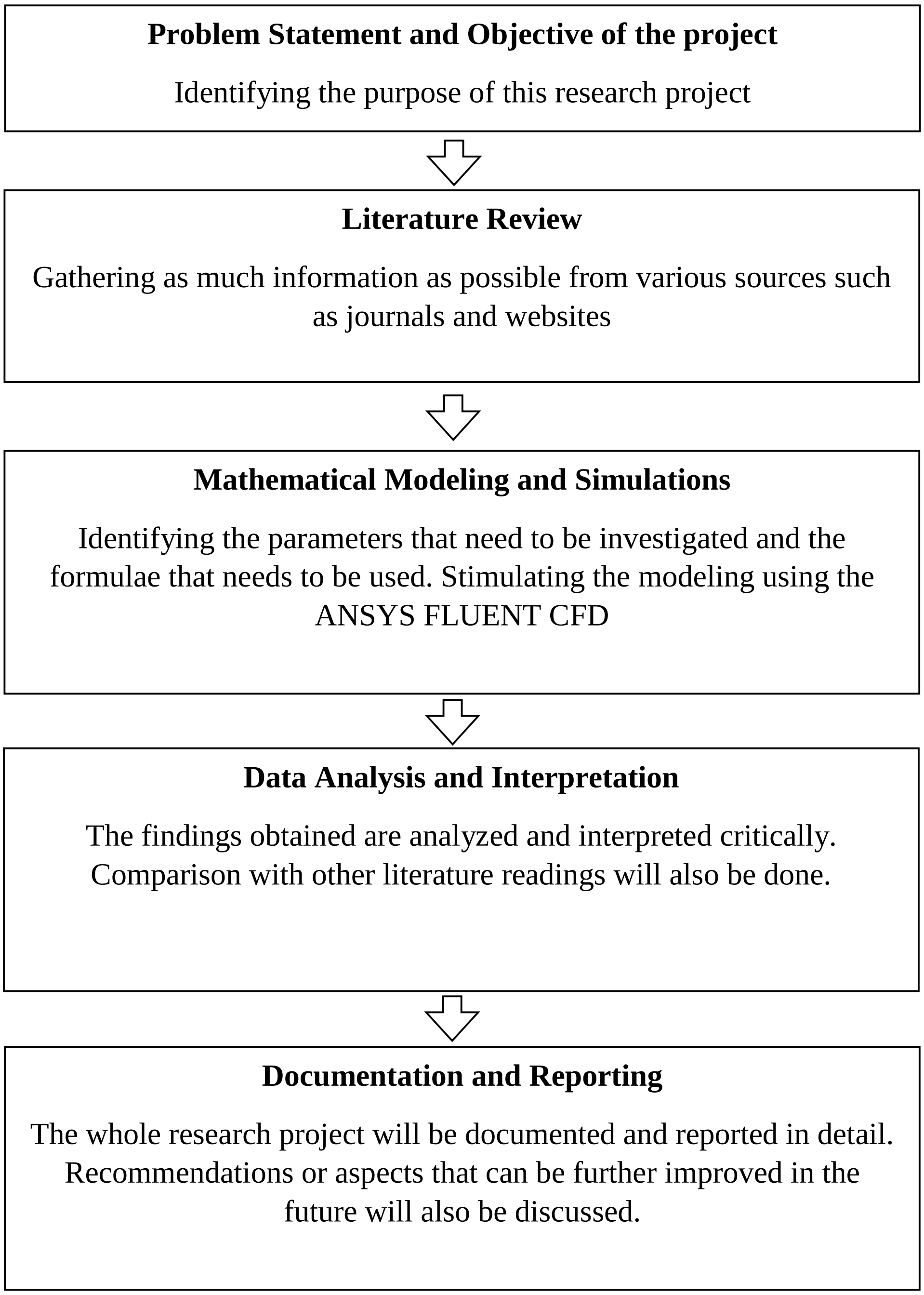

Figure 4: Project flow chart of the study

Figure 4 explains the process flow of the completion of the study. Several steps had been executed which the first step is the author defined the problem statements and the objectives of the topic. Later, the information related to the study were gathered. In order to do that, literature readings and review is one of the vital parts before the project was started. Mathematical modeling and simulation is the next phase of this study. For this phase, the author had found and had determined the parameters that were related to the study. Once the simulation of the flow was generated, the author interpreted the result as well as analyzed the outcome data. Documentation and reporting were the final steps had been done in the completion of the study

3.4 Gantt's Chart and Key Milestones

3.4.1 Final Year Project 1

Table 1: Project Gantt's Chart and The key milestones of the FYP1

No	Details / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Title															
2	Preliminary Research Work and Literature Review															
3	Submission of Extended Proposal Defence						★									
4	Preparation for Oral Proposal Defence															
5	Oral Proposal Defence Presentation															
6	Detailed Literature Review															
7	Preparation of Interim Report															
8	Submission of Interim Draft Report														★	
9	Submission of Interim Final Report															★

Remarks

★ - Key milestones of the activitie

3.4.1 Final Year Project 2

Table 2: Project Gantt's Chart and The key milestones of the FYP2

No	Details / Weeks	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continue (Literature readings and final dissertation completion)	■	■	■	■	■	■	■		■	■	■	■	■		
2	Familiarization and tutorial of using the CFD		■	■												
3	Develop and test the model constructed			■	■	■	■	■								
4	Submission of Progress Report									★						
5	Improvise and test the model constructed									■	■					
6	Finalized and conclude the model constructed										■	■				
7	Pre-SEDEX											★				
8	Submission of Draft Report												★			
9	Submission of Dissertation (Soft Bound)													★		
10	Submission of Technical Paper													★		
11	Oral Presentation														★	
12	Submission of Project Dissertation (Hard Bound)															★

Remarks

★ - Key milestones of the activities

CHAPTER 4

RESULT AND DISCUSSION

4.1 Parameters Finding

The given parameters for the simulation of the long pipeline are as follows:

Table 3: The given and the default parameters of the flow of the CO_2 in the pipeline used in the simulation

Pipeline length	170 km
Flow rate	1100 MMscfd
Take-off pressure	2200 psi
Geometry of the pipe in the CFD ANSYS	1. Straight pipeline (constant diameter) - diameter of 30inches (0.762 m) - length of 500m
	2. Bend pipeline - diameter of 30 inches (0.762 m) - bending at angle of 90 degrees - length of 5 m
	3. Contracted pipeline - diameter reduced from 30inches to 24 inches (0.762 m to 0.6096 m) - length of 5 m

Converting of the British units to the SI units are as follows:

1. Pressure (from pound per square inch atmosphere; psia to kiloPascal; kPa)

   Given that the take-off pressure is 2200psia.

   - ➔ Theoretically, (pound per square inch absolute; psia) = (pound per square inch gauge; psig) + (1atm@sea level)
   - ➔ whereby, 1atm =14.7psi =101.3529 kpa

   Therefore in converting the psi to kPa,

   - ➔ $= 2200\ psia\ x\ \frac{101.3529\ kPa}{14.7\ psi}$

     = <u>15168.465 kPa</u>

2. Flow rate to velocity (from Million Standard cubic feet per day; MMscfd to meter per second; m/s)

   Converting the flow rate which is the unit is in MMscfd, to meter cubic per second; m^3/s. are as follows

   - ➔ 1MMscfd $= 1\ x\ 10^6\ x\ \frac{ft^3}{day}\ x\ \frac{1m^3}{(3.28125)^3 ft^3}$

     = <u>28306.23043 m^3/day</u>

   - ➔ Thus, from :

     $$1100MMscfd = 1100MMscfd\ x\ 28306.23\ \frac{m^3}{day}\ x\ \frac{1\ day}{(24x3600)s}$$

     $$= 360.4\frac{m^3}{s}$$

   - ➔ From the flow rate, the velocity of the flow can be calculated using the formula:

$$q = Av$$

$$v = \frac{q}{v} = \frac{q}{\frac{\pi d^2}{4}}$$

➔ Therefore the equation used to determine the flow velocity is:

$$v = \frac{\frac{4}{\pi} x\ q}{d^2}$$

Where: v = velocity (m/s)

q = volume flow rate (m3/s)

d = inner diameter of the pipe

➔ Next, the all the values is substituted into the equation, where the author selected the diameter of the pipe is 0.762m (approximately 30 inches)

$$v = \frac{1.274\ x\ 360.4}{0.762^2}$$

$$v = 791\frac{m}{s}$$

Given the length of the pipeline in this problem is 170 km but for the model simulation the geometry of the pipeline in the ANSYS FLUENT had been categorized to three types of pipeline which had been shown in the Table 3 before.

The 3 main data needed in the model construction are:

- Diameter of the pipe = 0.762 m or 0.6096 m
- The flow velocity = 791 m/s
- The take-off pressure = 15168.465 kPa

4.2 Results and Discussions

The results and the discussions of this study will be divided into three parts which will follow the pipeline geometry used in the simulation.

4.2.1 Straight pipeline (constant diameter)

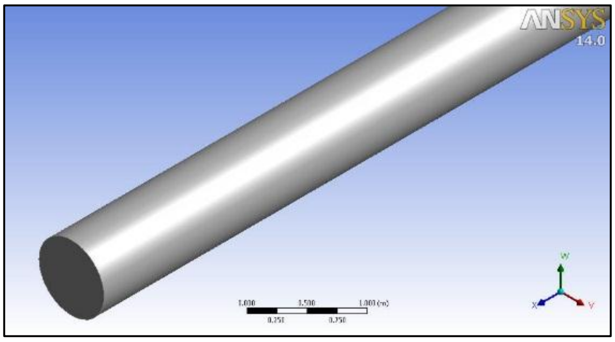

Figure 5: The outlet section of the straight pipeline with the diameter of 30" and length of 500m

Figure 5 shows a part of the designed geometry in the ANSYSS Workbench 14.0 which is the outlet of the pipeline with the constant diameter of 30inches (0.762m). For this model, the pipeline is designed with the length of 500m straight and long pipeline. For this part the assumptions that had been made are the external fluid flow is neglected, the wall friction between the gas and the wall pipe is neglected and the carbon dioxide flow is in a steady flow state.

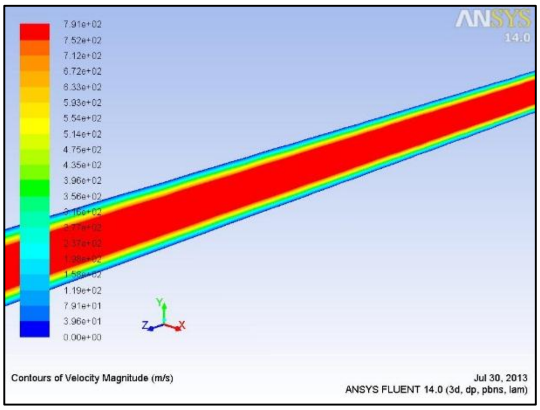

Figure 6: The velocity profile of the flow inside the pipeline with the diameter of 30" and length of 500m

Figure 6 shows the velocity distribution along the straight pipeline. The velocity is shown and differentiate in the figure using contours colors. From the color legend shows, the red color is the highest velocity if the flow and the blue color is the lowest velocity of the flow. From the figure, the highest CO_2 flow velocity that can be achieved in a long straight pipeline with a constant diameter (30" and 500m) is at the center of the pipeline. Though the wall friction of the CO_2 flow velocity is neglected, there is a slight changes to CO_2 flow velocity near the wall of the pipe.

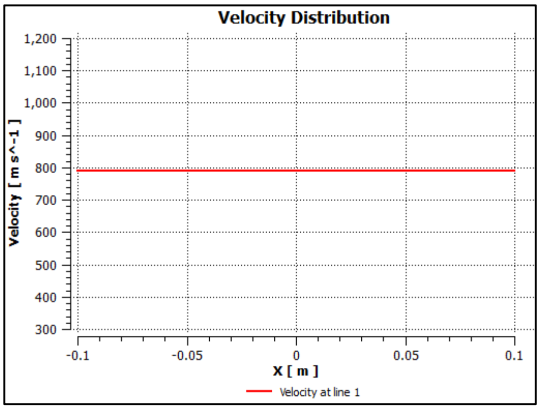

Figure 7: The graph of the flow velocity distribution vs the length of the pipe

Figure 7 above shows the graph of the CO_2 flow velocity distribution inside the pipleine versus the lengh of the pipline. From the figure, the conclusion that can be made is the velocity flow of the CO_2 is constant along the straight, long and constant diameter of the pipeline.

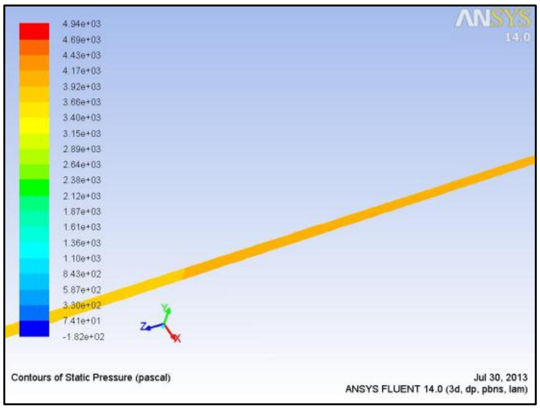

Figure 8: The pressure profile of the flow inside the pipeline with the diameter of 30" and length of 500m

Figure 8 shows the pressure profile of the flow inside the middle part of the pipeline. It shows how the pressure of the flow inside the pipeline will vary along the pipeline if it is an open ended and constant diameter pipeline. From the result, the pressure of the flow will be higher at the inlet of the pipeline and will be lower at the outlet.

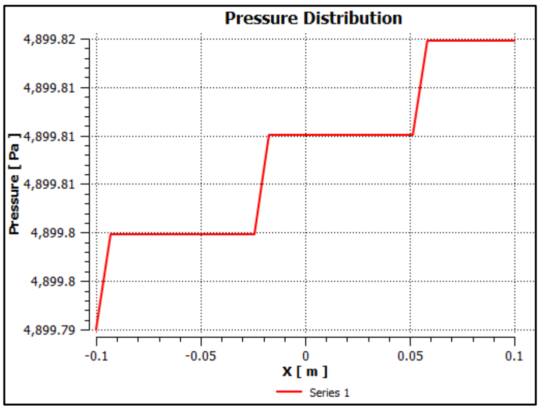

Figure 9: The graph of the flow pressure distribution vs. the length of the pipe

Figure 9 shows the graph of the pressure distribution of the flow inside the designed pipeline versus the length of the pipeline. From the figure above, in can be concluded that only small changes of the pressure loss will occur inside the pipeline.

4.2.2 Bend pipeline

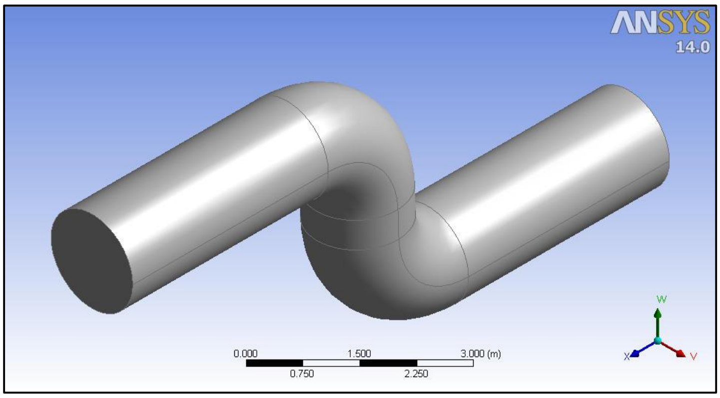

Figure 10: The geometry of the 90° bend of the diameter of 30" constant pipeline

Figure 10 is the geometry of the 90° bend of the pipeline with the constant diameter of 30". For this situation, the length of the modeled pipeline is 5 m. Reason why only 5 m length of the pipe is selected is due to the chages of the flow will be obeserved and study mostly at the bending area. For this region, the assumption that is concedered is the flow in the inlet and the outlet is in the steady state flow.

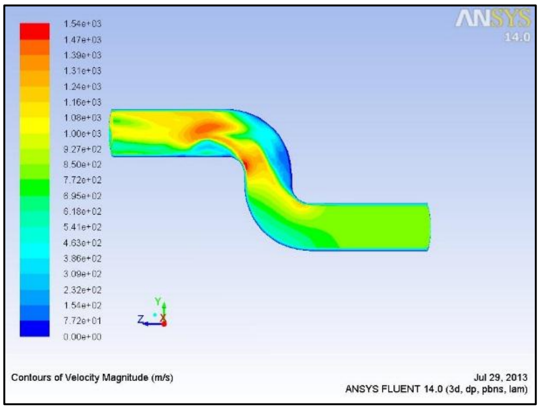

Figure 11: The velocity profile of the flow inside the 90^o bend pipeline

Figure 11 shows the velocity profile of the flow inside the 90^o bend pipeline. The diagram shows there will be decrease of the flow at the bending area where the velocity flow will drop at this area

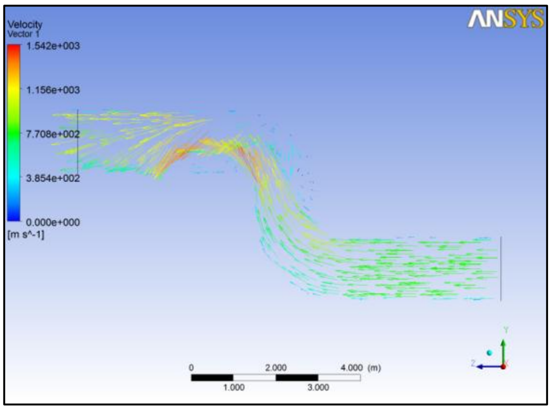

Figure 12: The velocity vector profile of the flow inside the 90^o bend pipeline

The velocity vector profile is shown in the Figure 12 above. In the figure it is clearly show there will be a backflow occurred at the bending area. The backflow will lead to the decreasing of the velocity of the flow that had been clearly shown in the Figure 11.

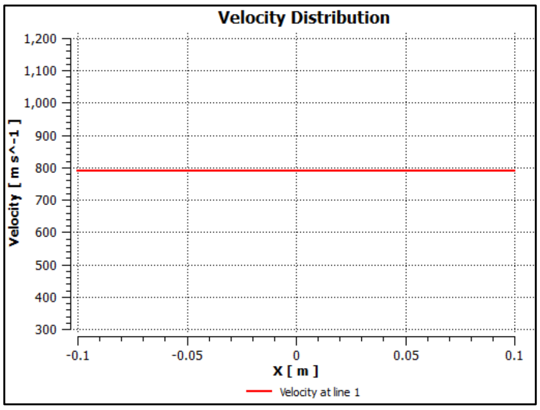

Figure 13: The velocity distribution of the flow inside the 90^o bend pipeline versus the length of the pipeline

Figure 13 shows the velocity distribution of the flow inside the 90^o bent pipeline versus the length of the pipeline are remain the same and constant at the center of the pipeline.

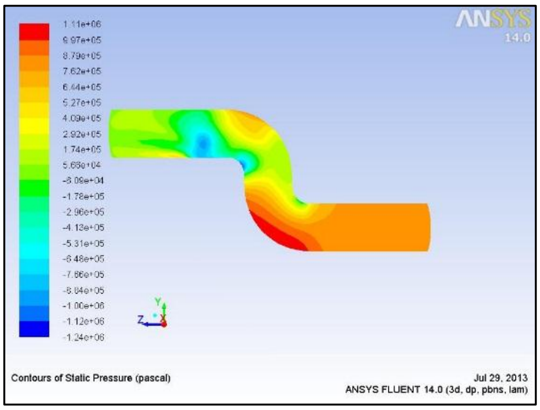

Figure 14: The pressure profile of the flow inside the 90^o bend pipeline

Figure 14 shows the pressure profile of the flow inside the 90^o bent pipeline. It is understood that the bending will give impact in the pressure loss inside the pipe. From Figure 14, the pressure at the inlet has the greater pressure compare to the outlet of the pipeline. At the first corner of the bend from the inlet, the pressure of the flow insight the pipeline is the most at this region.

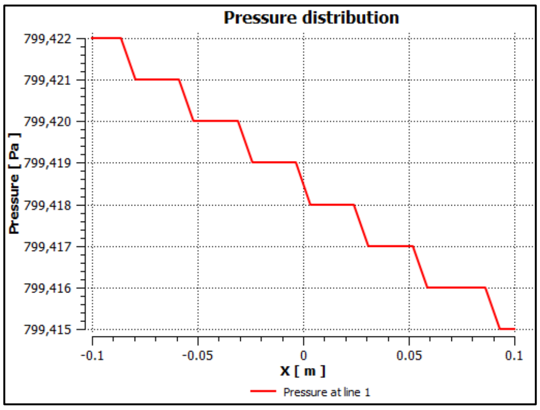

Figure 15: The pressure distribution of the flow inside the 90° bend pipeline versus the length of the pipeline

Figure 15 shows the graph of the pressure distribution of the flow inside the 90° bend pipeline versus the length of the pipeline. It can be concluded that only small CO_2 flow pressure loss can occurred along the pipeline and it is decreasing as the length of the pipeline is longer.

4.2.3 Contraction pipeline

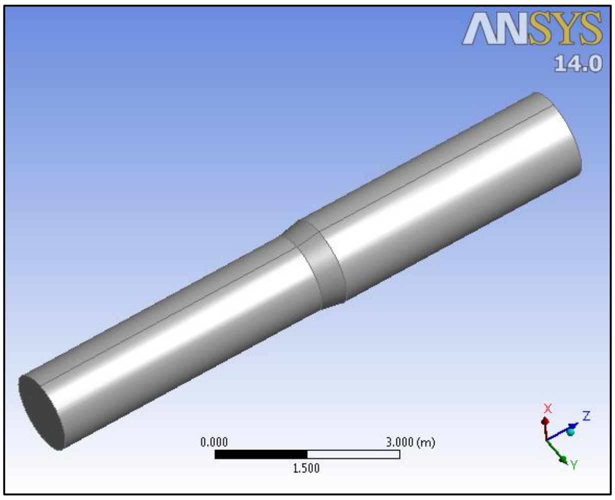

Figure 16: The geometry of the contracted pipeline of the diameter of 30" to the 24" in diameter

Figure 16 show the third type of the geometry of the pipeline that is studied in the project. It is the contracted pipeline of the diameter of 30" to 24" in diameter. The flow of the CO_2 gas will be transported from the larger pipeline with the diameter of 30 “to the 24”.

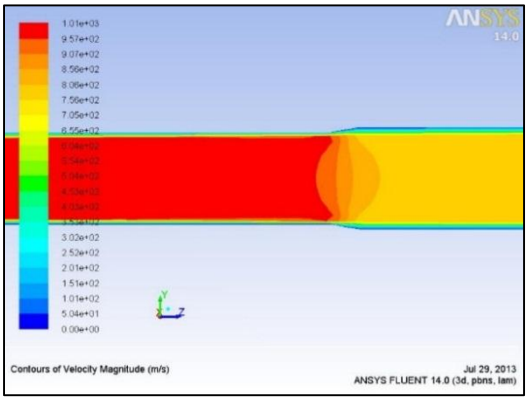

Figure 17: The velocity profile of the flow inside the contracted pipeline of the diameter of 30” to the 24"

Figure 17 shows the velocity profile of the flow inside the contracted pipeline of the diameter of 30” to the 24”. The inlet of the pipeline is at the larger diameter and the CO_2 gas will flow to the smaller diameter of the pipeline. At the inlet of the pipeline, the velocity is lower than the velocity at the outlet. At the contracted part

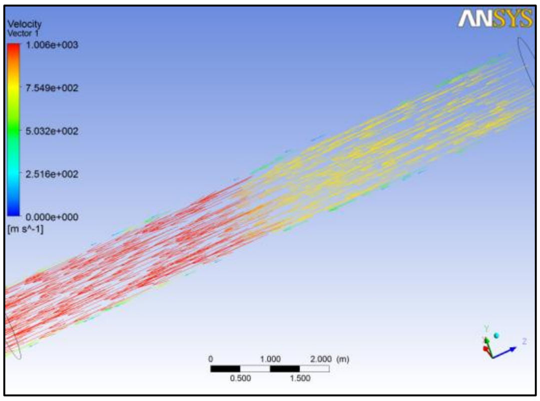

Figure 18: The velocity vector profile of the flow inside the contracted pipeline of the diameter of 30” to the 24"

Figure 18 shows the velocity vector profile of the CO_2 flow inside the contracted pipeline of the diameter of 30” to the 24”. From the figure above, there will be a slightly changes of velocity, whereby the velocity of the flow is at low speed near the wall of the pipeline.

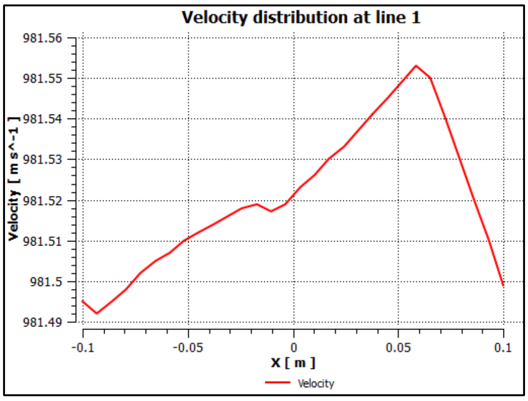

Figure 19: The velocity distribution of the flow inside the contracted pipeline of the diameter of 30” to the 24" versus the length of the pipeline

Figure 19 shows the graph of the velocity of the flow inside the contracted pipeline. The flow differs from one point to another point and it is shown clearly in the graph above.

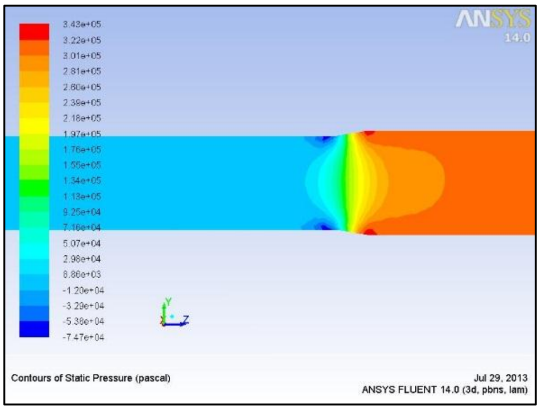

Figure 20: The pressure profile of the flow inside the contracted pipeline of the diameter of 30” to the 24"

The pressure profile of the flow is shown in the Figure 20. Figure 20 is pressure distribution of the flow inside the diameter of the 30” to the 24”. From Figure 20, the highest pressure inside the pipeline is at the intersection point between the 30” pipeline diameters with the 24”pipeline diameter of the contracted pipeline. Near the edge of the contracted part of the pipeline, the pressure of the flow is higher compare to the other part of the pipeline.

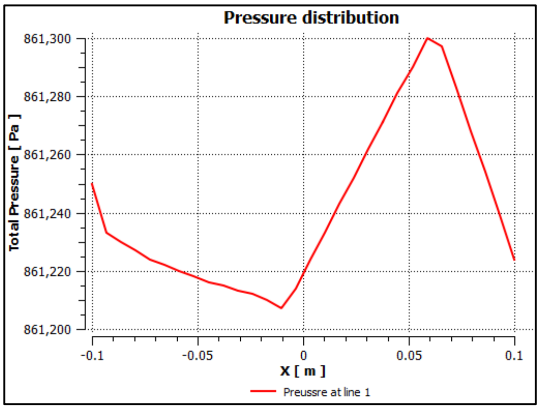

Figure 21: The pressure distribution of the flow inside the contracted pipeline of the diameter of 30” to the 24"

Figure 21 shows the pressure distribution of the flow inside the contracted pipeline of the diameter of 30” to the 24”. From the graph, the pressure is at the highest is at the intersection part of the pipeline.

CHAPTER 5

CONCLUSION

From all the results gained, it is proved that the dynamics flow of the carbon dioxide gas (CO_2) inside the pipeline will be affected according to the type of the pipeline and the geometry of the pipeline is used. From three cases or types of the pipeline used in the simulation, the cross sectional area of the pipeline will give much effects to the velocity of the flow. If the cross-sectional area of the pipeline is constant along the route, the velocity at the center of the CO_2 flow will be the same if the wall friction between the gas and the wall of the pipe is neglected and the fluid flows in a steady flow condition. For a very long and open ended pipeline, the pressure will drop as the length of the pipeline increases.

Besides that the bending angle of the pipe also give impact to the flow of the CO_2; the greater the bending angle of the pipeline, the higher the CO_2 flow pressure will loss. In addition, in the bending pipeline, there will be a back flow occurred to the CO_2 flow. From this situation the velocity near the pipeline wall will affected the mot and lead to the loss of the velocity of the flow. If the geographical factors lead to the usage of the bending pipeline, the incline angle should be not greater than 90^o so that the losses of the flow velocity can be reduced.

With slight changes of the CO_2 properties like the density and the temperature if the fluid, it will give a big impact to the dynamics flow of fluid in the pipeline.

From the study it can be concluded that a lot of recommendation and improvement that can be done for the further research in the future. In this study the type of fluid in the pipeline is only CO_2 gas and some of the parameters had been neglected such as the friction loss between the flowing fluid and the pipeline internal wall. Besides that, the fluid flow outside the pipeline also had been neglected in this study.

For the better result in the future study; all parameters which had been neglected should be included in the pipeline model and simulation. Regarding the geometry of the pipeline, few more designs should be considered in the pipeline model construction which are the design should be widely used in everyday applications and usage.

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APPENDICES