Parametric Studies of Carbon Dioxide Separation using Inline Separator: Effect of Concentration of Carbon Dioxide and Flow Rate of Mixed Gases

by

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Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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CERTIFICATION OF APPROVAL

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BACHELOR OF ENGINEERING (Hons)
(CHEMICAL ENGINEERING)

Approved by,

____

(Dr. Lau Kok Keong)

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September 2013

CERTIFICATION OF ORIGINALITY

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

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(NUR MAIZATUL MASTURA MUSTAFA)

ABSTRACT

Inline separation technology has taken the heart of the oil and gas field operators due to the considerable weight, less space needed and also the most important thing is the cost savings that can be achieved. Most of the inline separation technology now can be a role in debottlenecking and also to replace the conventional method of separation in the meantime. The production of natural gas in the Malaysia gas wells is quite becoming challenging due to the increase of high CO_2 gas field in the region. Inline Separator for absorption is a new breath of inline separation technology that built especially to handle the separation of carbon dioxide gaseous from natural gas employing the concept of ejector and physical absorption implemented in the design. This paper will basically study the performance of inline separator by focusing on the effect of feed concentration of carbon dioxide and the effect of feed flow rates of mixed gases (natural gas and carbon dioxide) towards the carbon dioxide absorption. The performance of inline separator is compared with the straight pipe performance to observe the CO_2 absorbed pattern.

ACKNOWLEDGEMENT

The past 28 weeks of my enrolment in this final year project have been truly a valuable experience to me. Therefore, I would like to take this opportunity to express my gratitude to a number of people that have helped me throughout this project. First and foremost, all praises to the Almighty, Allah S.W.T. for His mercy and grace, I was able to complete this project in good health and well-being. Next, I would like to sincerely thank you my Supervisor, Dr Lau Kok Keong who has supervised me throughout my project period. His willingness to guide and advise me has helped me in achieving the goals of my project. Besides, he was constantly supportive of the decisions that I make and always share his knowledge and experiences with me. Very special thanks to MSc student, Nur Hidayah binti Khalid who guided me along the experimental and not to forget for both of my parents and family for their love and supports. Last but not least, thanks to my colleagues, friends and those who involved directly and indirectly towards accomplishing my final year project objectives. In short, I feel blessed to have successfully completed my final year project and for all help that the aforementioned parties have given me. My final year project only becomes a success with their help.

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CHAPTER 1

INTRODUCTION

1 INTRODUCTION

This chapter consists of (1) project background, (2) problem statement, (3) objectives, (4) scope of study, and (5) significance of this project.

1.1 Project Background

Natural gas is one of the most important sources for the world in other to supply energy. The International Energy Outlook 2013 (IEO, 2013) predicted that the energy consumption will keep increasing by 56 percent between 2010 and 2040. Total world energy use rises from 524 quadrillion British thermal units (Btu) in 2010 to 630 quadrillion Btu in 2040. Natural gas consumption in Asia is expected to triple the current levels (Karasalihović, Maurović, & Šunjerga, 2003).

The higher demands of natural gas is because it is a safe energy source which can be applicable to many industries such as in domestic households, industry, and power plants (Correljé, 2013).

Natural gas is a natural mixture of hydrocarbons that can be found from the ground or from specially driven wells (PETRONAS Gas Bhd, 2011). The combustible mixture of the hydrocarbons gases produces a lot amount of energy when burned. Typically, natural gas comprises of methane, ethane, propane, butane, carbon dioxide, water vapour, nitrogen and condensate natural gasoline. The presence of the hydrocarbons and also impurities in the natural gas can lead to pipeline corrosion and environmental issues where removal process is indeed to be important (Ahmad, 2011). Table 1.1 below shows a typical composition of raw natural gas.

Table 1.1: Typical composition of raw natural gas (Jusoh, 2013)

Component	Molecular Formula	Range (mol%)
Methane	C_1	70-90
Ethane	C_2	0.20
Propane	C_3	
Butane	C_4	
Pentane	C_{5+}	0.05-2
Carbon Dioxide	CO_2	0-8
Oxygen	O_2	0-0.2
Nitrogen	N_2	0-5
Hydrogen Suphide	H_2S	0-5
Rare gases	Ar, He, Ne, Xe	Trace
Metals	Nickel and Mercury	Trace

1.1.1 Natural Gas Separation Technologies

Current technologies in removing CO_2 the from natural gas include chemical or physical absorption, membrane, adsorption and cryogenic (low temperature distillation) (Gupta, Coyle, & Thambimuthu, 2003). The importance of removing CO_2 that present in the natural gas are basically to increase the heating value of the gas, prevent corrosion of pipeline and also to avoid the corrosion in the process equipment (Ebenezer & Gudmundsson, 2005). Table 1.2 shows some of the advantages and also the disadvantages of the current technologies.

Table 1.2: Comparison of purification technologies for natural gas (Jusoh, 2013)

Technology	Advantages	Disadvantages
Absorption	• Simple process • Low pressure loss if light product • Very low hydrocarbon losses	• Poor separation characteristics; low purity light ends or low recovery of heavy ends • Relatively complex
Adsorption	• Very high purity of light product • Simple process • Can remove minor components completely	• Low recovery • Operates most favorably at lower pressures (20-30 bar) • Expensive for bulk removal of impurities
Cryogenic	• High recovery of products • High purity of light products when using hydrocarbon wash processes • Can operate at high pressures • Good purity of heavy products • Low pressure loss of light product	• High cost • High energy consumption
Membrane	• Low energy consumption, unless compressed • Low operating cost • Low maintenance cost • Relatively simple • Low environmental impact • Short time for on-site installation	• Pretreatment of the feed is required to remove particulate and liquid.

1.1.2 Physical Absorption

Physical absorption is widely used for decades. The concept of physical absorption where the CO_2 is absorbed under high pressure and a low temperature, and desorbed at decreasing pressure and increased temperature (Yu, Huang, & Tan, 2012). Some of the known commercial processes such as Selexol Process, Rectisol Process, Purisol Proces, Morphysorb Process and Flour Process which are using chemicals absorbent like dimethylether, propylene glycol, methanol and propylene carbonate to remove CO_2 and H_2S basically using the concept of physical absorption and reacts differently on each of the processes depends on the partial pressure and solubility of CO_2 (Yu et al., 2012). Contact time is directly associated with physical absorption, where longer contact time means higher surface area that leads to higher CO_2 absorption (Park et al., 2004).

1.2 Problem Statement

With the presence of high feed pressure under the offshore conditions, physical absorption is potentially to be used to remove bulk CO_2 from the natural gas. Nevertheless, physical absorption using conventional bulk separator such as the packed column is certainly not viable under the offshore conditions due to the requirement of larger footprint and tonnage.

With the advantages of compact design, compact inline separator is potentially to be applied to separate bulk CO_2 from natural under offshore conditions. Yet, there is very limited works conducted on CO_2 absorption using compact separators. Most of the published works are related with CO_2 absorption using conventional packed column (provide ref).

Therefore, a parametric study on inline separator for physical absorption is crucial to explore the potential of employing this new technology in physical absorption of CO_2 under offshore conditions.

1.3 Objectives

The objectives of this project are:

a) To study the effect of feed concentration of carbon dioxide on CO_2 absorption performance using absorption using compact inline separator.

b) To study the effect of feed flow rate of the mixed gases (natural gas and carbon dioxide) on CO_2 absorption performance using compact inline separator.

1.4 Scope of Study

This project is limited to the use of carbon dioxide separation only. The experimentation will be executed to ensure the effectiveness of the prototype which using the inline separator. The experiment is conducted by varying two parameters; concentration and flow rate of the carbon dioxide and natural gas that affects the efficiency of CO_2 absorption.

1.5 Significance of Study

Inline separator is a prototype to capture the CO_2 from the natural gas with the implementation on offshore. Some cases of the petroleum industry which having some experienced with the bulky separators which consume a lot of space and also the cost is high. Therefore, it is very important to have the effective separator to make sure that the efficiency of CO_2 separation high to be parallel with the demands of the natural gas. The available literature is complying with the petroleum industrial standards which mainly focus on data gathering, evaluation and analysis of the experimentation.

CHAPTER 2

LITERATURE REVIEW

2 LITERATURE REVIEW

The literature review consists of (1) conventional carbon dioxide absorption process, (2) concept of inline gas-liquid separation, (3) concept of ejector type separation and (4) inline separator.

2.1 Conventional Carbon Dioxide Absorption Process

It is important to know the carbon dioxide absorption process which will be used in this project. Absorption processes with chemical solvents are currently the most used technology for carbon dioxide separation from natural gas (Tan, Lau, Bustam, & Shariff, 2012). According to Jeffery Kuntz (2007), the cost of CO_2 capture by gas absorption is still prohibitively high for the environmental application.

Chemical absorption usually using amine based processes that efficiently removed acid gas impurities (CO_2 and H_2S) from the process gas streams. By using amine based processes, the solvent regeneration can be operates at low pressure in order to increase the desorption of CO_2 from the liquid (Wong & Bioletti, 2002). Usually, the popular type of chemicals used for CO_2 absorption is alkanolamines such as monoethanolamine (MEA), diethanolamine (DEA), diisopropanolamine (DIPA), methyl diethanolamine (MDEA), and 2-amino-2 methyl- 1- propanol (AMP) (Aroonwilas, 2008). Some of diglycoamine (DGA) also is being used as for the CO_2 separation (Chakma & Islam, 1989).

Absorption process is where the two liquids or liquid and gas is achieved by allowing the fluids to have a few minutes retention time (Humoud, Boudi, & Al-Qahtani, 2008). Packed column usually use absorption as a process to remove the CO_2 from natural gas. The conventional packed colums have a problem with the big size that is not suitable for the implementation on offshore where the space is limited.

Conventional technology require massive equipment to allow for required separation of oil, gas, water and sand (Fantoft, Akdim, Mikkelsen, Abdalla, Westra, & de Haas, 2010). Other problem related to the conventional separator to be installed on the offshore is the limited available space on the offshore platform, the high operational cost and the capital cost is subjected for a change to a separator that can operates in high efficiency and also can minimize the operational cost (Johannesen, BjC8rkhaug, & Eidsmo, 2011). Rather than using the conventional separation, there is a need to search for more economical and practical alternative technology (Chakma & Islam, 1989).

There are some implementations of upgrading the conventional bulk separator with the inline separator. For example, Statoil Company is implementing the Flow Induced Inline Separation (FIIS) which consist of the De-sander for separating sand from oil, the De-liquidizer for separating liquid from gas, the Phase Splitter for separating gas from liquid and De-watering unit for separating water from oil. This four elements of separation process is initiated by using a swirl element or similar to the force the multiphase flow onto a tangential flow (spin), thus utilizing centripetal force to separate two phases of different density (Johannesen et al., 2011).

The implementation in Statoil is slightly different with this project which is to use the ejector type inline separator. FIIS is using desorption method of separation while the suggested approach in this paper is to capture the CO_2 by using the absorption method where the conventional approach is remained, but only the structure of the separator is compact and operates in high efficiency. Therefore, the use of a systematic operation which is using the ejector type inline separator with the use of absorption method will be promising future separation to upgrade the existing separator in industry.

2.2 Concept of Inline Gas-Liquid Separation

Inline gas-liquid separation is the most promising inline technology to replace the conventional bulk separator that already been used for decades (Kremleva, Fantoft, Mikkelsen, & Akdim, 2010). Inline separator now already taken the heart of separation for oil, sand, gas and water where the technology was initially developed for de-bottlenecking of processing plants where it is difficult to solve specific operating challenges by conventional technologies (Fantoft, Akdim, Mikkelsen, Abdalla, Westra, & de Haas, 2010).

The main concern of using the inline separator is because of the compact design, pipe code, low cost to fabricate, less manufacturing time, less space and weight (Okimoto, Klaver, Verschoof, & Stanbridge, 2004). Many industries now are implementing the inline separator for example Gulfaks, Shell, Statoil and maybe in the future, all the conventional separator will be replace with the inline separator (schook & asperen, 2005).

High intensity inline devices are often used to mix fluids in the process industries. According to Andrew Green in his paper entitled “Inline and High Intensity Mixer”, when two phases are mix together (gas-liquid, immiscible liquid-liquid), a fine dispersion of bubbles drops and a high specific interfacial area are produced because of the intensive turbulence and shear. In addition, Green stated that the resistance to the interphase mass transfer is considerably smaller than in conventional equipment. There are several types of gas-liquid mixing for example motionless mixers and gas-liquid ejectors.

To give further clarification, inline separators are actually having the same function as the conventional separators, but it is in a smaller shell (Chin, Stanbridg, & Schook, 2003). Separation is achieved by the use of centrifugal force which is thousand times greater than the force of gravity resulting in flow patterns to separate fluid phases of different densities (Humoud et al., 2008). Humoud et al., (2008) says that inline separation might not produce a good quality of outlet streams, but it is sufficient enough for the use of many practical applications. Other than that, inline separator also tends to be sensitive to flow variation, therefore high continuous flow is needed for the separation to occur efficiently (Humoud et al., 2008).

In the PDO Al Huwaisah Water Injection Project, inline separator is used that known as Degasser which to separate the gas from a liquid stream and Dewaterer as to separate bulk of oil from water. Basically, the process inside the Dewaterer and also Degasser are the same where a stationary, horizontal swirl element creates centrifugal forces to separate gas from the oil or water mixture (Okimoto et al., 2004). There are other inline separation systems in the current technologies which have already proved that it is efficient in separation such as Inline Deliquidizer as to separate liquids from a gas stream and Inline PhaseSplitter for splitting multi-phase stream into two single phases which are a gas and a liquid phase. The common mechanism from the Dewaterer, DeLiquidiser, PhaseSplitter and also Degasser is where it used desorption process as the swirling effect is implemented inside the equipment. Figure 2.1, 2.2, 2.3 and 2.4 shows the inline equipment used in the current technologies.

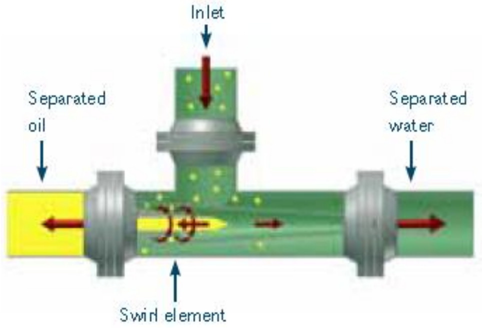


Figure 2.1: Inline DeWaterer (Johannesen et al., 2011)

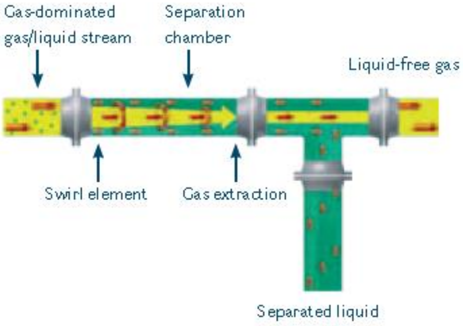


Figure 2.2: Inline DeLiquidiser (Johannesen et al., 2011)

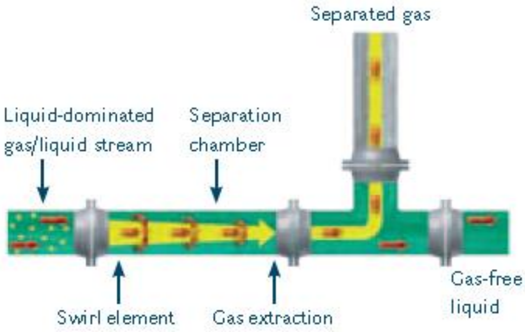


Figure 2.3: Inline DeGasser (Johannesen et al., 2011)

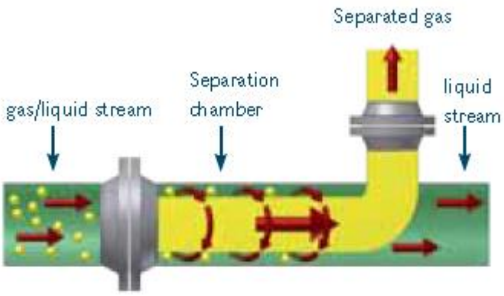
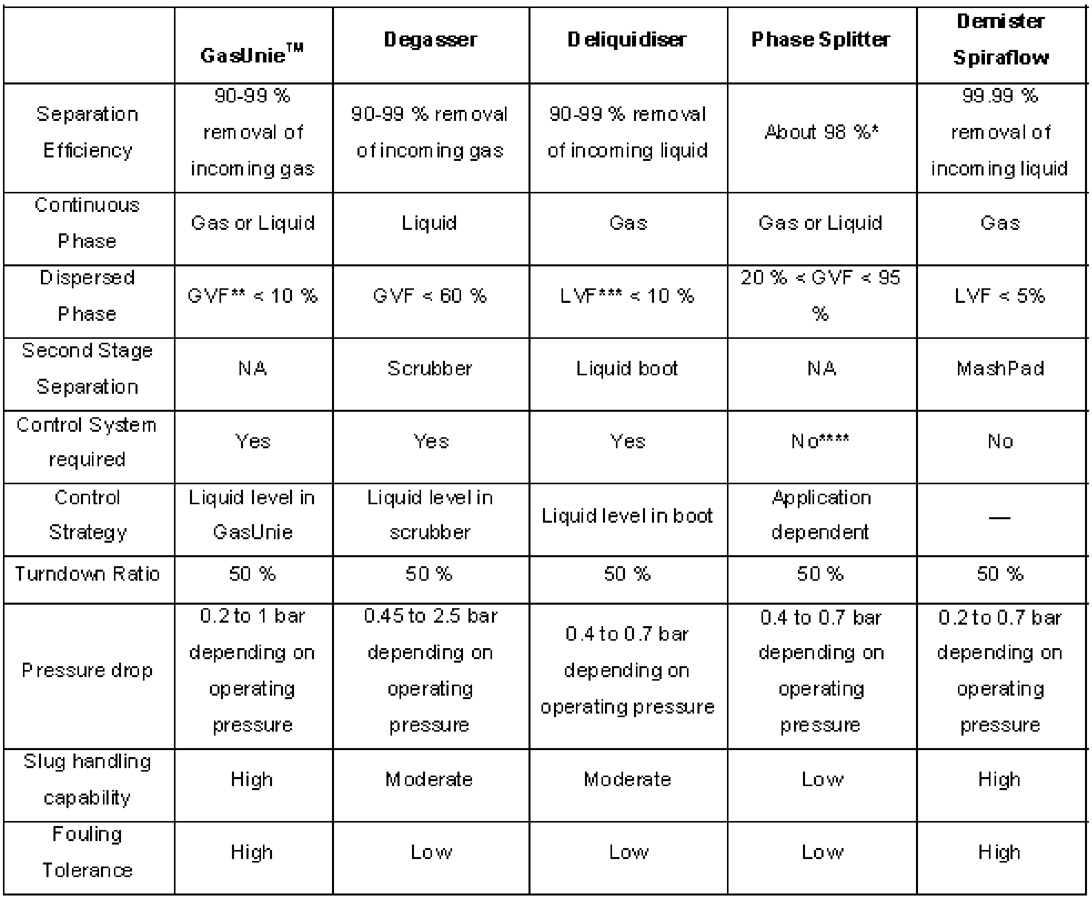


Figure 2.4: Inline Phase Splitter (Johannesen et al., 2011)

Table 2.1 shows that somehow, inline separators are effective since the separation efficiency is more than 90 percent. Shell company also implementing the FMC Technologies inline equipment in PDO Al-Huwaisah, Oman where the floating production, storage and offloading (FPSO) cause operational problems such as spurious alarms and shutdown. As to solve the problem, inline equipment is installed since it does not affected by movement and best to apply to the FPSO.

Table 2.1: Main characteristics of Inline Gas/Liquid separation equipment (Fantoft, Akdim, Mikkelsen, Abdalla, Westra, & Haas, 2010)



	GasUnie™	**Degasser**	**Deliquidiser**	**Phase Splitter**	**Demister Spiraflow**
Separation Efficiency	90-99 % removal of incoming gas	90-99 % removal of incoming gas	90-99 % removal of incoming liquid	About 98 %*	99.99 % removal of incoming liquid
Continuous Phase	Gas or Liquid	Liquid	Gas	Gas or Liquid	Gas
Dispersed Phase	GVF** < 10 %	GVF < 60 %	LVF*** < 10 %	20 % < GVF < 95 %	LVF < 5%
Second Stage Separation	NA	Scrubber	Liquid boot	NA	MashPad
Control System required	Yes	Yes	Yes	No****	No
Control Strategy	Liquid level in GasUnie	Liquid level in scrubber	Liquid level in boot	Application dependent	—
Turndown Ratio	50 %	50 %	50 %	50 %	50 %
Pressure drop	0.2 to 1 bar depending on operating pressure	0.45 to 2.5 bar depending on operating pressure	0.4 to 0.7 bar depending on operating pressure	0.4 to 0.7 bar depending on operating pressure	0.2 to 0.7 bar depending on operating pressure
Slug handling capability	High	Moderate	Moderate	Low	High
Fouling Tolerance	High	Low	Low	Low	High

2.3 Concept of Ejector Type Separation

Ejectors, jet-nozzles and similar devices are used for dispersion of gas in liquid (Balamurugan, Gaikar, & Patwardhan, 2006). It is used the co-current flow systems, where simultaneous aspiration and dispersion causes continuous formation of fresh interface and generation of large interfacial area of contact between phases (Balamurugan et al., 2006). The objectives for ejector design is to get large entrainment of the secondary fluid, to produce intense mixing between the primary and secondary fluids also to pump fluids from a region of high pressure, depending on its area of application (Li, Li, & Wang, 2012).

In the existing industry, C100 Injection Mixer is using the ejector type to capture the hydrogen sulphide. The mechanism works when the liquid is supplied to the contactor through an annulus where the liquid is transformed to small liquid droplets by locally increasing the dynamic pressure of the flow (Wang et al., 2006). Mixing of the liquids is resulted from the internal mixer geometry that sets up turbulent eddies in order to have high degree of mixing with large interfacial surface at low pressure drop. The main components of an ejector consist of a primary nozzle, the suction chamber, the mixing chamber and the diffuser (S. He, Li, & Wang, 2009).

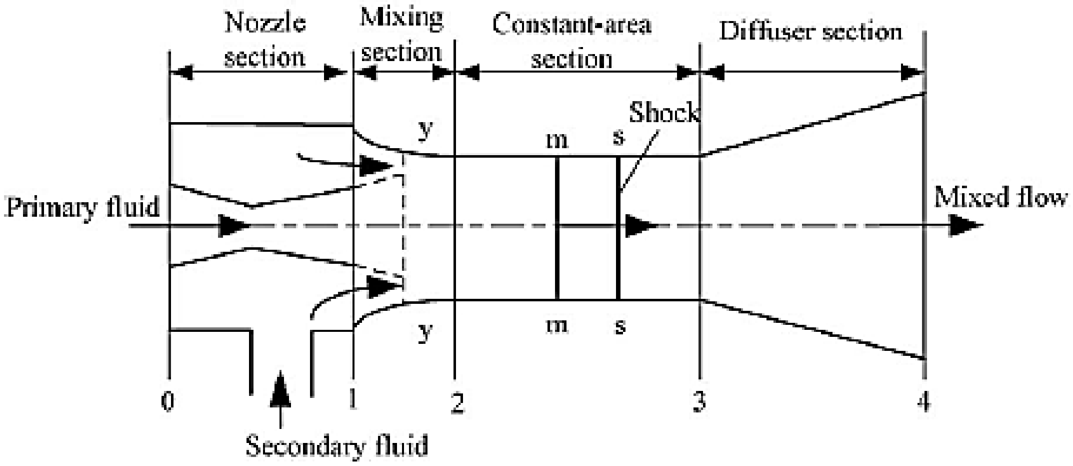


Figure 2.5: Principle structure of ejector (S. He et al., 2009)

From Figure 2.6, a primary fluid is accelerated to supersonic speed by the convergent-divergent primary nozzle, which forms low pressure region at the nozzle exit plane. From Figure 2.7, the theory is proved where experimentation done by S.

Balamurugan (2006) shows that the pressure is low inside the nozzle and this satisfied the Bernoulli's principle. The same principles also applied in the ejector to produce the entrainment effect of the liquid to entrain the secondary fluid (S. He, 2009).

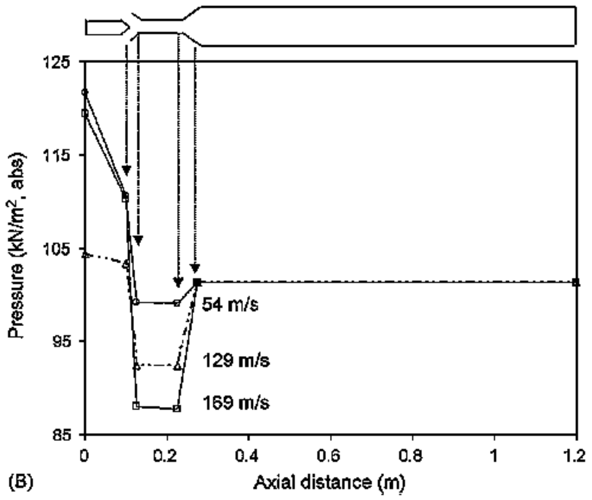


Figure 2.6: Effect of nozzle velocity on the pressure profile (Balamurugan et al., 2006)

In the mixing section, a sudden reaction in the mixture velocity and a rise pressure takes place and makes the fluid mixture easily undergoes phase change (S. He et al., 2009). On the diffuser section, the mixture of primary and secondary flows passes through the diffuser, and converts kinetic energy into pressure energy. According to He et al., (2009), at the diffuser exit, the velocity is reduced to zero and the pressure is lifted high enough to cause discharge.

Ejectors produce higher mass transfer rates by generating very small bubbles or droplets of the dispersed phase where it resulted in improving the contact between phases (Balamurugan et al., 2006).

2.4 Literature Summary

In this section, literature summary provides the research done in using inline separator that already being discussed in the literature review part.

A Compact High-Performance Absorber for Small-Size Remote Field Gas Processing	(Chakma & Islam, 1989)
Device for Atomizing Liquid or for Comminuting Gas into Small Bubbles	(Jogindar M. Chawla, 1991)
A Vortex Contactor for Carbon Dioxide Separations	(Raterman et al., 2001)
Development and Installation of an Inline Deliquidiser	(Chin et al., 2003)
Compact In-line Separation Project	(Okimoto et al., 2004)
Compact Separation by Means of Inline Technology	(schook & asperen, 2005)
Hydrodynamic Characteristics of Gas–Liquid Ejectors	(Balamurugan et al., 2006)
Modeling and Experimental Study of CO_2 Absorption in a Hollow Fiber Membrane Contactor	(Zhang, Wang, Liang, & Tay, 2006)
Compact Multiphase Inline Water Separation (IWS) System—A New Approach for Produced Water Management and Production Enhancement	(Wang et al., 2006)
Hydrodynamics and Mass Transfer Characteristics Of Gas–Liquid Ejectors	(Balamurugan, Lad, Gaikar, & Patwardhan, 2007)

Performance of Spray Column for CO_2 Capture Application	(Kuntz & Aroonwilas, 2007)
Separation of CO_2 from CH4 using Mixed-Ligand Metal-Organic Frameworks	(Bae et al., 2008)
New Application of an Inline Separation Technology in a Real Wet Gas Field	(Humoud et al., 2008)
Progress of Mathematical Modeling on Ejectors	(S. He et al., 2009)
Revolutionizing Offshore Production by InLine Separation Technology	(Fantoft, Akdim, Mikkelsen, Abdalla, Westra, & de Haas, 2010)
Effect of Operating Conditions on the Physical and Chemical CO_2 Absorption through the PVDF Hollow Fiber Membrane Contactor	(Mansourizadeh, Ismail, & Matsuura, 2010)
Inline Technology—New Solutions for Gas/Liquid Separation	(Kremleva et al., 2010)
Power Plant with CO_2 Capture based on Absorption	(Ystad, 2010)
Flowsheet Development and Simulation of Off-Shore Carbon Dioxide Removal System at Natural Gas Reserves	(Ahmad, 2011)
Flow Induced Inline Separation (FIIS) De-watering Tests at the Gullfaks Field	(Johannesen et al., 2011)
Performance Assessment of an Inline Horizontal Swirl Tube Cyclone for Gas-Liquid Separation at High Pressure	(Mellon & Shariff, 2011)

Configuration Dependence and Optimization of the Entrainment Performance for Gas-Gas and Gas-Liquid Ejectors	(Li et al., 2012)
Removal of High Concentration CO_2 from Natural Gas at Elevated Pressure via Absorption Process in Packed Column	(Tan et al., 2012)

2.5 Research Gap

There have been a number of studies that highlighted the use of inline separator in the oil and gas stream. The separation is achieved by the use of centrifugal force (Humoud et al., 2008). However, none of these studies using the absorption as the process in it and also the concept of ejector which the liquid is injected in a sprayed droplet size. Compact inline separator design is equipped with three main concepts which are using the compact design of separator, absorption process and also the concept of the ejector in spraying the liquid in droplet size. It is believed that inline separator using absorption process can be used to separate the CO_2 from natural gas.

CHAPTER 3

METHODOLOGY

3 METHODOLOGY

The research methodology for this project is mostly done by research, self-reading from journals, articles, books, and self-exploration on various matters related to technical knowledge and tools required to understand about the inline separator for absorption. This chapter consists of (1) research methodology, (2) gantt chart and key milestone and (3) tools and equipment.

3.1 Research Methodology

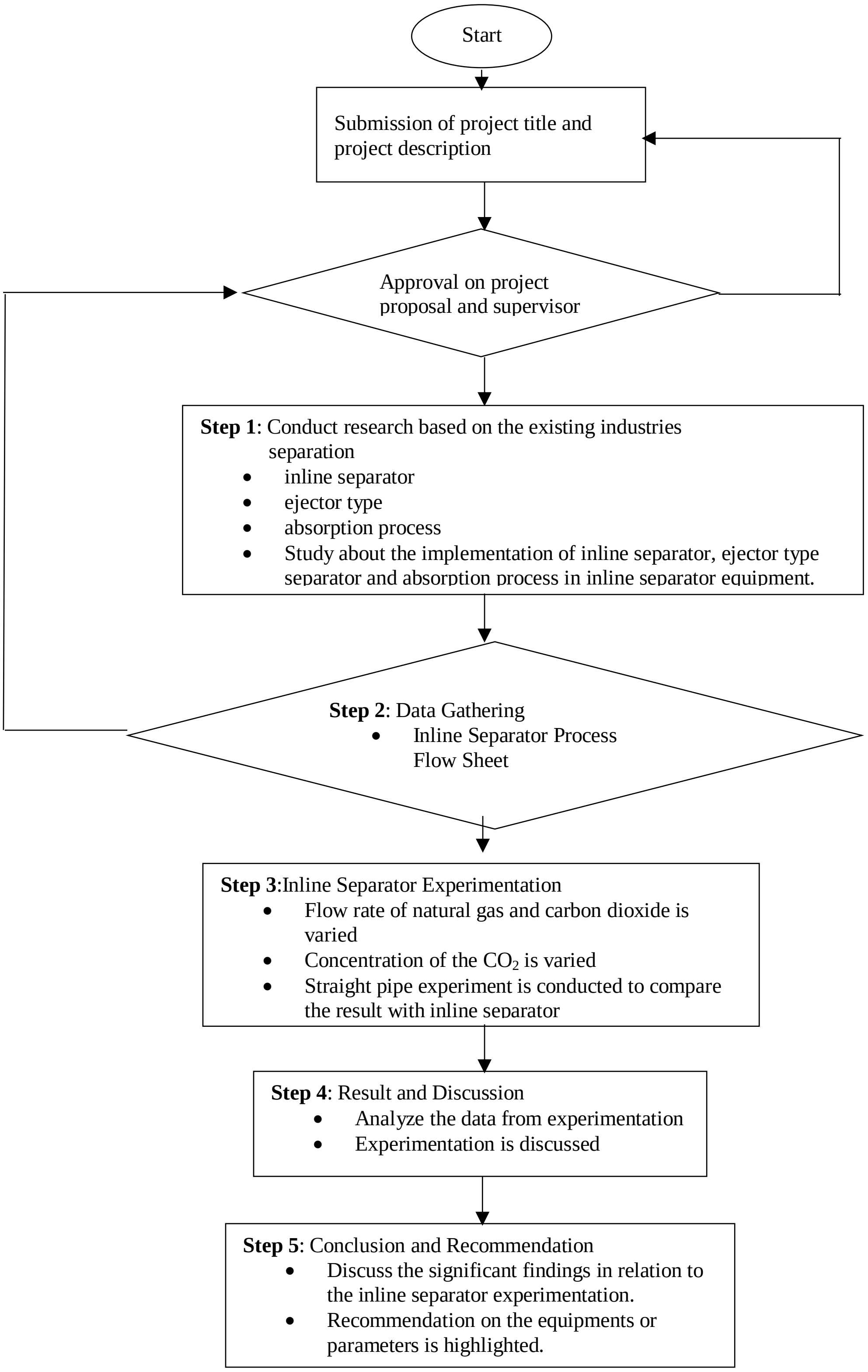


Figure 3.1: Research Methodology

Figure 3.1 illustrates the project methodology that need to be carry out in order to implement the project smoothly. The flowchart shown is a guide for the overall project work throughout this final year project and it is ensured to accomplish within the time given. The details of each step are as follows:

Step 1: Preliminary Research

Initial research is conducted which consist of background study related to three main things which are absorption process, inline separator concept and also ejector type separator type. The objectives, scope of study and significant of study are identified to create the boundary of this project. Literature review is also conducted to further identify the practice of inline separator, absorption process and the ejector type separator in the current technologies and industry. Then, further research on the application on the three main things in this project to the implementation of the inline separator using absorption process that are going to be used for the experimentation later.

Step 2: Data Gathering

The process flow sheet is sketched to have a clear view on the inline separator equipment and also the process to conduct the experiment. The process which includes the control mechanism of inline separator equipment is also highlighted. The suitable flow rate of the equipment is identified and the concentration of the natural gas and also the carbon dioxide is determined from the previous research to make sure optimum amount is going to be used in the experimentation.

Step 3: Inline Separator Experimentation

Inline separator using absorption process will be test using the test rig provided in Universiti Teknologi PETRONAS.

The parameters highlighted in this project are the feed concentration of the carbon dioxide and also the feed flow rates of the mixed gases (natural gas and CO_2).

To identify the concentration used in the inline separator process, the flow rates will be determined first. As the flow rates that are going to be control in this experiment is planned to be a range from 3 to 7 SLPM, therefore, the concentration of each of the gases injected to inline separator will be calculated based on the flow rates requirements.

Step 4: Result and Discussion

The results obtained from the experimentation will be collected. The performance of the inline separator by varying the feed flow rates and also the feed concentration of the gases will be calculated and discuss further.

Step 5: Conclusion and Recommendation

The significance findings in relation the objective of this project will be highlighted. As for the concern on the improving any inline separator using absorption process experimentation, the recommendations also will be discuss.

3.2 Inline Separator

Inline separator configuration in this project implementing the physical absorption process in order to capture the carbon dioxide from the natural gas and in advance, inline separator is using the ejector type which will reduce the size more. The absorbent used is distilled water which is revealed in case of physical absorption, CO_2 absorption using distilled water has effects on the higher solubility of CO_2 (Mansourizadeh et al., 2010). The absorbent will be injected through the liquid inlet while the natural gas and carbon dioxide is injected through the gas inlet. The absorption will occur in the body of the inline separator. It is expected that the absorption will occur effectively at the body. According to EIA study, chemical or physical absorption technologies process the highest near term potential for the low-cost and effective separation of dilute CO_2 from mixed gases (Raterman et al., 2001). The absorption process can offer a very high selectivity and a high driving force for mass transfer even at very low concentrations (Mansourizadeh et al., 2010).

The process continues to the compressor which the flow rate of the mixed gases will be varied. Lastly, the mixed gases will be sent to the inline separator where inside it, the absorption process takes place. The absorption process of gas and liquid injected are joined into a two-phase mixture in an inline mixer that transformed the gases into small droplets (Jogindar M. Chawla, 1991). Higher intensity of mixing can minimizes the liquid film resistance while finer droplets provide greater interfacial area per unit volume thereby enhance the mass transfer rate (Chakma & Islam, 1989).

The operating condition that varies in the amount of flow rate and concentration of natural gas and the carbon dioxide is the main parameters in this project. In the experiment later, the efficiency of the inline separator will be determined by varying the flow rate and also the concentration of the carbon dioxide gas. The goal is to observe the patterns when the concentration of the gases is high, what will be the effect of the absorption and the same applied to the flow rates, where the optimum flow rates can be determine to get a good absorption. According to Mansourizadeh et al., the absorption process can offer a very high selectivity and a high driving force for mass transfer even at very low concentrations. This shows that the absorption of CO_2 will still operates in high efficiency even the concentration of the gas is less. At the time where the natural gas and the carbon dioxide injected into the inlet nozzle of the inline separator, the flow rate of the gases injected is expected to be high as there will be a pressure drop. When the absorption process completed, the pressure at the outlet of the inline separator is expected to be high as to recover the pressure loss from the process.

The inline mixer can operates pressure from 50 up to 100 bar. It is equipped with series of pressure indicators to study the pressure distribution. The pressure needs to be higher in order to have a good absorption. When the pressure of CO_2 is low, the separation task becomes difficult due to the low driving force for the transfer of CO_2 into the liquid phase (Chakma & Islam, 1989).

3.3 Detailed Methodology for inline separator setup

a) Test condition

- Pressure set : 70 bar
- Heater temperature: 30˚C

b) Starting the system

- Main power supply is switched on.
- Main power supply is turned on to computer.
- NI lab view is activated and the software is allowed to complete loading.
- The analyzer switch is turned ON

Figure 3.2: System starting for inline separator

c) Heat-up Hot Water System

- The main power is powered up.
- The heater is set up to 80℃.
- The water pump is run to circulate the hot water inside the heat exchanger.

Figure 3.3: Water system heat-up

d) Setup Feeding Gas

- The natural gas and carbon dioxide gas is chosen to be used.
- Valve is opened at the cylinder gas.

Figure 3.4: Feeding gas setup

e) Setup Feed Gases at Feed Panel

- Inlet and outlet valve is opened for CO_2 and natural gas.
- The feed regulator is set at 7 bar.
- The flow rate is set for both types of gases at MFC at NI interface.

Figure 3.5: Feed gases setup at feed panel

f) To start collecting data for data acquisition, the toggle is tapped ON.

- All valve which suitable to experiment is opened.
  - Through saturation vessel or bypass
  - Permeate line or retente line
  - Manual BPR or Auto BPR

g) Start Compressor

- The compressor switch is turned ON at control panel.
- The "START" button is pressed at compressor.
- Inlet COMP1 valve is immediately opened.
- Inlet pressure is set up to 0.4 bars.

Figure 3.6: Compressor start-up

h) Monitoring the readings

- Monitoring via National Instrument Interface.
- Monitoring via instrument indicator at test rig.

Figure 3.7: Monitoring the reading at the equipment

i) Analyze sampling

- The needle valve is slowly opened.
- The “START” button at compressor is pressed.
- Inlet COMP1 valve is immediately opened.
- Inlet pressure is set up to 0.4 bars.

Figure 3.8: Setup to analyze sampling

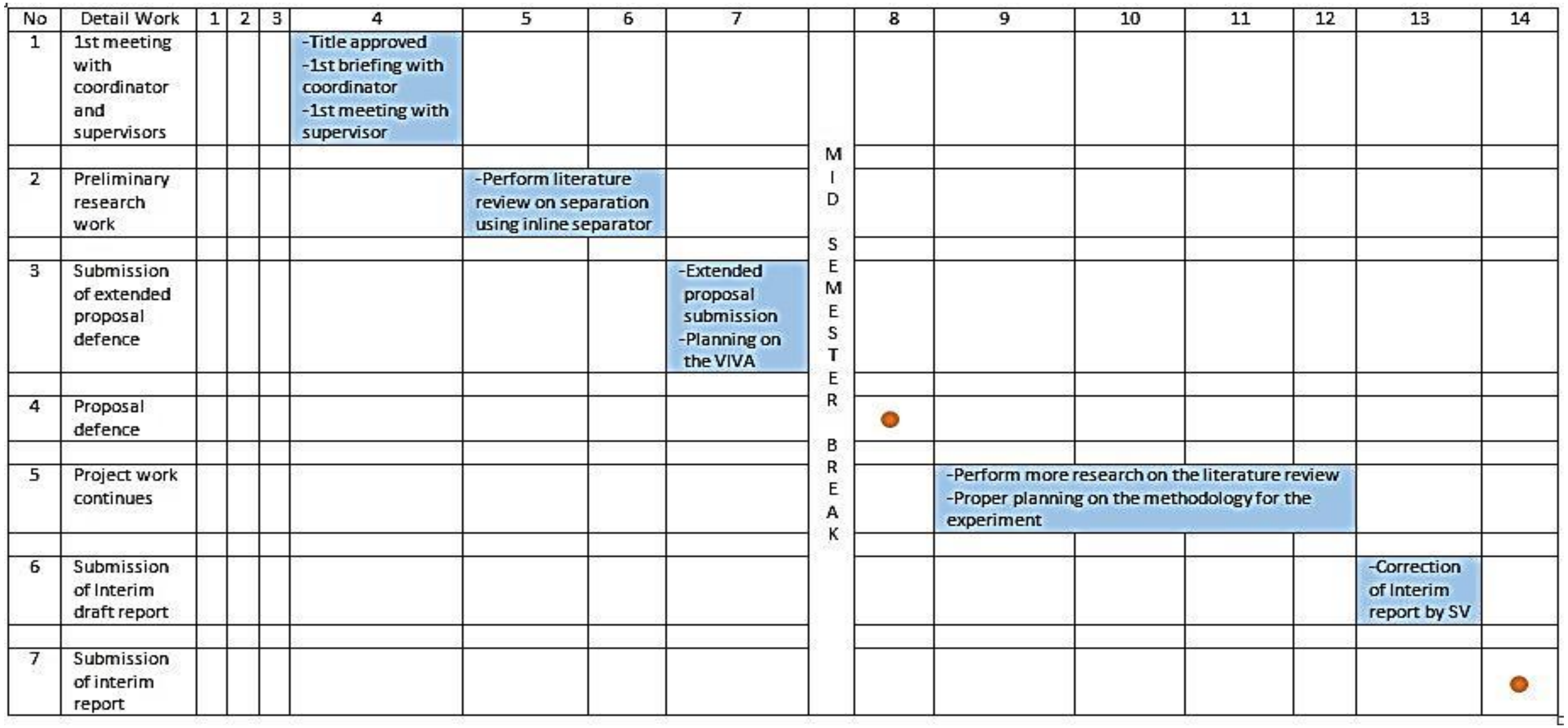
j) Stop Compressor

- To shut down, the inlet ball valve to compressor 1 is closed.
- The “STOP” button at compressor is immediately pressed.
- “Comp1 switch” is stopped to stop compressor 1

3.4 Gantt Chart and Key Milestone

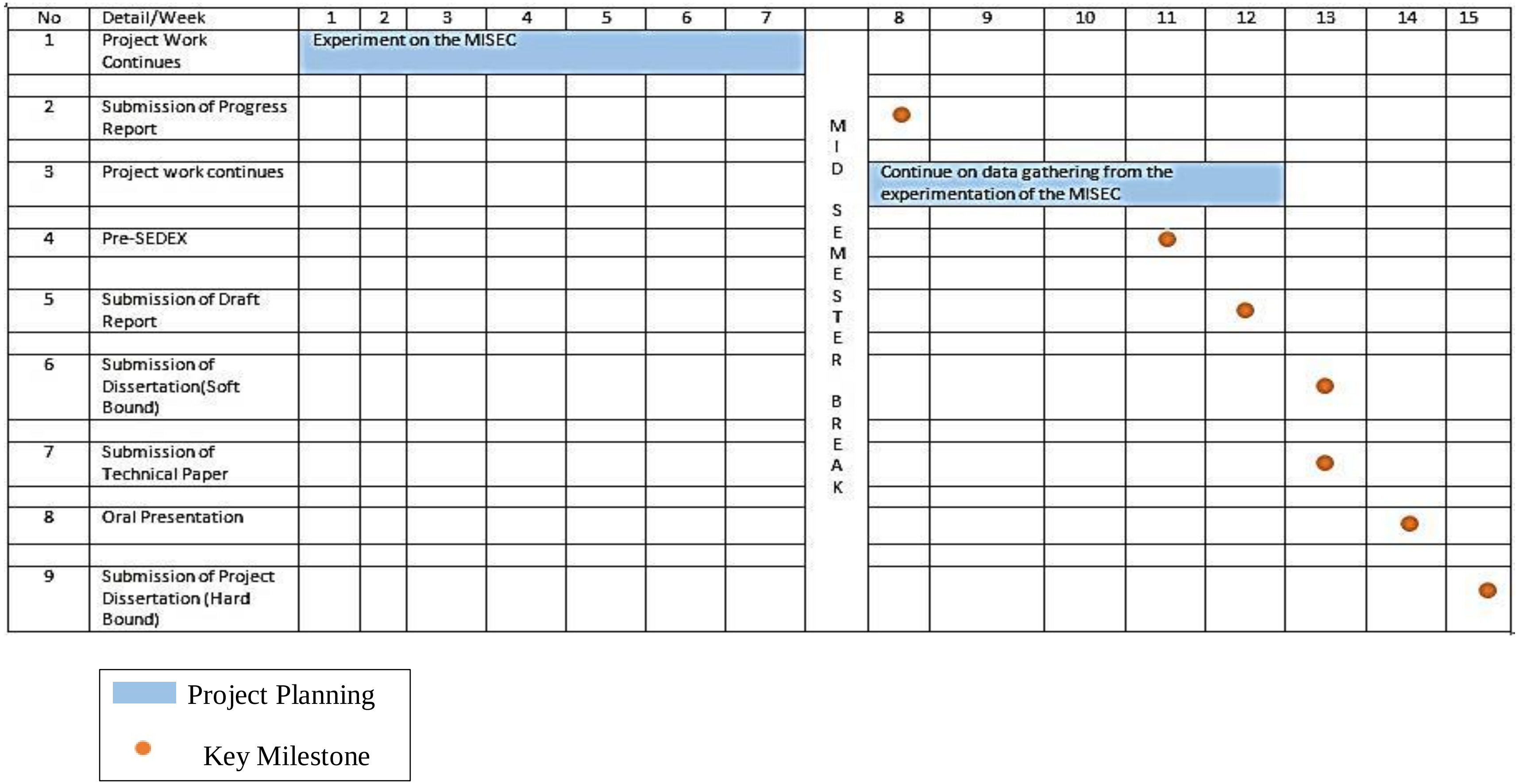
All activities involves in project methodology have been put in an appropriate Gantt chart to accomplish the prototype simulation of this project. The Gantt chart includes the timeframe for first and second semester together with the key milestone to be achieved. Gantt chart for FYP I is shown in Table 3.2 while Gantt chart for FYP II is shown in Table 3.3.

Table 3.1: FYP 1 Gantt Chart



No	Detail Work	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	1st meeting with coordinator and supervisors				-Title approved -1st briefing with coordinator -1st meeting with supervisor											
									MID SEMESTER BREAK							
2	Preliminary research work					-Perform literature review on separation using inline separator										
3	Submission of extended proposal defence							-Extended proposal submission -Planning on the VIVA								
4	Proposal defence									●						
5	Project work continues										-Perform more research on the literature review -Proper planning on the methodology for the experiment					
6	Submission of Interim draft report														-Correction of Interim report by SV	
7	Submission of interim report															●

Table 3.2: FYP 2 Gantt Chart



No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues	Experiment on the MISEC							MID SEMESTER BREAK								
2	Submission of Progress Report									●							
3	Project work continues									Continue on data gathering from the experimentation of the MISEC							
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)																●

▨ Project Planning

● Key Milestone

3.5 Tool and Equipment

The only equipment used in this project is the new inline separator which already being fabricated. In order to support the inline separator, test rig is used at Blok N as shown in (refer to Appendix C).

The carbon dioxide will be purchase from Air Product Malaysia with 99.9% of purity while natural gas with 97% CH_4, 2% CO_2 and heavier hydrocarbons is supplied by Petronas Dagangan Bhd (L. S. Tan, 2011) (Refer to Appendix A).

CHAPTER 4

RESULTS AND DISCUSSION

4 RESULTS AND DISCUSSION

The results and discussion part consist of (1) Effect of feed carbon dioxide concentration on CO_2 absorption and (2) Effect of flow rates of mixed gases on CO_2 absorption by using the inline separator.

4.1 Effect of Feed Carbon Dioxide Concentration

Figure 4.1 illustrates the effect of feed CO_2 concentration on gas absorption using inline separator. The concentrations of the CO_2 varied from 0.5 mol to 0.7 mol. The pressure and flow rate of solvent (water) injected to the inline separator was maintained at 70 bar and 0.5 SLPM throughout the experiment. The flow rate of natural gas was maintained at 1.5 SLPM while the carbon dioxide varied from 1.5 to 3.5 SLPM.

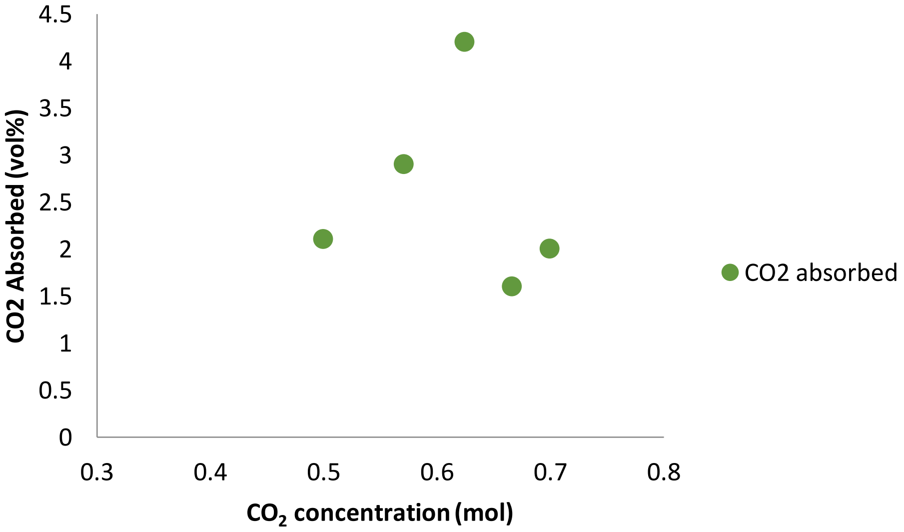


Figure 4.1: Effect of feed CO_2 concentration on CO_2 absorption on inline separator

Based in Figure 4.1, the increase of the feed CO_2 concentration (from 0.5 mol, to the peak of 0.625 mol of CO_2 causes the increasing of CO_2 absorption performance. This happened because according to Henry's law, CO_2 can be physically absorbed in a nonreactive solvent (Q. He, Chen, Meng, Liu, & Pan, 2010). The CO_2 absorption decreasing after reaching the optimal value (approximately 0.6 mol) because the solvent pumped to the inline separator was insufficient to further absorbed the increased in CO_2 gas injected. The solvent used (water) much more soluble to CO_2 and it explains the increased of the CO_2 absorption to the optimal value (Force, 2009). For the separation to takes place efficiently, the amount of solvent needed to be pumped through the inline separator is need to be taken into consideration (Emmanuel Keskes). Murlidhar (2003) stated that the solvent capacity followed Henry's law which assumed almost linear dependence on the gas partial pressure. Higher CO_2 partial pressure, and lower temperature leads to higher solubility of the CO_2 in the solvents or absorbent (Ebenezer & Gudmundsson, 2005).

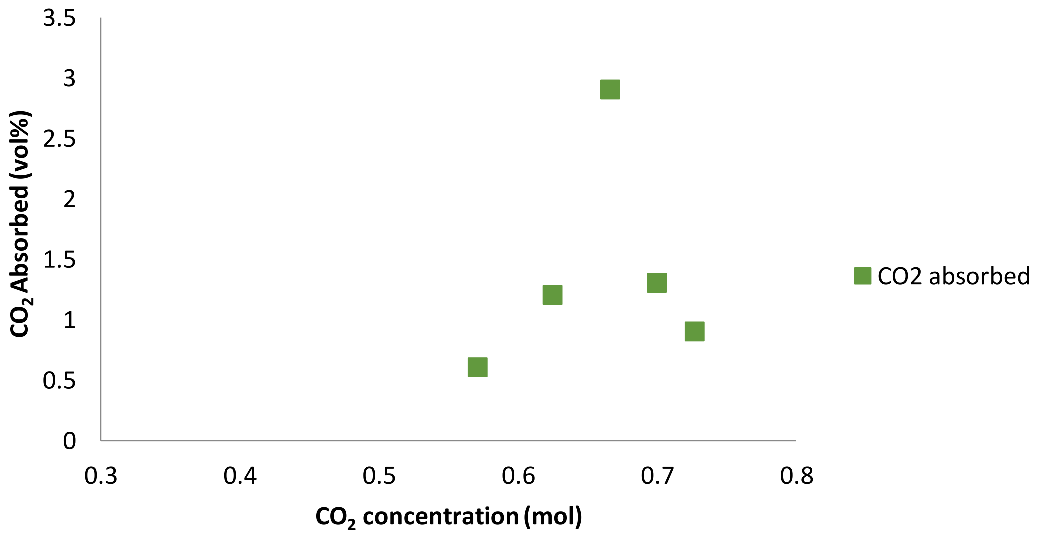


Figure 4.2: Effect of feed CO_2 concentration on CO_2 absorption on straight pipe

Figure 4.2 shows the effect of feed CO_2 concentration on CO_2 absorption on straight pipe. The increase of the feed CO_2 concentration (from 0.5 mol, to the peak of 0.625 mol of CO_2 causes the increasing of CO_2 absorption performance and it decreased from the peak of 0.625 mol to 0.7 mol. The highest CO_2 absorbed by using straight pipe is only 2.9 vol% and the lowest is 0.6 vol%.

In comparison with the performance of inline separator, the highest CO_2 absorbed is 4.2 vol% and the lowest is 1.6 vol%. This result shows that by using inline separator, the percentage of CO_2 absorbed can reach until 71% which considered higher separation occur using inline separator rather than using straight pipe.

4.2 Effect of Feed Flow Rates of Mixed Gases (Natural Gas and Carbon Dioxide)

Figure 4.2 shows the effect of different feed flow rates of mixed gases (natural gas and CO_2) of gas absorption performance. The pressure and flow rate of solvent (water) were maintained at 70 bar and 0.5 SLPM. In this experiment, the flow rates of natural gas and CO_2 is increases but maintain at 50% of CO_2 and 50% of natural gas.

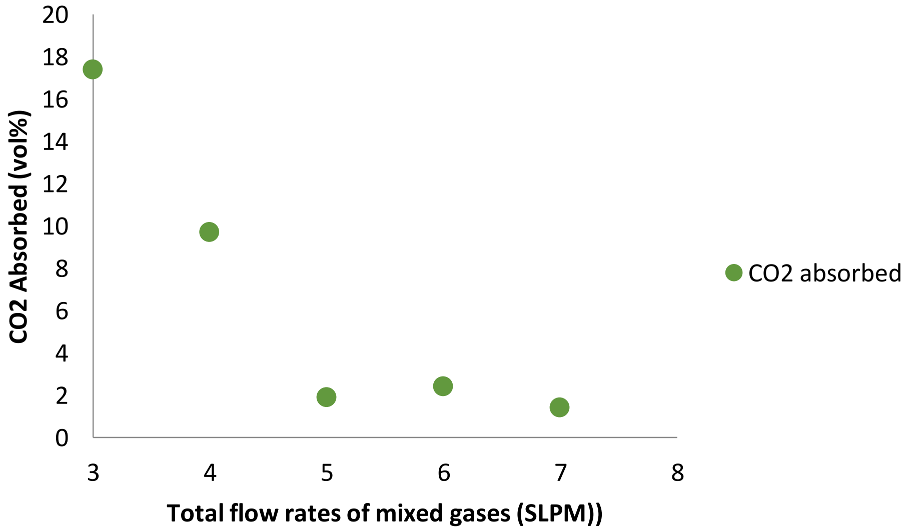


Figure 4.3: Effect of feed flow rates of mixed gases (natural gas and CO_2) on CO_2 absorption on inline separator

Based on Figure 4.2, the pattern of the CO_2 absorption decreases gradually when the total mixed gases flow rates increased. The performance reaches a plateau profile when the flow rate achieves 5 SLPM. The results can be associated with the first experiment on the effect of CO_2 concentration towards the CO_2 absorption. The CO_2 absorption reached a level where the solvent was limited to absorb the increase of the flow rates of natural gas and CO_2. To compare with absorption of CO_2 using packed column absorber (refer to Figure 4.3), it shows that higher flue gas flow rate under constant absorbent flow rate means shorter gas liquid contact time and leads to decreasing of CO_2 absorption (Park et al., 2004). This phenomenon is similar with the finding of current experiment.

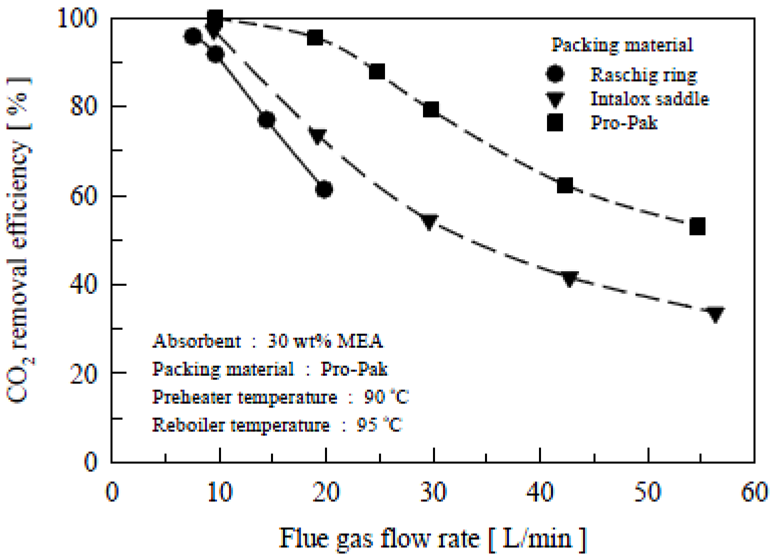


Figure 4.4: CO_2 removal efficiencies under different flue gas flow rates and packing material (Park et al., 2004)

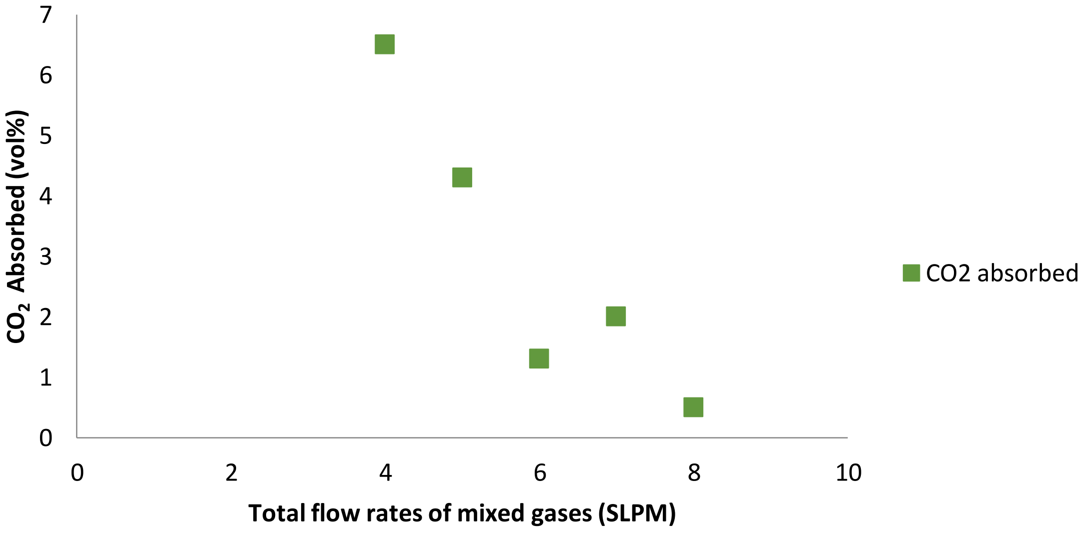


Figure 4.5: Effect of feed flow rates of mixed gases (natural gas and CO_2) on CO_2 absorption on straight pipe

Based on Figure 4.5, the pattern of the CO_2 absorbed is the same as the effect of feed flow rates of mixed gases (natural gas and CO_2) on CO_2 absorption on inline separator. When the feed flow rates of mixed gases increased, it is found that the CO_2 absorbed is decreases. The highest CO_2 absorbed can be achieved by using straight pipe is only 6.5 vol% and the lowest is 0.5 vol% which are much lower than the CO_2 absorbed using inline separator. The percentage of CO_2 absorbed using inline separator is 62% which is still high for a laboratory scale.

4.3 Summary

From the experiment conducted by using inline separator equipment, it can be concluded that the inline separator can still be absorbing the CO_2 even though the size smaller than the packed bed absorber.

Based on the experiment on the effect of feed concentration of CO_2, the CO_2 absorbed increases from 0.5 mol to the peak of 0.625 mol of CO_2 where 4.2 vol% of CO_2 absorbed and decreases until 0.7 mol of CO_2 where 2 vol% of CO_2 absorbed. This phenomenon happened because of the insufficient solvent injected to the inline separator where it is not able to further absorbed the increased of CO_2 gas. To compare with the straight pipe, the highest CO_2 absorbed is only 2.9 vol% which are 71% more efficient by using inline separator.

For the effect of feed flow rates of mixed gases, the CO_2 absorbed decreases steeply from 3 to 5 SLPM of mixed gases and decreases from 5 to 7 SLPM. This phenomenon can be associated with the first experiment on the effect of CO_2 concentration, where the solvent is limited and causes shorter gas liquid contact time to absorb the increase of the flow rates of natural gas and CO_2. In comparison with the use of straight pipe, inline separator shows that for the effect of feed flow rates of mixed gases it can reach until 62% of CO_2 absorbed.

Based on the parametric study, existing packed bed absorber is large and need a larger space while inline separator is compact and easily to be installed. The process of absorption in the packed bed absorber need to undergo retention time and also the experiment has to be conducted in steady state condition. Inline separator does not involve any steady state conditions where it still can absorb CO_2 from natural gas.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The main objective of current work to study the separation of CO_2 performance by using inline separator at different feed concentrations of CO_2 and also feed flow rates of mixed gases has been successfully achieved.

The physical absorption that has been implemented in inline separator shows that it is efficient enough to absorb the CO_2 from natural gas even though only use water as the absorbent.

Parametric studies have been conducted under unsteady state conditions where the experiment does not need to wait for the gas to stabilize in inline separator to undergo absorption. The pressure and the flow rate of the solvent were kept constant at 70 bar and 0.5 SLPM. The experiment on the effect of feed concentration of CO_2 on CO_2 absorption shows that when CO_2 concentration increased, the CO_2 absorbed increased until optimal absorption, and then decrease. For a laboratory scale, inline separator can absorb up until 71 percent of CO_2 at optimal conditions, 0.625 mol of CO_2 which considered high to be compared with the straight pipe. This is because it approaches the saturation loading of the solvent where solvent cannot absorb CO_2 more since it is limited to only 0.5 SLPM.

For the second experiment on the effect of feed flow rates of mixed gases (natural gas and CO_2), Figure 4.2 shows that when the flow rates of the mixed gases increased from 3 to 7 SLPM, the absorption of carbon dioxide decreases along the graph. The highest absorption occurred at 3 SLPM, which was about 62 percent of CO_2 absorbed in laboratory scale. The decrement of the CO_2 absorption is because the limited of solvent injected to the inline separator. This result can be associated with the first experiment where the solvent is not enough to support the increase of the CO_2 gases. In comparison with the straight tube, the CO_2 absorbed is higher and it shows that the efficiency of the inline separator is undeniable.

5.2 Recommendations

It is recommended to further study on the specification modeling of the inline separator to improve the absorption of CO_2. Simulation of the modeling can be done in order to get more accurate results of the absorption since inline separator is new equipment and there is a need to further study on it.

Some other parameters such as pressure, temperature, types of solvent, flow rates can be added to the experiment to show the performance of inline separator to absorb CO_2 from natural gas.

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APPENDICES

Appendix A: Physical Properties of Carbon Dioxide

Gas	Carbon Dioxide
Formula	CO_2
Molecular Weight (g/mol)	28.01
Density (kg/m^3)	1.977
Freezing temperature (K)	194.7
Boiling temperature (K)	216.6
Critical temperature (K)	304
Dynamic viscocity (µP)	147

Appendix B: Calculations and Data from Experiment

Calculation of mole fraction of carbon dioxide

$$mole\ fraction\ of\ CO_2 = \frac{V_{CO_2}(SLPM)}{V_{CO_2}(SLPM) + V_{NG}(SLPM)}$$

$$mass\ fraction\ of\ CO_2 = \frac{V_{CO_2}(SLPM) \times M_{CO_2}}{(V_{CO_2}(SLPM) \times M_{CO_2}) + (V_{NG}(SLPM) \times M_{NG})}$$

Where,

$\mathrm{V_{CO_2}}$ = flow rate of carbon dioxide

$\mathrm{V_{NG}}$ = flow rate of natural gas

$\mathrm{M_{CO_2}}$ = molecular weight of carbon dioxide

$\mathrm{M_{NG}}$ = molecular weight of natural gas

Data for Experiment A: Effect of Carbon Dioxide Concentration towards Carbon Dioxide Absorption

Natural Gas Flow Rate (SLPM)	Carbon Dioxide Flow Rate (SLPM)	Mole Fraction of Carbon Dioxide (mol)	Mole Fraction of Natural Gas (mol)	Carbon dioxide Absorbed
1.5	1.5	0.500	0.500	2.1
1.5	2.0	0.571	0.429	2.9
1.5	2.5	0.625	0.375	4.2
1.5	3.0	0.667	0.333	1.6
1.5	3.5	0.700	0.159	2

Data for Experiment B: Effect of Flow Rates of Mixed Gases towards Carbon Dioxide Absorption

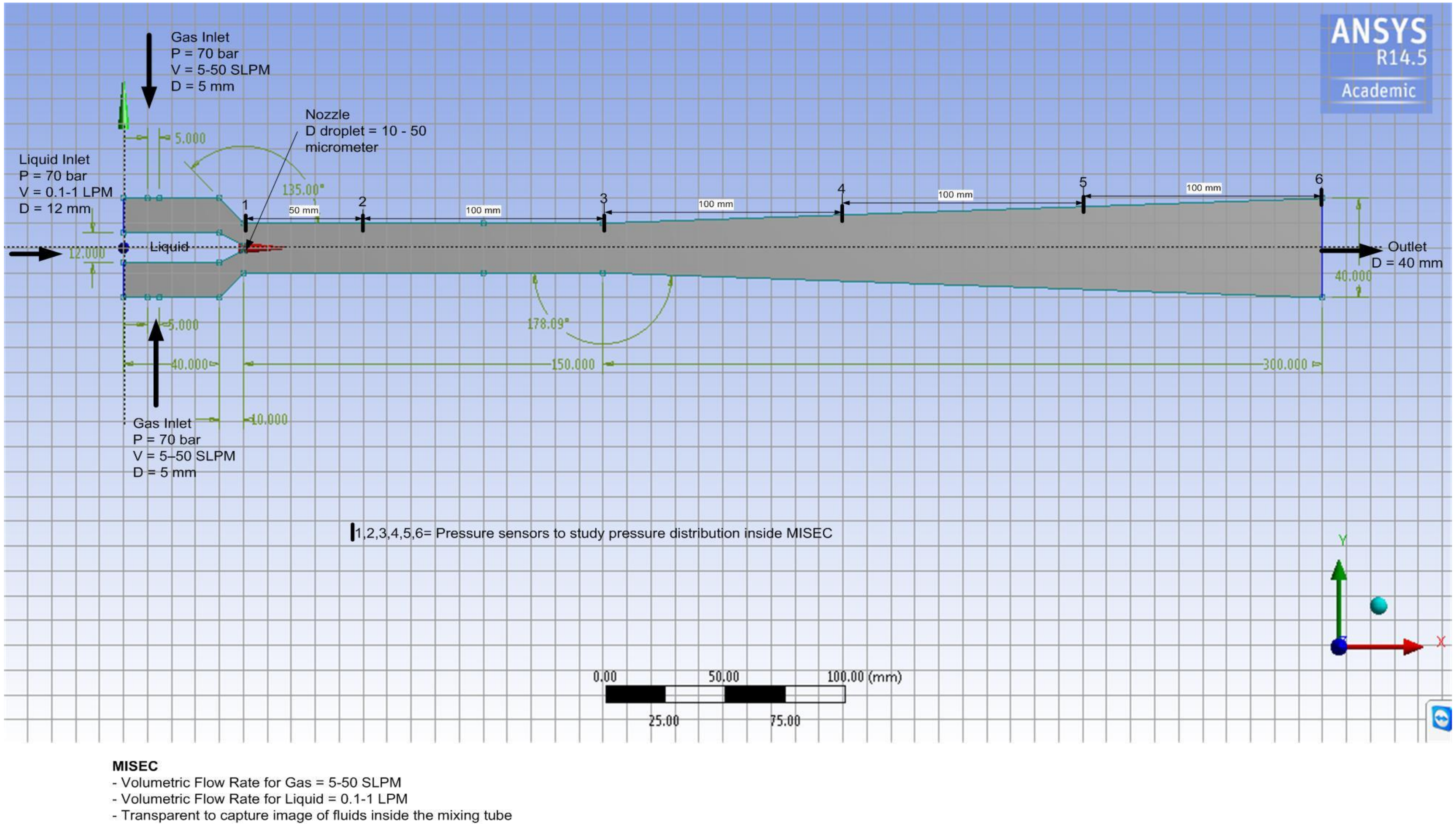
Natural Gas Flow Rate (SLPM)	Carbon Dioxide Flow Rate (SLPM)	Mole Fraction of Carbon Dioxide (mol)	Mole Fraction of Natural Gas (mol)	Carbon dioxide Absorbed
1.5	1.5	0.500	0.500	2.1
2.0	2.0	0.500	0.500	2.9
2.5	2.5	0.500	0.500	4.2
3.0	3.0	0.500	0.500	1.6
3.5	3.5	0.500	0.500	2.0

Appendix C: (CO_2SMU) Equipment

Figure C. 1: Inside view of permeation equipment (CO_2SMU)

Figure C. 2: Outside view of gas permeation equipment (CO_2SMU)

Figure C. 3: Inline separator equipment



MISEC
- Volumetric Flow Rate for Gas = 5-50 SLPM
- Volumetric Flow Rate for Liquid = 0.1-1 LPM
- Transparent to capture image of fluids inside the mixing tube

Figure C. 4: Inline separator configuration (Khalid, 2013)