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DISSERTATION REPORT

Experimental Measurement of Dew Points for High Carbon Dioxide Natural Gas

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CERTIFICATION OF APPROVAL

**Experimental Measurement of Dew Points for
High Carbon Dioxide Natural Gas**

By

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Approved by,

(DR. KHALIK BIN MOHD SABIL)

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CERTIFICATE 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.

(ANDREW DEVASAHAYAM THANARAJU)

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1. ABSTRACT

This project is all about the experimental measurement of dew points of natural gas which is high in carbon dioxide. Even though, there are several means to measure dew points, this project put its main focus on the PVT apparatus measurement which is the Fluid-Eval Vinci Standard Version. Carbon dioxide has a unique ability to reduce the dew point pressures and hence, measuring accurate and precise dew points for this kind of gas definitely going to be a challenging affair. Nevertheless, the main objectives of this particular project are to study and get a deep knowledge on the phase behavior for high carbon dioxide natural gas, to measure experimentally the dew points for high carbon dioxide natural gas using PVT equipment and also to predict the same dew points using commercial software. The final objective is to make a good comparison between the measurement and prediction results. The research methodology used in this project is firstly reading many articles and research papers to get good understanding on the fluid phase behavior. Secondly, measuring experimentally the dew points for high carbon dioxide natural gas and then predicts the dew points with the aid of commercial PVT software such as HYSYS, Multi Flash or CSMGem. Lastly, making comparison between the experimental measured dew points with the prediction to see how closely the deviations are related by calculating the average absolute deviation percent (AAD_p) and also percentage deviation (% DEV). Thus, by calculating the AAD_p value and % DEV value, we would be to minimize error in measuring in order to obtain much reliable and accurate dew points.

2. INTRODUCTION

2.1 Background of Study

There is always a hazard of hydrocarbon condensation in natural gas transmission pipelines because hydrocarbon liquid from condensation will increase the pressure drop and introduce operational problems resulting from two-phase flow. Therefore, it is very significant to prevent condensation by keeping the natural gas temperature and pressure in the single-phase region. Optimal control of the hydrocarbon dew point is consequently important for economical, operational and safety reasons.

Dew point pressure determination is an important measurement for any wet gas reservoir. Condensate blockage is liable to occur when the reservoir pressure decreases below the dew point pressure and this can effect in a reduction of gas productivity. Errors in measuring dew point pressures or temperatures can lead to errors in the estimation of the onset of condensate blockage and hence can bring negative impacts to the management of wet gas fields.

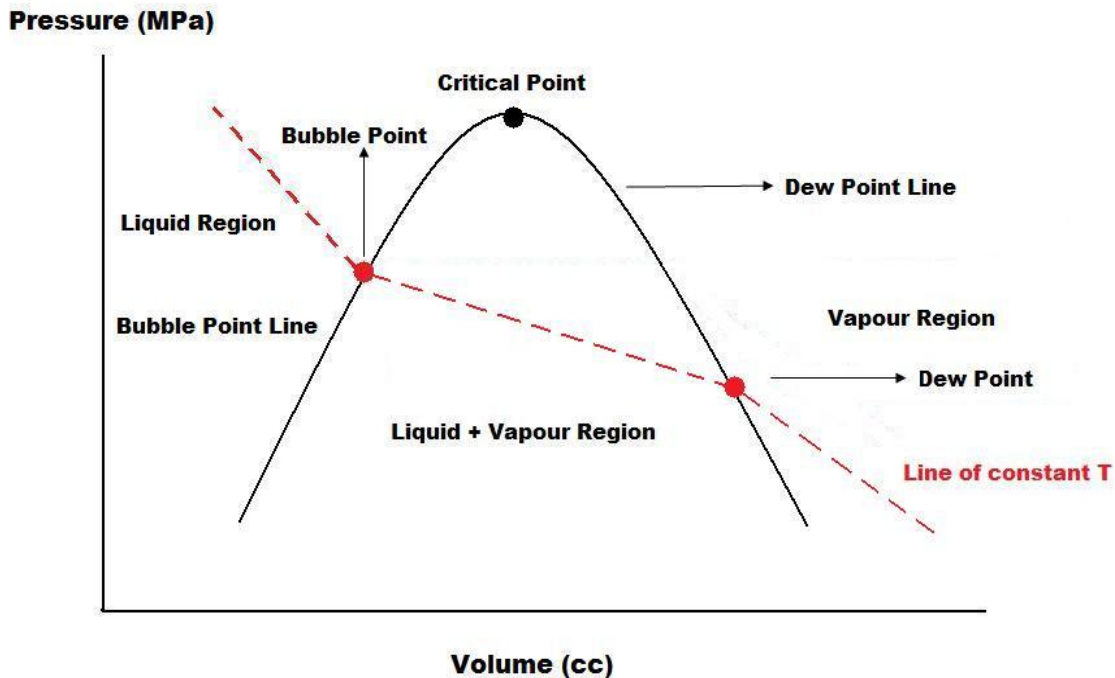


Figure 1: Pressure-Volume (P-V) Diagram which shows the dew point at the line of constant temperature

Based on Figure 1, the dew and bubble point method is suitable for binary mixtures only and has been used mostly for the investigation of high-pressure vapor-liquid equilibrium. The dew and bubble point pressures are determined from the P-V curve for each isotherm or from the T-V curve when isobaric measurements are made. The critical points can also be determined. Visual determination of the dew and bubble points was used in early studies. When a liquid composition is decompressed at constant temperature from a particular pressure to its saturated vapor pressure, an infinitesimal amount of vapor composition appears in the form of small bubbles. The point at which this occurs is called the bubble point as the formation of bubbles can be observed whereas; the dew point is observed when vapor composition is compressed from lower pressure to higher vapor pressure. Micro-drops of condensed liquid composition are visible in the form of opalescence as the pressure reaches the value of higher vapor pressure [13].

Carbon dioxide, CO_2 is a naturally occurring chemical compound composed of two oxygen atoms covalently bonded to a single carbon atom and exists as a gas at standard temperature and pressure. Production of carbon dioxide has many beneficial uses in the chemical industry and food industry. However, in the oil and gas industry, it is widely used for Enhanced Oil Recovery (EOR) where carbon dioxide is injected into or adjacent to producing oil wells usually under supercritical conditions when it becomes miscible with the oil. Hence, extensive pipe networks are used to carry the carbon dioxide to the injection points in the mature oil fields.

Besides that in enhanced coal bed methane recovery, carbon dioxide would be pumped into the coal seam to displace methane, as opposed to current methods which are predominantly just from water, which makes the coal seam to liberate methane. Undoubtedly, good pipelines are needed for the transportation of high carbon dioxide natural gas for the recovery processes. Nevertheless, carbon dioxide corrosion of carbon and low-alloy steels remains a major operational obstacle to successful hydrocarbon production, and its optimum control and management is regarded necessary for the cost-effective design of facilities and their safe operations [10].

Carbon dioxide corrosion or also known as sweet corrosion is not a new problem faced by the industry since it is recorded back in 1940s in USA. Dry CO₂ gas by itself is not corrosive at the temperatures encountered within oil and gas production. It needs to be dissolved in an aqueous phase to promote an electrochemical reaction between steel and the contacting aqueous phase. Hence, maintaining the proper dew point for the high carbon dioxide natural gas is indeed very fundamental with good operational condition in order to curb the sweet corrosion due to the condensed carbon dioxide.

2.2 Objectives

There are basically four main objectives that I would like to achieve via this project which are;

- i) To study and get a deep knowledge on the phase behavior for high carbon dioxide natural gas.
- ii) To measure experimentally the dew points for high carbon dioxide natural gas using PVT Fluid-Eval.
- iii) To predict the dew points for high carbon dioxide natural gas using commercial software.
- iv) To make a good comparison between the measurement and prediction results in order to obtain much accurate and reliable dew points.

2.3 Problem Statement

As for now, there is limited information provided for systems or equipments which are operating under high carbon dioxide natural gas. Even though, there are many projects related to experimental measuring of dew points but very few or none is very specific about measuring dew points for high CO₂ natural gas. Experimental measuring the dew point for high CO₂ natural gas is not an easy task to be done but needs lots of determination and proper skills with good experimental procedures to be employed. Besides that, carbon dioxide has a unique ability in reducing the dew point pressures. Hence, measuring dew points for high concentrated CO₂ of natural gas with minimum error as possible and a close deviation result with the prediction of PVT software is indeed a great challenge for an engineer to achieve.

2.4 Scope of Study

By carrying out this project, I will be exposed with the following studies;

- a) Fundamentals of reservoir fluid behaviors and properties
- b) Good understanding on the pressure- temperature diagram and phase envelope
- c) Understanding on the Equation of State such as Peng-Robinson and Soave-Redlich-Kwong
- d) PVT equipment Fluid-Eval and familiarize with commercial software such as HYSYS, CSMGem and Multi-Flash

2.5 Relevancy and Feasibility of the Project

This project is relevant to my field of engineering which is Petroleum Engineering since my two core subjects; Reservoir Engineering and Gas Field Engineering are very much about handling natural gas and its properties. Besides that, it is indeed an opportunity for me to implement all my theoretical studies into practice by carrying out this project. The time given to complete this project is feasible as I will be having adequate period from the beginning of January 2013 semester till the end of my final year semester on August 2013 which is approximately eight months. The given time frame is very suitable to conduct this project systematically as possible and also effectively.

3. LITERATURE REVIEW

3.1 Experimental Measurement of Dew Point

In order to accurately identify minimum pressure level that must be maintained in a gas reservoir, dew point pressure measurements can be conducted using a representative sample of the reservoir fluid in a PVT apparatus. For a wet gas reservoir, PVT experiments and analysis are needed to measure the dew point pressure at the known reservoir temperature. The simplest conventional method of determining the dew point pressure of a hydrocarbon gas mixture is a visual test that requires collection of a representative wet gas sample at reservoir conditions and testing it in a PVT cell chamber with a glass window [1].

During the dew-point experiment, the sample is first equilibrated at the initial reservoir conditions of pressure and temperature and then, starting from a high pressure gas phase, it is gradually depressurized in the PVT cell to observe physical changes through the glass window into the cell. The first instant of condensation, seen as slight clouding of the window, is referred to as the dew point pressure for the sample. The drawback of this method is that the observation of condensation can be biased and lead to erroneous estimation of dew point pressure leading to inaccurate wet gas characterization [2].

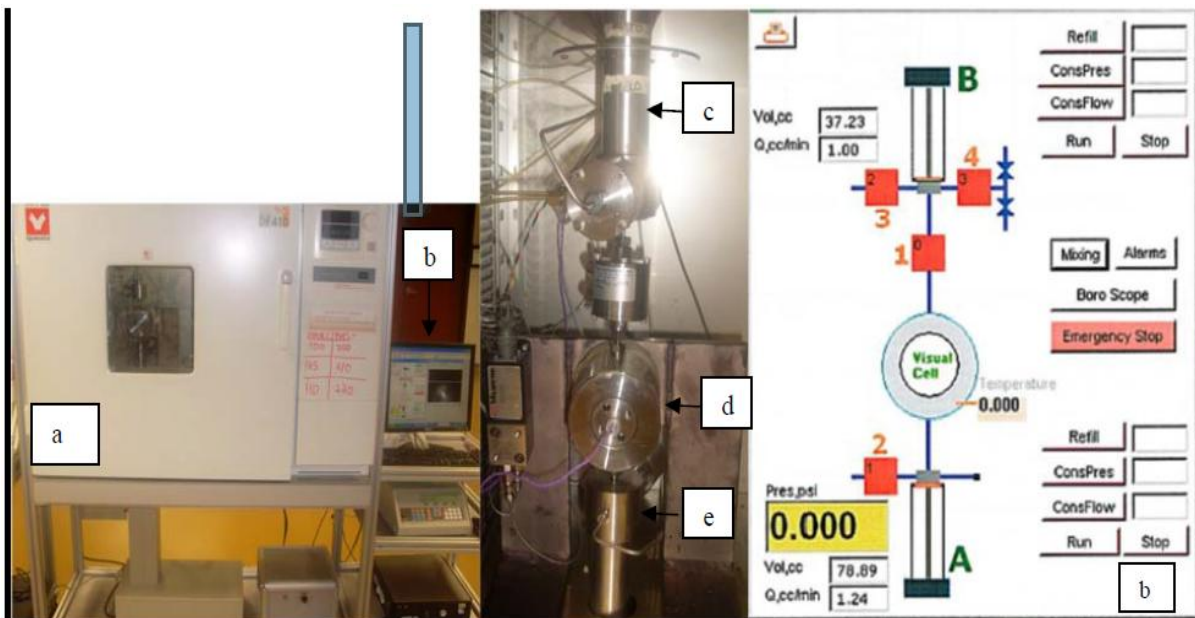


Figure 2: PVT System for Dew Point Measurement (a) Oven (b) Computer Gathering Equipment (c) Top Pump B (d) PVT Visual Cell (e) Bottom Pump A

A custom made chilled mirror apparatus for measurement of hydrocarbon dew points of dry- and rich natural gasses has been built up in the Statoil R&D laboratories in Trondheim, Norway. The experimental equipment consists of a piston circulating the sample back and forth between two equally large chambers. As the gas is circulated in a closed loop, it passes a mirror whose temperature is controlled by fitting a cooled copper rod to the back of it. The copper rod is cooled by a manually controlled liquid carbon dioxide cooling system. The cooling system allows dew point detection down to 230K at pressures up to 40MPa. The dew point mirror and cooling system are manufactured by Chandler Engineering [3].

Before conducting the dew point measurement, the experimental apparatus and all external piping are vacuumed at a controlled temperature of 320K for a minimum of 12 hours. Then, the system is filled with the gas sample to the highest possible pressure (gas bottle pressure was typically 10–12MPa). The system is stabilized by circulating the gas back and forth between the two chambers for half an hour. The mirror is cooled steadily and slowly while the gas was circulating at 400 accm/h until a visually observable amount of hydrocarbon precipitated on the mirror. The layout of the experimental equipment is illustrated as below.

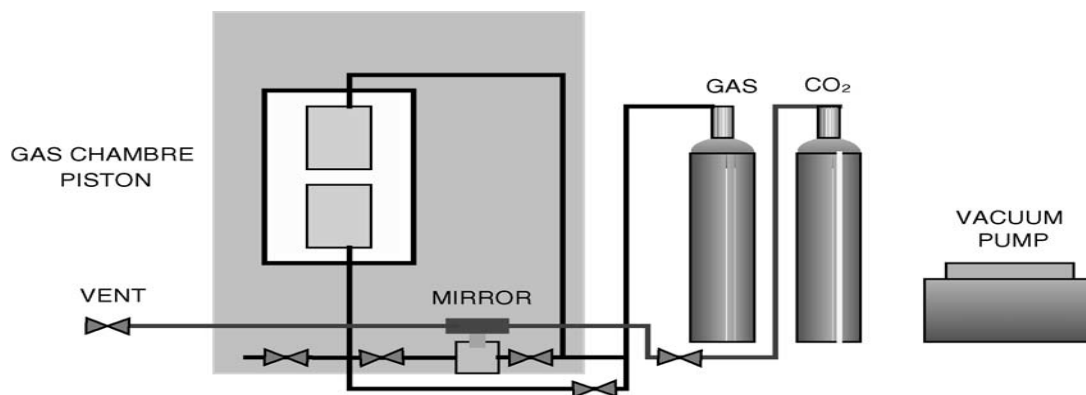


Figure 3: The dew point rig

All of the measured dew points are detected visually. It has been reported that measured dew point temperatures can be up to 5K lower than the true dew point for a detectable amount of gas to condense on the mirror. Nevertheless, the relatively large volume of the closed loop, constant gas circulation and the low cooling rate are expected to result in a measurement close to the true dew point.

In a research paper entitled measurement and prediction of dew point curves of natural gas mixtures, dew point measurements for six synthetic natural gas (SNG) mixtures were performed using a custom made chilled mirror apparatus. The experimental data cover a temperature-range from 253 to 285 K and a pressure-range from 3 to 105 bar. The recently developed universal mixing rule of Peng Robinson (UMR-PRU) model was revised and applied to these experimental data as well as to other dew point data for synthetic and two real natural gas mixtures reported in the literature [11]. One of the SNG contained the highest carbon dioxide concentration which is about 25.9080 percent and the rest components are nitrogen, methane, ethane, propane, i-Butane, n- Butane, i-Pentane and n- Pentane. The figure below shows the phase envelope that been plotted for SNG 10 which has the highest CO₂ composition.

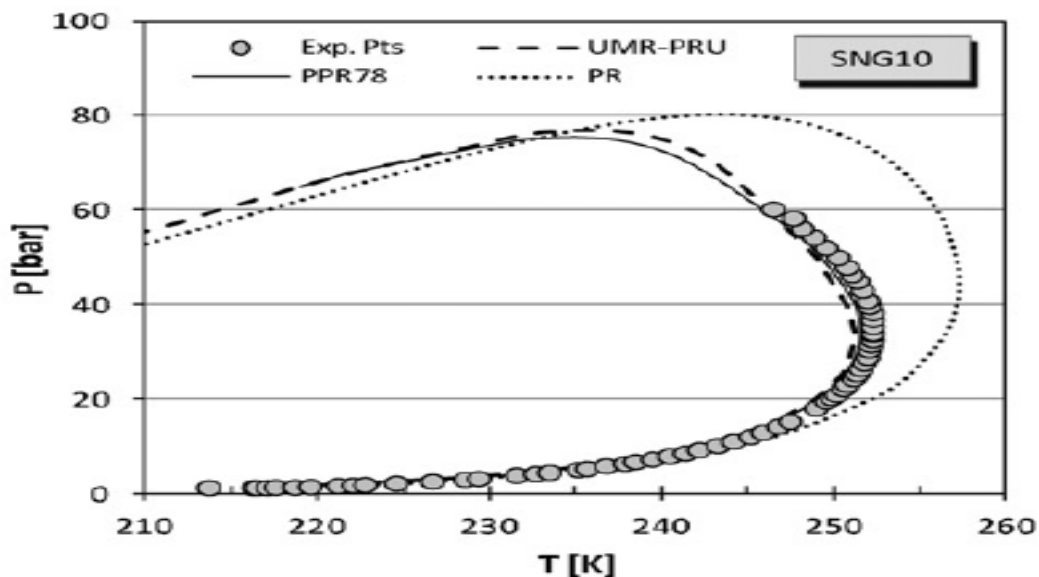


Figure 4: Phase envelope for SNG 10

Based on the Figure 4, we could see that the experimental points of the phase envelope of SNG 10 shift towards a bit to the left which indicates that SNG 10 consists of heavier hydrocarbons that is more on the liquid region. However, phase envelope of lighter hydrocarbons tends to be more on the right hand side where the region of vapor is more. Even though, the experimental points much deviated from the Peng Robinson (PR) prediction, it is much aligned to the UMR-PRU model prediction and also the PPR 78 model.

3.2 Development of Experimental Equipment and Method

In a research paper by Antonin Chapoy, Rod Burgass, Hooman Haghighi and Bahman Tohidi (2011), they have presented an experimental equipment which is the bubble point apparatus. The experimental set-up consists of an equilibrium cell, cryostat, rocking/pivot mechanism, and temperature/pressure recording equipment controlled by a PC. The equilibrium cell is a piston-type variable volume which has a maximum effective volume of 300 ml, titanium cylindrical pressure vessel with mixing ball, mounted on a horizontal pivot with associated stand for pneumatic control and rocking through 180 degrees. Rocking of the cell, and the subsequent movement of the mixing ball within it, ensures adequate mixing of the cell fluids. For the tests reported here, the cell was rocked through 180 degrees at a rate of 8 times per minute. Cell volume, therefore pressure, can be accustomed by injecting or withdrawal of liquid behind the moving piston.

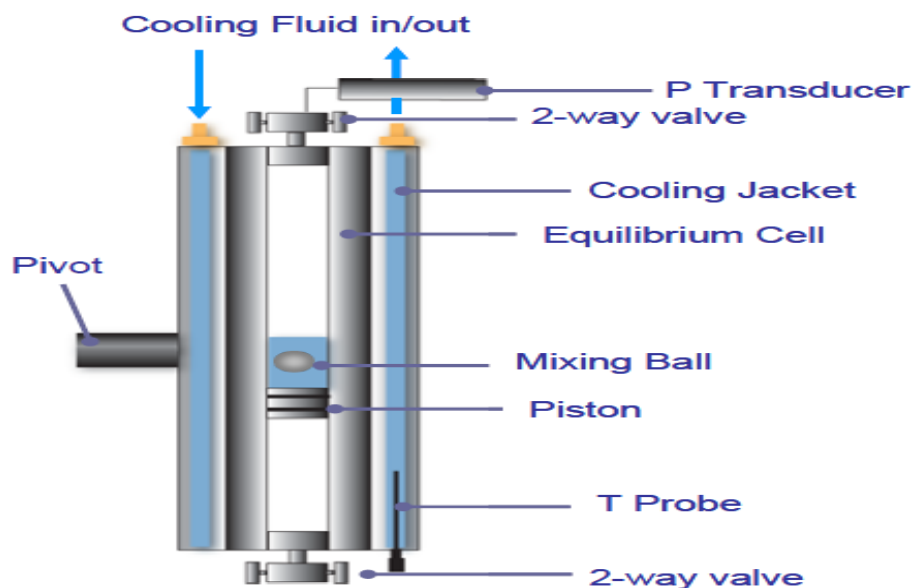


Figure 5: Schematic Illustration of Equilibrium Rig

The rig has a working temperature range of -80 to 50 °C, with a maximum operating pressure of 700 bar. System temperature is controlled by circulating coolant from a cryostat within a jacket surrounding the cell. The cryostat is capable of maintaining the cell temperature stability to within better than 0.05 °C. To achieve good temperature stability,

the jacket is insulated with polystyrene board, while connecting pipe work is covered with plastic foam. The temperature is measured and monitored by means of a Platinum Resistance Thermometers (PRT) located within the cooling jacket of the cell which is calibrated regularly against a Prema 3040 precision thermometer. Cell temperature can be measured with an accuracy of ± 0.05 °C. A Quartzdyne pressure transducer with an accuracy of ± 0.08 bar is used to monitor pressure. Temperature and Pressure are monitored and recorded by the PC through an RS 232 serial port.

A typical test to determine the bubble point of the CO₂/H₂ mixture can be conducted firstly with the cell is charged with the test sample and set to the desired temperature for the measurement. The sample volume is then reduced by pumping liquid into the cell which is actually behind the moving piston, at the opposite end to the sample. By this means the sample pressure is increased such that the sample is at a pressure significantly higher than the expected bubble point pressure. The cell is then rocked to mix the contents and ensure equilibrium. The sample volume is then increased step-wise by removing measured quantities of the pumped liquid behind the piston. At each step mixing is continued until equilibrium is achieved, indicated by a constant pressure. The stabilized equilibrium pressures and change in sample volumes are plotted and the bubble point is indicated by a sharp change in the pressure versus volume plot [4].

3.3 Wet Gas Dew Point Change with CO₂ Concentration

According to Odi, El Hajj and Gupta [1], they have claimed that carbon dioxide (CO₂) has a unique ability in reducing the dew point pressures. It is experimentally observed in a plot of relative volume which is the PVT volume divided by the volume at dew point. The relative volume plot indicates that CO₂ decreases the corresponding pressure observed during CCE. The Peng Robinson approximation of the relative volume also indicates the same relationship. In fact, the overall phase diagram of the gas condensate illustrates that the phase envelope decreases as a function of CO₂ concentration. This can be vividly shown in Figure 6 below.

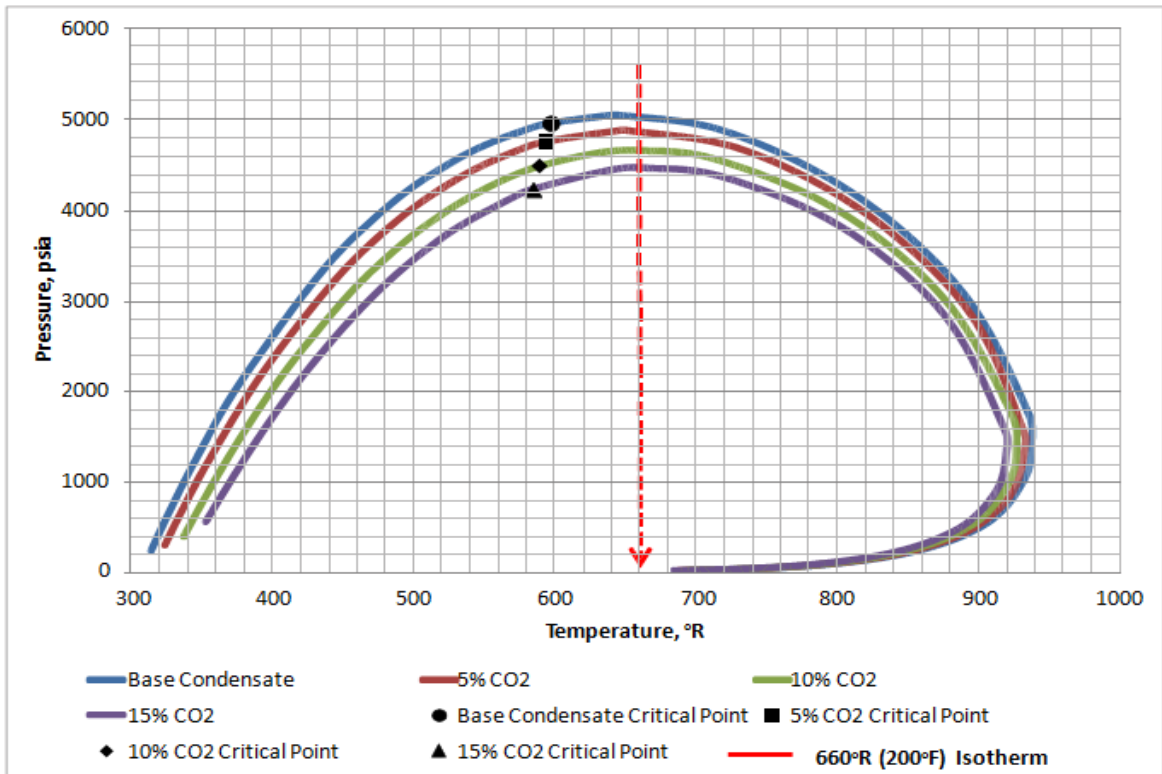


Figure 6: Peng Robinson Phase envelope of gas condensate as function of CO₂ Concentration

In addition to that, Monger et al. (1981) observed that CO₂ has the ability to lower miscible pressures for paraffin fluids that do not contain large amount of aromatic content. In terms of gas condensate system, this means that CO₂ forces the lighter end hydrocarbons into the rich CO₂ rich phase. This is beneficial because the CO₂ rich phase is a supercritical gas in typical reservoir conditions which implies that CO₂ is lowering the hydrocarbon's dew point pressure.

3.4 Dew Point Prediction with model based on Equation of State (EOS)

In order to describe the phase envelopes for five synthetic natural gas mixtures, the Redlich-Kwong (RK) equation of state [5] with Mathias and Copeman (MC) temperature dependent term [6] are implemented (RKMC). The pressure–volume–temperature relationship for the RKMC equation of state may be expressed as below:

$$P = \frac{RT}{v - b} - \frac{a_C \alpha(T_r)}{v(v + b)} \quad (1)$$

with

$$b = 0.08664 \frac{RT_C}{P_C} \quad (2)$$

$$a_C = 0.42748 \frac{R^2 T_C^2}{P_C} \quad (3)$$

While the temperature dependent attractive term for the Soave-Redlich-Kwong (SRK) equation of state [7] is expressed by ;

$$\alpha(T_r) = [1 + (0.48 + 1.574\omega - 0.176\omega^2)(1 - \sqrt{T_r})]^2 \quad (4)$$

the temperature dependent terms for the RKMC equation are:

$$\alpha(T_r) = [1 + c_1(1 - T_r^{0.5}) + c_2(1 - T_r^{0.5})^2 + c_3(1 - T_r^{0.5})^3]^2, \quad T_r \leq 1 \quad (5)$$

and

$$\alpha(T_r) = [1 + c_1(1 - T_r^{0.5})]^2, \quad T_r > 1 \quad (6)$$

where subscripts C and r stand for the critical and reduced properties, respectively, P the pressure, R the universal gas constant, T the temperature, v the specific volume, b the molar co volume, a_C the attractive parameter at the critical point and ω is the acentric factor. The coefficients c_1 , c_2 and c_3 are specific to each component and are normally determined by fitting the equation of state with the Mathias and Copeman temperature dependent term to the vapor pressure of pure compound. Nasrifar and Moshfeghian [8] and Nasrifar et al. [9] provided tables of Mathias and Copeman coefficients. Hence, a new model is introduced which is similar to RKMC equation of state aforementioned in order to improve dew point predictions.

4. METHODOLOGY

4.1 Research Methodology

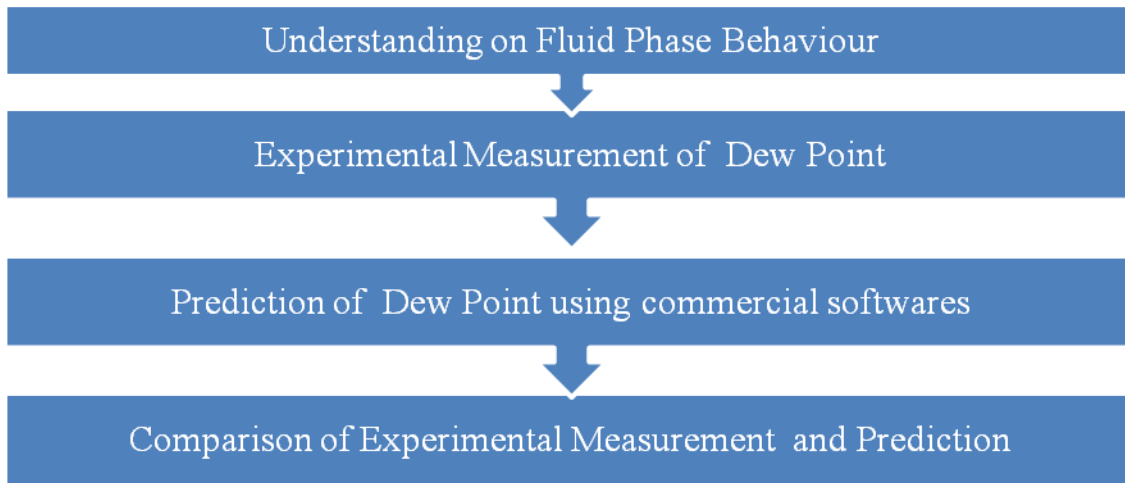


Figure 7: The schematic diagram depicting the general approach in this project

4.1.1 Understanding on Fluid Phase Behavior

- Reading articles, journals and books regarding the reservoir fluid behavior to get a deep understanding on how fluid behaves at various pressures and temperatures.
- Grasp the main idea behind the pressure-temperature diagram and understand how significant the dew-point measurement is.

4.1.2 Experimental Measurement of Dew Point

Materials:

No	Material	Supplier
1	carbon dioxide	Gas Walker Sdn. Bhd
2	methane	
3	ethane	
4	propane	
5	i-butane	
6	n-butane	
7	nitrogen	

Apparatus: Fluid Eval Standard Version – PVT system for oil and gas system

The mercury free Fluid Eval analyser in its standard version is designed to study phase behaviour of hydrocarbon fluids at reservoir conditions of pressure and temperature. It is based on an embedded high pressure pump used to generate the pressure and to measure accurately the volume of test fluid.

Features of the PVT equipment:

Pressure: 10,000 psi or 15,000 psi

Temperature: Ambient to 175°C (350 °F) higher range upon request option

Cooling: -20°C to ambient

Temperature regulation: ± 0.5 oC

Cell volume: 500 cc

Volume accuracy: 0.01 ml

Pressure accuracy: 0,1% Full scale

Liquid deposit accuracy: ± 0.01 ml

Stirring mechanism: Magnetic drive

Power supply: 220 VAC 50 Hz



Figure 8: Fluid-Eval Standard Version which is used to measure bubble and dew points.

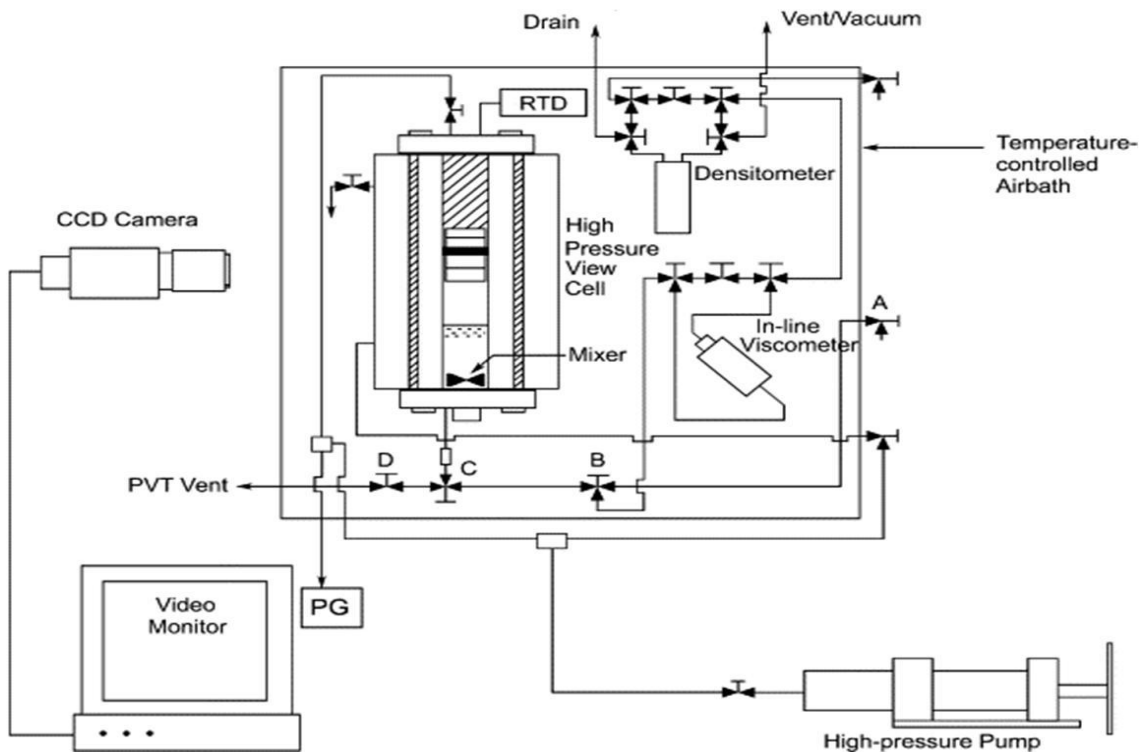


Figure 9: Schematic Diagram of Fluid Eval Standard Version

Preparation of Apparatus:

- 1) The equipment and personal computer is switched on.
- 2) All connections are checked to be properly connected.
- 3) The cell and the tank are vacuumed to 12 psig.
- 4) The cell is filled with prepared test sample
- 5) The pressure and temperature with test conditions are set.

Experimental Procedures:

- 1) Firstly, the gas sample is set with the dew point measurement condition with temperature of 0 degree Celsius and starting pressure with 4.6 MPa (referring to point C in the Figure 10).
- 2) With isothermal process at constant temperature, the pressure is increased to point D where a drop of liquid is formed and the process is continued till point E until we have enough liquid formation in the PVT cell.

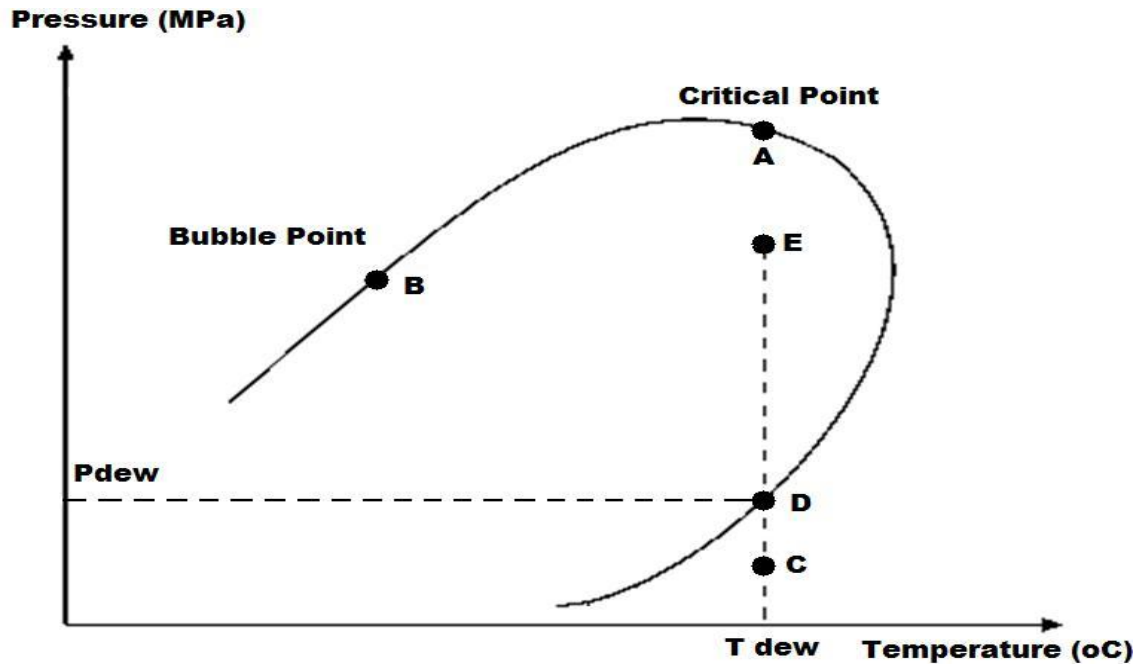


Figure 10: Pressure – Temperature Diagram

- 3) Once the liquid build-up is adequate, the system is depressurized gradually in the PVT cell from point E to D back to observe physical changes through the glass window into the cell.
- 4) The point where the last drop liquid disappears at point D is referred to as the dew point pressure at the required fix temperature for the gas sample. The dew point pressure is noted down and captured in the Excel file.
- 5) Step 1 till 4 are repeated thrice for the same fix temperature in order to obtain much accurate and precise dew point pressure to avoid any biasness and error in measuring.
- 6) Once all the dew point pressures are noted down and captured, smoothening of the data is needed with the aid of Polyfit of Matlab to produce good quality experimental data without any fluctuations.

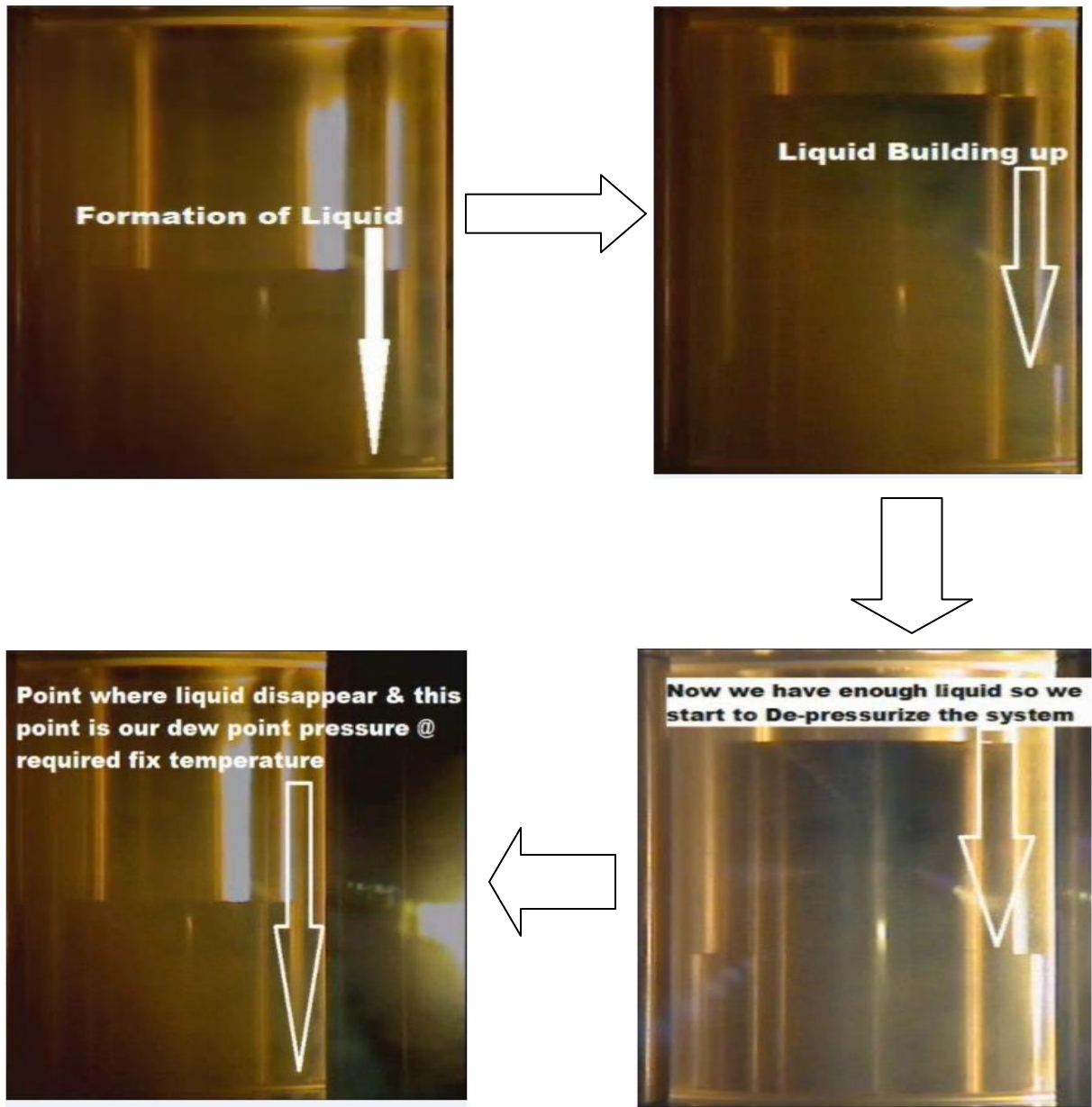


Figure 11: Sequence Diagram of the Experimental Procedure

4.1.3 Prediction of Dew Point Using Commercial Software

- Get familiarize with PVT software such as Multi Flash, CSMGem and HYSYS and get to know the features well.
- Predict the dew points for high CO₂ natural gas by applying the most suitable equation of state and also insert the correct value of composition for each gas mixture into the software.

- Run the prediction with appropriate operating condition of setting temperature and pressure.

4.1.4 Comparison of Experimental Measurement and Prediction

- Compare the results of dew point from the experimental measurement and prediction by calculating the average absolute deviation percent (AAD_P). Given below is the formula for AAD_P [22]:

$$AADP\% = \frac{100}{n_p} \sum_1^{n_p} \left| \frac{P_{cal} - P_{exp}}{P_{exp}} \right|$$

n_p = number of components

P_{cal} = Calculated pressure from software prediction

P_{exp} = Experimental pressure from Fluid-Eval

- And also by calculating percentage deviation (% DEV). By applying the formula below, % DEV can be calculated [16] :

% DEV = (P_{cal} – P_{exp}) / P_{exp} * 100%

P_{cal} = Calculated pressure from software prediction

P_{exp} = Experimental pressure from Fluid-Eval

- See how reliable and consistent both experimental and predicted data to each other and make steps in reducing error of dew points measurement.

4.2 Project Activities

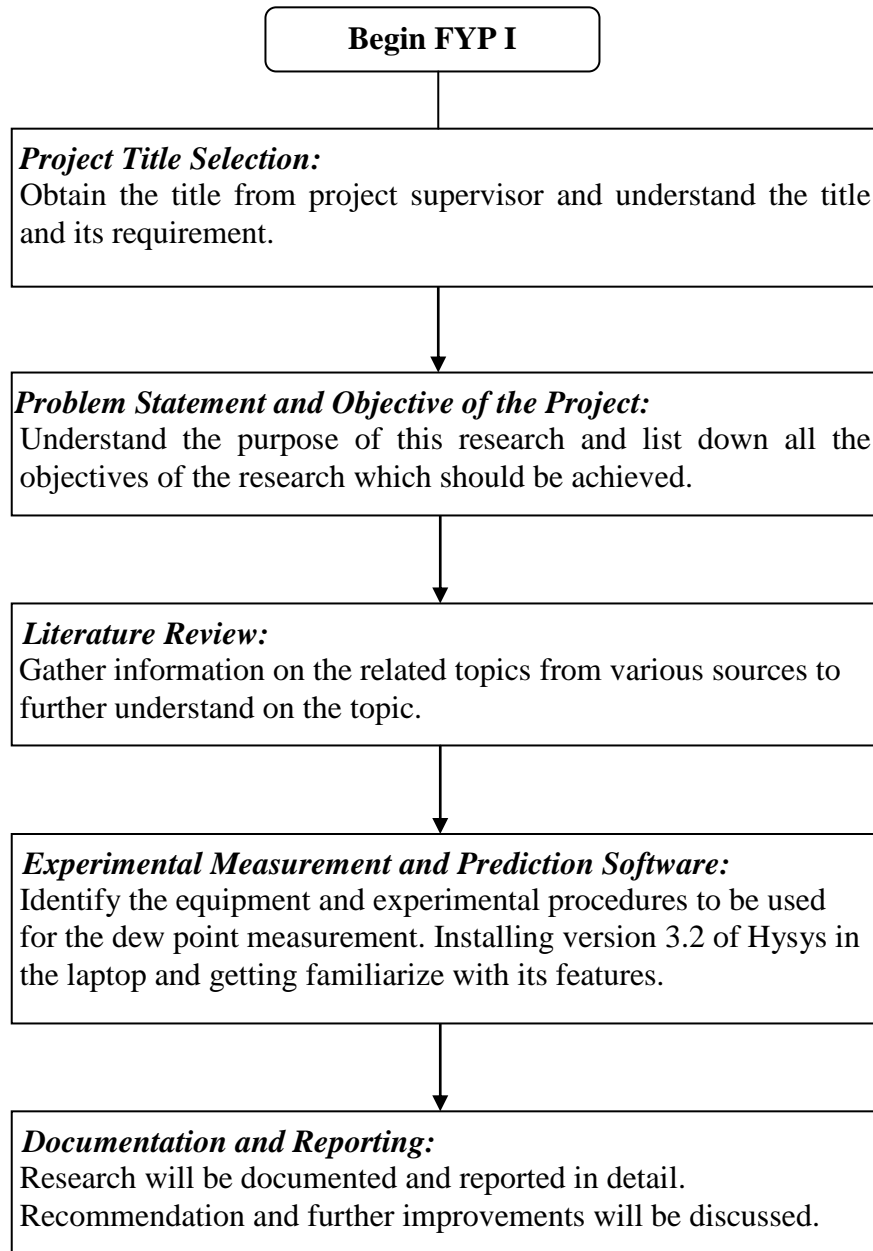


Figure 12: Project Activities Flowchart for FYP 1

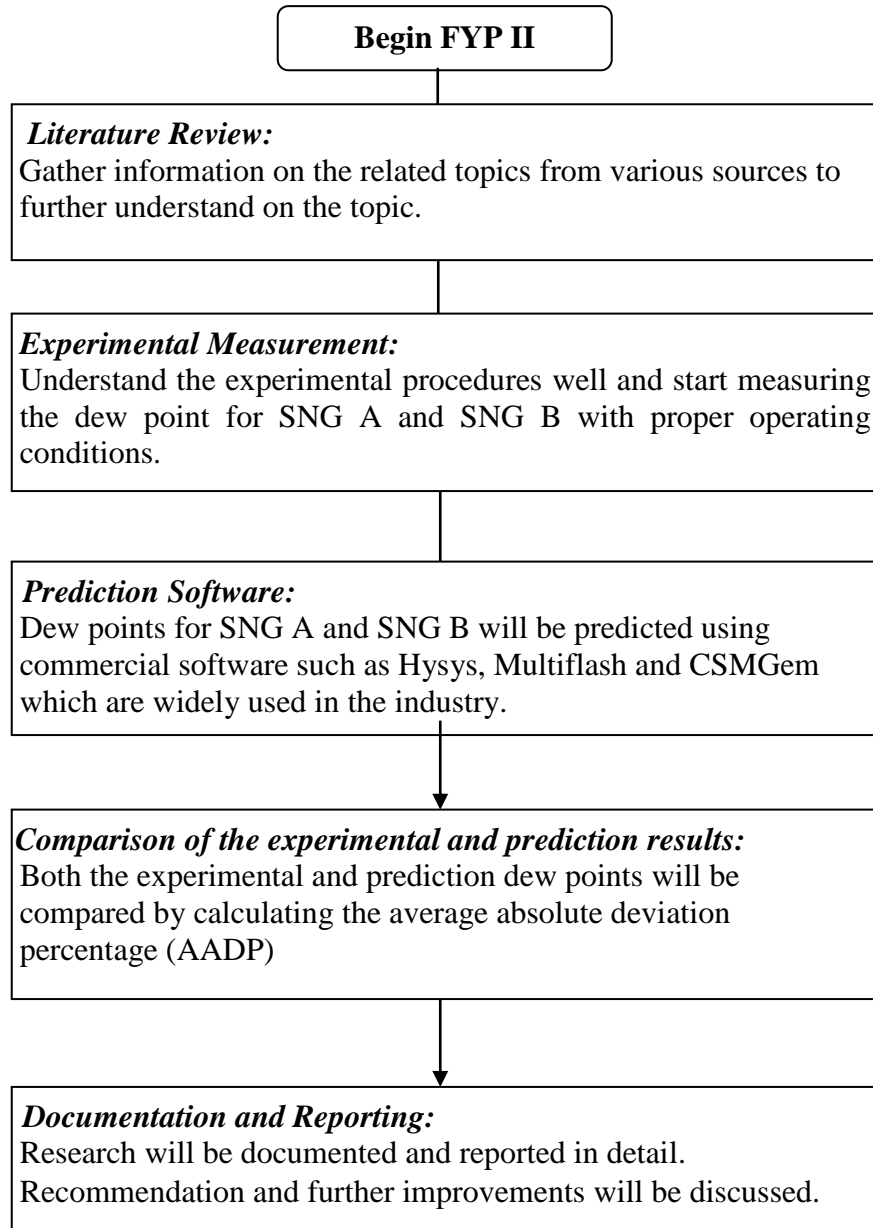


Figure 13: Project Activities Flowchart for FYP II

4.3 Key Milestones

The key milestone for Final Year Project 1 is as follows;

Events or Deliverable	Week	Responsibility
Project Selection and Acceptance by Supervisor	Week 1-2	Discuss the project topic and approval of topic from Supervisor.
Project execution initiated	Week 2-5	Research of project. Understanding the main concepts behind the reservoir fluid behavior and properties.
Submission of Extended Proposal	Week 7	Submission of Extended Proposal to FYP Coordinator.
Proposal Defense (Seminar Presentation)	Week 8-9	Report on the progress of project to supervisor, examiner and fellow students.
Project execution continued	Week 10-12	Continue on project activities.
Submission of Interim Report	Week 14	Hand in Interim Report to FYP Coordinator.

Table 1: Events or Deliverable of Key Milestones of FYP I

The key milestone for Final Year Project II is as follows;

Events or Deliverable	Week	Responsibility
Experimental Measurement of SNG A	Week 1-3	Measure the dew points for SNG A with the proper operating conditions with the PVT Fluid-Eval.
Experimental Measurement of SNG B	Week 3-5	Measure the dew points for SNG B with the proper operating conditions with the PVT Fluid-Eval.
Dew Point Prediction for SNG A	Week 5-6	Predict the dew points for SNG A with some commercial softwares
Dew Point Prediction for SNG B	Week 6-7	Predict the dew points for SNG B with some commercial softwares
Submission of Progress Report	Week 8	Submission of Progress Report to FYP Coordinator.
AADP calculation	Week 9	Calculate the AADP value with the proper formula.
Report and Documention	Week 9-14	Compiling and making full report on the research.
Pre-Sedex Presentation	Week 10	Poster presentation to be conducted in front of the SEDEX examiners.
Submission of Draft Report, Dissertation and Technical Paper	Week 11-12	Hand in soft bound of Dissertation and Technical Paper to FYP Coordinator.
Viva Presentation	Week 13	Prepare Power Point Slides and present the project to supervisor and external examiners
Submission of Project Dissertation	Week 15	Hand in the hardbound of Project Dissertation to FYP Coordinator.

Table 2: Events or Deliverable of Key Milestones of FYP II

4.4 Study Plan (Gantt Chart)

No.	Details / Weeks	1	2	3	4	5	6	7		8	9	10	11	12	13	14	
1	Selection of Project Topic	■	■						MID SEM BREAK								
2	Preliminary Research work i. Literature reviews ii. Understanding the theory and concepts		■	■	■	■	■										
3	Submission of Extended Proposal							●									
4	Proposal Defense										■	■					
5	Project work continues i. Literature reviews (continue) ii. Getting familiarize with PVT Equipment iii. Getting familiarize with PVT Software												■	■	■		
6	Submission of Interim Draft Report																●
7	Submission of Interim Report																●

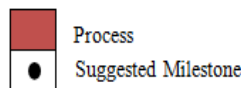


Table 3: Gantt chart and Key Milestones for FYP I

No	Description	Week No														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	PVT Measurement of Dew Point for SNG A	■	■	■												
2	PVT Measurement of Dew Point for SNG B		■	■	■	■										
3	Dew Point Prediction for SNG A				■	■	■									
4	Dew Point Prediction for SNG B					■	■									
5	Submission of Progress Report								●							
6	AADP Calculation									■						
7	Reporting and Documentation									■	■	■	■	■	■	
8	Pre-SEDEX Presentation										●					
9	Submission of Draft Report											●				
10	Submission of Dissertation (Soft Bound)												●			
11	Submission of Technical Paper												●			
12	Viva Presentation													●		
13	Submission of Project Dissertation (Hardbound)															●

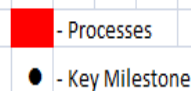


Table 4: Gantt chart and Key Milestones for FYP II

4.5 Tools

Besides the main equipment, PVT Fluid-Eval, it is necessary to have certain commercial software in order to fulfill this project. Listed below are the software which will be used to conduct the project to aid with the dew points prediction;

a) Aspen HYSYS®

Aspen HYSYS is an easy to use process modeling environment that enables optimization of conceptual design and operations. Aspen HYSYS has a broad array of features and functionalities that address the process engineering challenges of the energy industry.

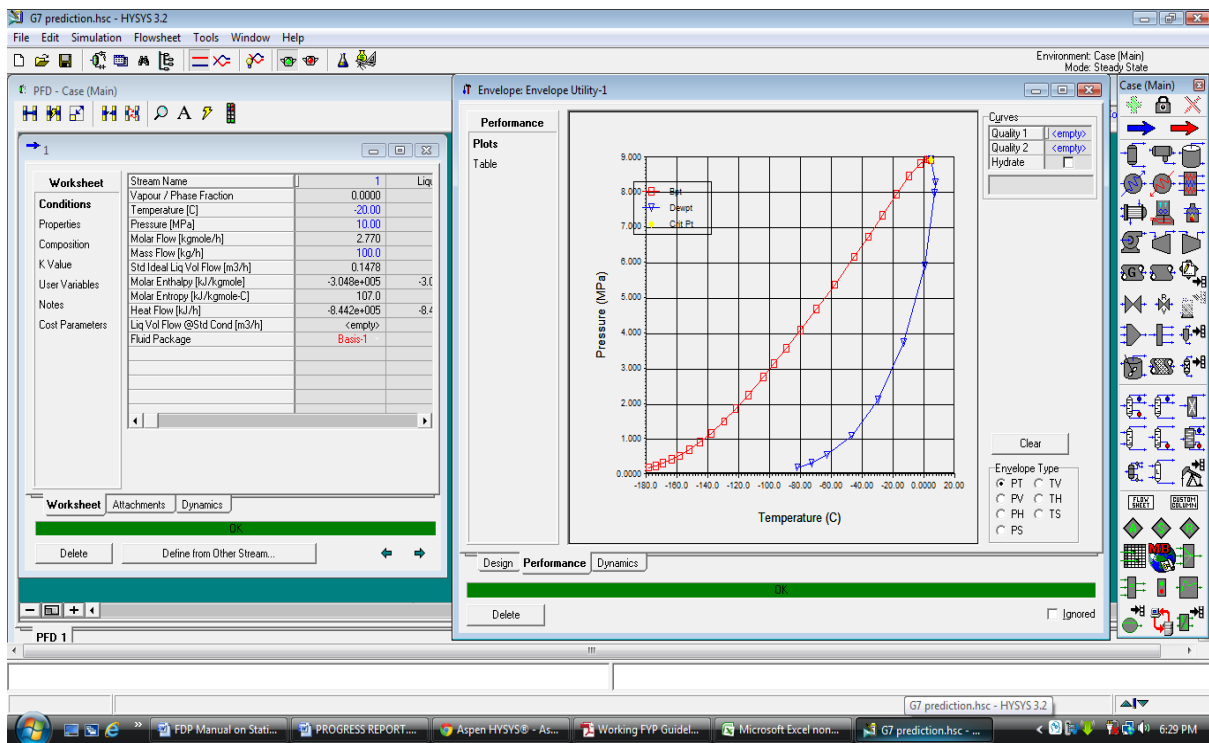


Figure 14: Screen shot of Aspen HYSYS software with its graphical user interface

b) MutiFlash™

An Infochem's rich software and intellectual property in the chemistry of oil and gas fluids enable accurate modelling of reservoir fluids to maximise production.

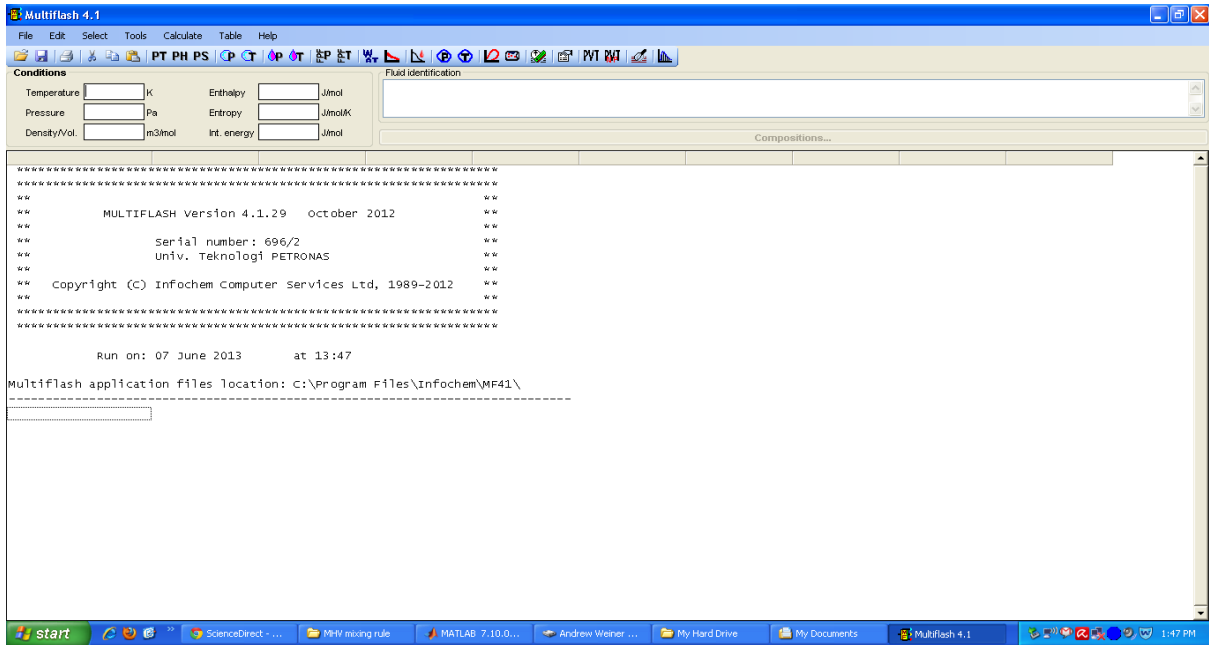


Figure 15: Screen shot of MultiFlash version 4.1 with its graphical user interface

c) CSMGem

CSMGem is a program written for the prediction of the thermodynamically stable hydrates structures and cage occupancy at given pressure, temperature and composition conditions by minimization of the Gibbs free energy of the specified system.

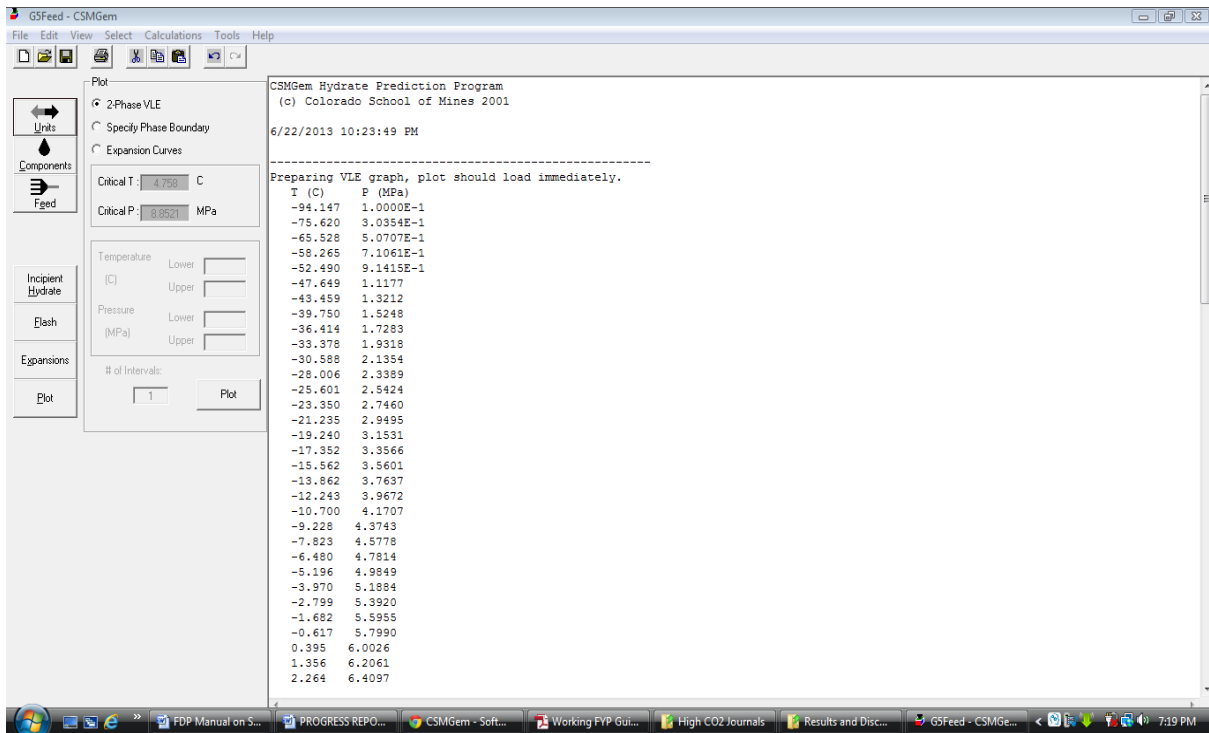


Figure 16: Screen shot of CSMGem with its graphical user interface.

5. RESULTS AND DISCUSSION

5.1 Experimental Data

The composition for the SNG A and SNG B are given in Table 3 and Table 4 respectively. SNG A consists of seven gas components and SNG B consists of five gas components. SNG A has carbon dioxide concentration of 69.14 mole percentage; where as SNG B has carbon dioxide concentration of 69.37 mole percentages which is slightly higher. Besides that, both SNG have methane, ethane, propane and nitrogen. However, only SNG A has i-butane and n-butane gas composition which makes SNG A much heavier gas mixture compared to SNG B. All the gases were supplied by Gas Walker Sdn. Bhd.

Components	Mole Percentage
Methane	26.20
Ethane	0.93
Propane	0.29
i-Butane	0.17
n-Butane	0.17
CO ₂	69.14
Nitrogen	3.10
Total	100

Table 5: Composition of SNG A

Components	Mole Percentage
Methane	26.30
Ethane	0.94
Propane	0.29
CO ₂	69.37
Nitrogen	3.10
Total :	100

Table 6: Composition of SNG B

Using the procedures mentioned earlier, the dew point conditions for the two synthetic natural gas mixtures (SNG A and SNG B) which are typical raw gas composition from the gas reservoirs were measured in PVT Fluid Eval from Vinci Technologies. The experimental data gives the dew point conditions for wide ranges of temperature and pressure. The temperature ranges approximately from -20 to 2 °C and pressure from 3 to almost 6 MPa. In addition, both the experimental pressure and temperature range are chosen to best suit the pipeline condition and also the cryogenic process separation. The experimental data of SNG A and SNG B were plotted in graphical form in Figure 17 and Figure 18 respectively.

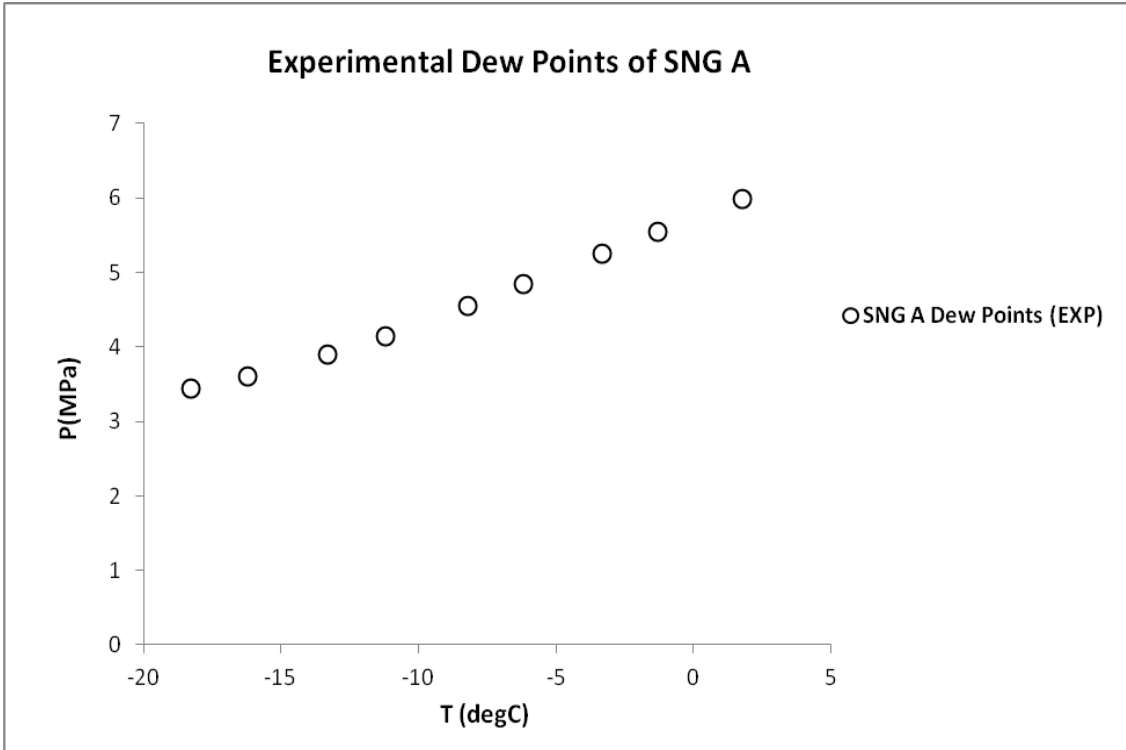


Figure 17 : Experimental Dew Points of SNG A

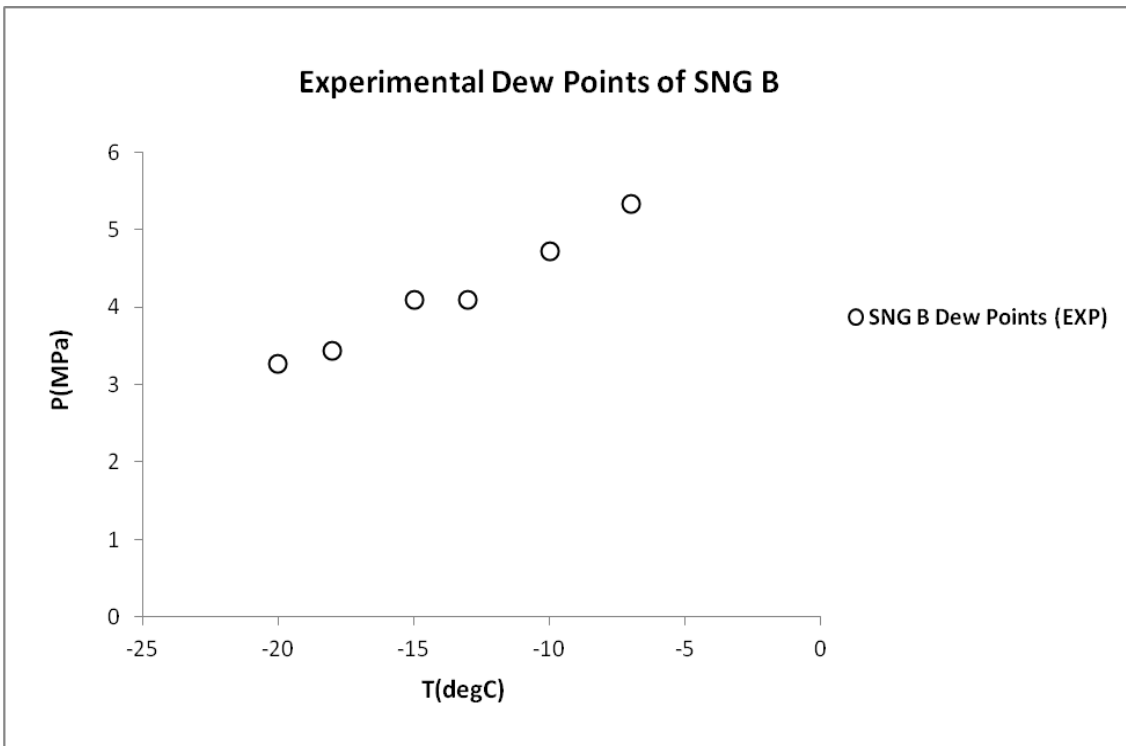


Figure 18: Experimental Dew Points of SNG B

Based on Figure 17 and 18, those dew point pressures were noted down manually by looking through the glass window into the equilibrium cell of PVT Fluid Eval. Both pressures during the formation and disappearance of liquid in the isothermal process were noted down but only the disappearance pressure is considered highly since it is much accurate and also lack of hysteresis. Furthermore, Log P versus 1/T is plotted for both the SNG A and SNG B to show the Clausius – Clapeyron relation of the experimental data.

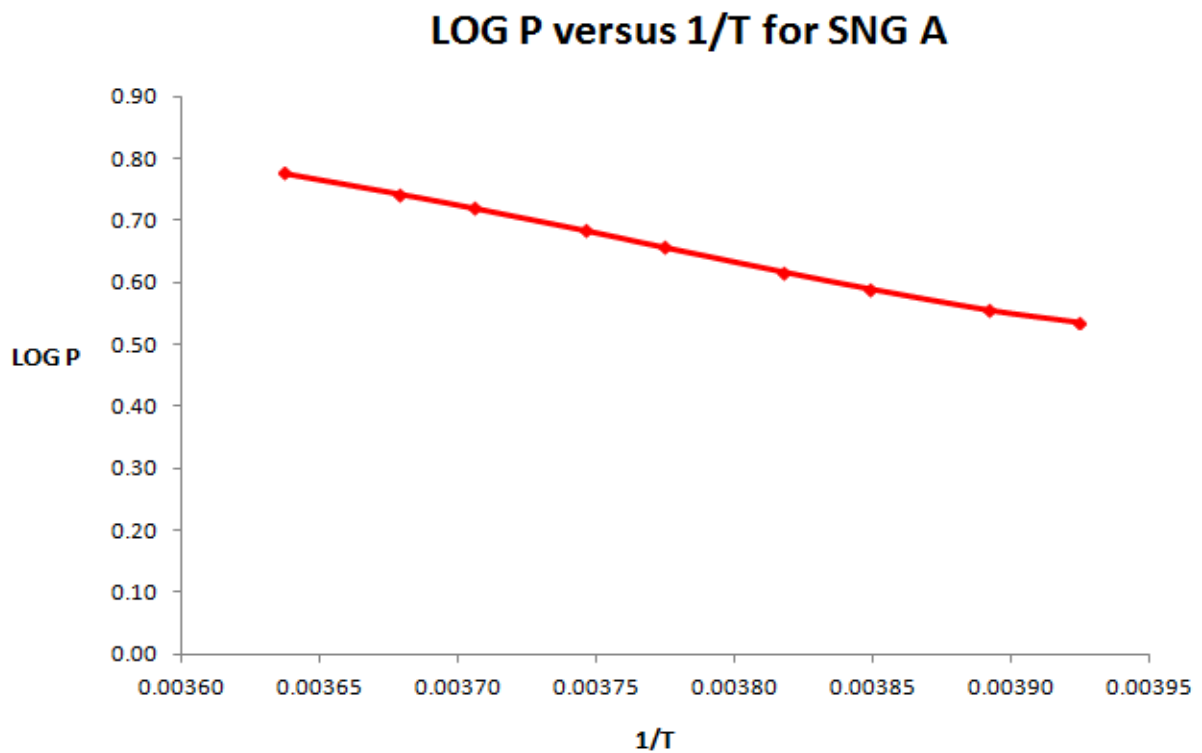


Figure 19: Clausius- Clapeyron Relation for SNG A

Based on Figure 19, it vividly shows that the graph exhibits straight line slop which shows the experimental data falls nicely on the saturated vapour line. This Clausius – Clapeyron relation further validates the reliability of the experimental data for SNG A.

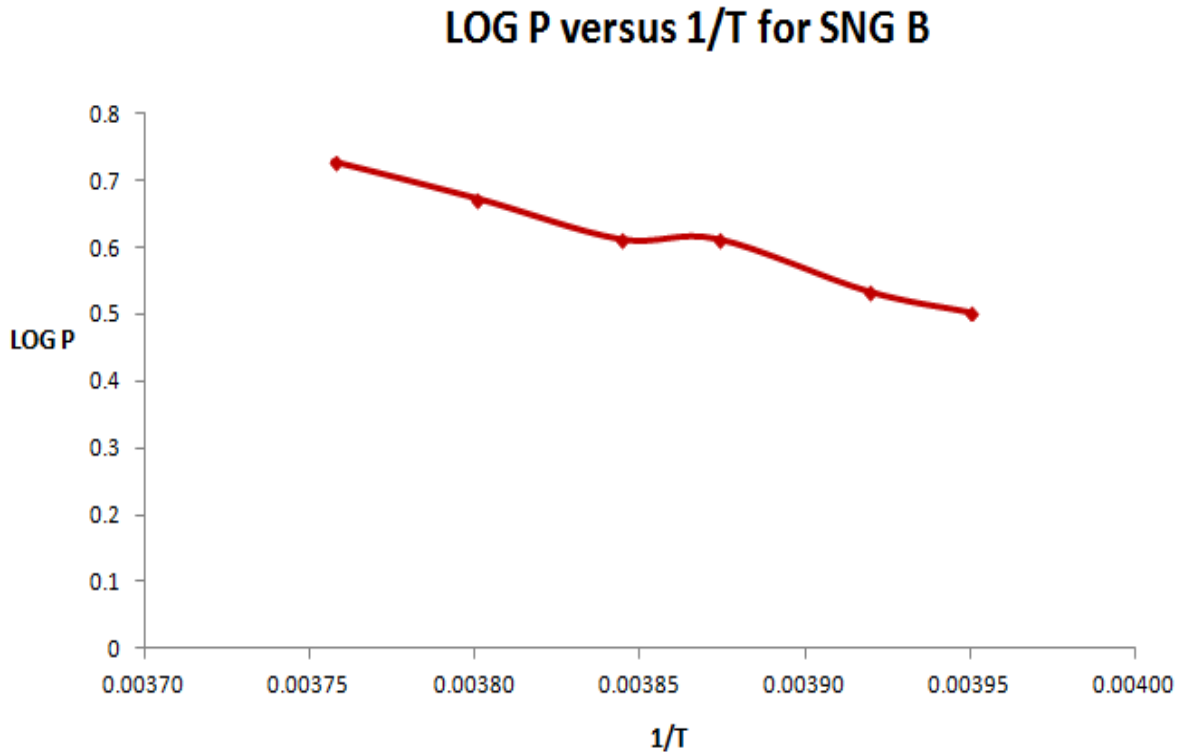


Figure 20: Clausius- Clapeyron Relation for SNG B

In Figure 20, there is a sudden small peak in the middle of the slope line. This is because two different temperatures are having the same dew point pressures. However, the experimental data for SNG B falls fairly close enough to the saturated vapour line.

5.2 Prediction Data

The same composition value of SNG A and SNG B were inserted into the commercial software such as CSMGem, MultiFlash and Hysys to run prediction for the dew points ranging from 0 to 10 MPa of pressure and temperature ranges from -60 °C till 10 °C. Both Multi Flash and Hysys applied Peng-Robinson Equation of State (EOS) to run the dew point prediction since Peng-Robinson is widely used in the industry and has less complication compared to other EOS. However, CSMGem uses Soave-Redlich-Kwong (SRK) EOS in running the prediction. Both dew point pressure and temperature predictions of SNG A and SNG B were tabulated in Table 7 onwards to Table 11.

Dew Point Pressure and Temperature Prediction for Synthetic Natural Gas A via CSMGem

P(MPa)	T(°C)	P(MPa)	T(°C)	P(MPa)	T(°C)
0.708	-57.955	3.546	-15.058	6.384	2.757
0.911	-52.144	3.749	-13.355	6.587	3.607
1.114	-47.276	3.952	-11.734	6.790	4.401
1.316	-43.061	4.154	-10.190	6.993	5.136
1.519	-39.333	4.357	-8.718	7.195	5.807
1.722	-35.980	4.560	-7.312	7.398	6.407
1.924	-32.930	4.763	-5.969	7.601	6.926
2.127	-30.129	4.965	-4.687	7.803	7.350
2.330	-27.536	5.168	-3.462	8.006	7.655
2.533	-25.123	5.371	-2.293	8.209	7.802
2.735	-22.864	5.573	-1.178	8.412	7.715
2.938	-20.743	5.776	-0.115	8.614	7.203
3.141	-18.742	5.979	0.894		
3.344	-16.851	6.182	1.852		

Table 7: Dew Point Prediction for SNG A via CSMGem

Dew Point Pressure and Temperature Prediction for Synthetic Natural Gas B via CSMGem

P(MPa)	T(°C)	P(MPa)	T(°C)	P(MPa)	T(°C)
0.914	-52.490	3.560	-15.562	6.206	1.356
1.118	-47.649	3.764	-13.862	6.410	2.264
1.321	-43.459	3.967	-12.243	6.613	3.117
1.525	-39.750	4.171	-10.700	6.817	3.915
1.728	-36.414	4.374	-9.228	7.020	4.654
1.932	-33.378	4.578	-7.823	7.224	5.329
2.135	-30.588	4.781	-6.480	7.427	5.933
2.339	-28.006	4.985	-5.196	7.631	6.456
2.542	-25.601	5.188	-3.970	7.834	6.884
2.746	-23.350	5.392	-2.799	8.038	7.193
2.950	-21.235	5.596	-1.682	8.241	7.344
3.153	-19.240	5.799	-0.617	8.445	7.258
3.357	-17.352	6.003	0.395	8.649	6.744

Table 8: Dew Point Prediction for SNG B via CSMGem

Dew Point Pressure and Temperature Prediction for Synthetic Natural Gas A via MultiFlash

P(MPa)	T(°C)	P(MPa)	T(°C)
8.8085	5.73	3.2189	-17.561
8.3452	7.58	2.8125	-21.58
7.4043	6.341	2.4503	-25.61
6.8417	4.602	2.1309	-29.604
6.3467	2.676	1.8488	-33.567
5.8690	0.508	1.5993	-37.507
5.4033	-1.891	1.3789	-41.425
4.9477	-4.519	1.1843	-45.326
4.5014	-7.382	1.0128	-49.21
4.0643	-10.495	0.86224	-53.08
3.6365	-13.878	0.73036	-56.937

Table 9: Dew Point Prediction for SNG A via MultiFlash

Dew Point Pressure and Temperature Prediction for Synthetic Natural Gas B via MultiFlash

P(MPa)	T(°C)	P(MPa)	T(°C)
8.8089	5.589	3.3548	-17.008
8.3211	7.123	2.9452	-20.902
7.5585	6.151	2.5671	-24.936
6.9996	4.538	2.2338	-28.933
6.4994	2.678	1.9391	-32.900
6.0187	0.571	1.6785	-36.842
5.5506	-1.765	1.4479	-40.764
5.093	-4.325	1.2442	-44.668
4.6446	-7.114	1.0646	-48.557
4.2053	-10.144	0.90667	-52.433
3.7752	-13.434	0.76826	-56.296

Table 10: Dew Point Prediction for SNG B via MultiFlash

Dew Point Pressure and Temperature Prediction for Synthetic Natural Gas via Hysys			
SNG A		SNG B	
P(MPa)	T (°C)	P(MPa)	T(°C)
1.101003	-46.7331	0.876746	-52.5276
2.115498	-29.5352	1.705283	-35.8658
3.752323	-12.7942	3.091016	-19.0886
5.918156	0.759512	5.070733	-4.25281
7.991854	7.481103	7.268599	5.480193
8.287445	7.671888	8.323245	7.306836
8.924896	4.926686	8.801437	6.329661
		8.972186	4.499709

Table 11: Dew Point Prediction for SNG A and SNG B via Hysys

5.3 Analysis of Experimental Data and Prediction Data

Both the experimental data and prediction data were plotted in the same pressure-temperature diagram for SNG A in Figure 21 and SNG B in Figure 22.

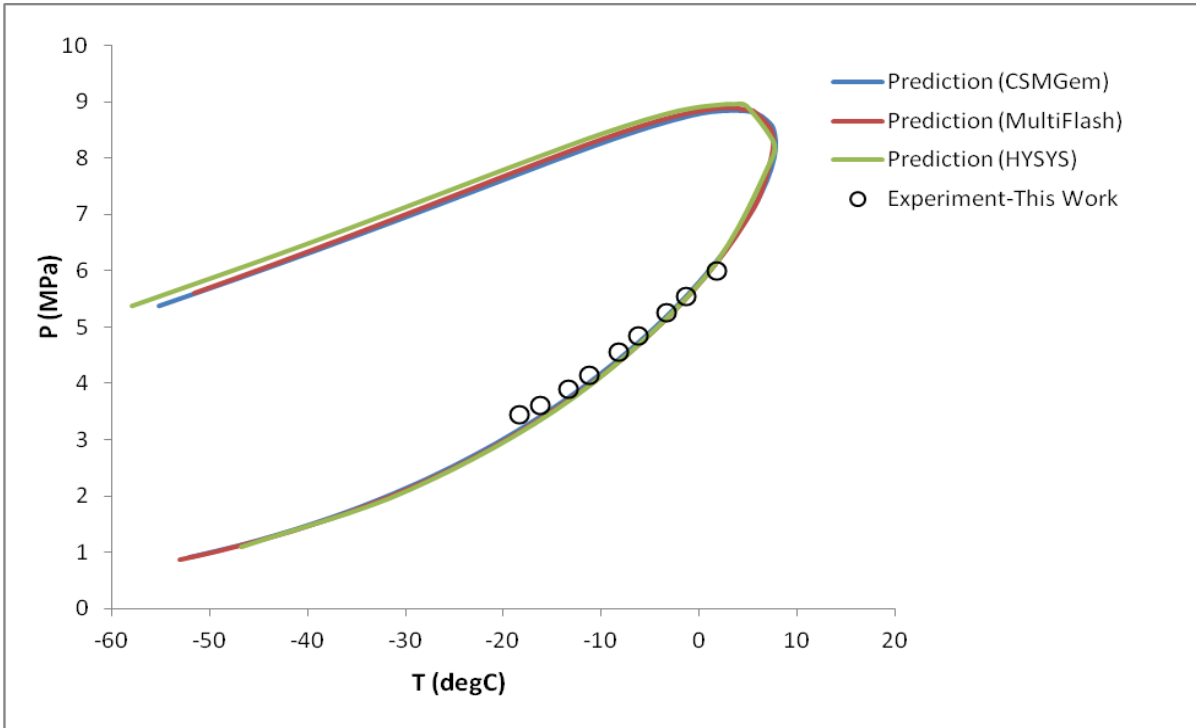


Figure 21: Phase envelope of SNG A

Based on Figure 21 above, it can be vividly seen that all the three software dew point line predictions are perfectly aligned together between the pressure ranges from 0 to 9 MPa and between the temperature ranges from -60 to 10 °C. Hence, it shows that CSMGem, Hysys and MultiFlash are very reliable and persistent in plotting the phase envelopes. Furthermore, the experimental dew points of SNG A which are represented by small black circles, having a very good agreement with the dew point line prediction. Thus, it validate the prediction dew points are indeed accurate. However, AAD_p calculation should be done to further validate the prediction dew points.

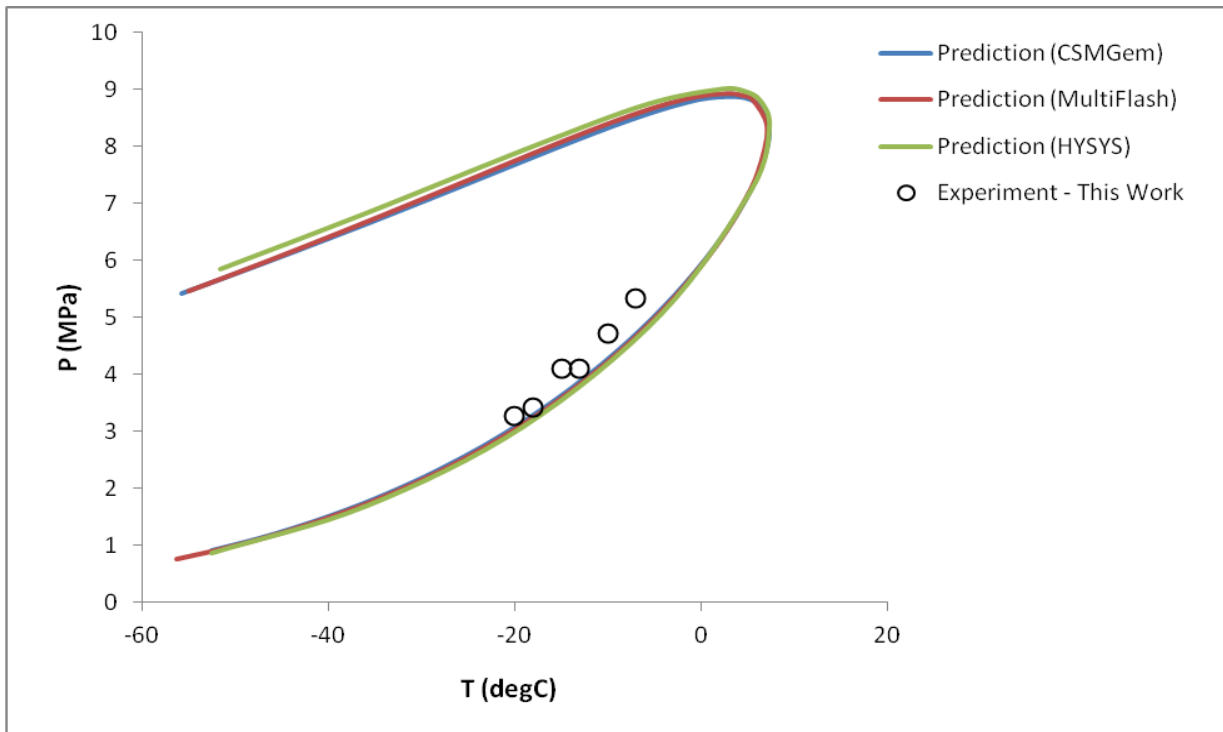


Figure 22: Phase envelope of SNG B

From the Figure 22, it can be also seen that all the three software dew point line prediction are completely aligned together between the pressure ranges from 0 to 9 MPa and between the temperature ranges from -60 to 10 °C. Therefore, it shows the reliability and continual of the prediction software in plotting the phase envelopes for SNG B. In addition, the experimental dew points which are also represented by small black circles are having fairly good agreement with the dew point line prediction. Even though, certain experimental dew points were seen slightly offset from the dew point line prediction, it does not mean that those dew points were not accurate. However, it could be the software that over-predicted the dew points for SNG B at the temperature ranges from -15 to 0 °C. As a result, the prediction dew points for SNG B are acceptable.

Based on Figure 21 and 22, both phase envelope of SNG A and SNG B are quite similar and there is no much difference since the difference in mole percentage of carbon dioxide is very little approximately 0.23 mole %. Nevertheless, the addition of i-butane and n-butane in SNG A makes the phase envelope slightly narrower compared to SNG B.

5.4 Comparison of Experimental Data and Prediction Data

In order to compare the experimental and prediction results and also to see how closely the deviations are related, calculating the average absolute deviation percent (AAD_P) is one of the alternatives that is very necessary to be carried out. Besides, it is also another mean to minimize error in measuring the dew points experimentally. Table 12 and Table 13 below shows the deviation pressure which is the difference between the calculated pressure, prediction pressure output by the commercial software for both SNG A and SNG B, and the experimental pressure. These deviation pressures with the corresponding temperatures obtained are necessary for the AAD_P calculation and percentage deviation (% DEV) calculation later on.

Dew Point Pressure and Temperature for Synthetic Natural Gas A			
	Deviation Pressure – Pcal - Pexp (MPa)		
T (°C)	CSMGem	MultiFlash	Hysys
1.8	0.18	0.16	0.25
-1.3	0.00	-0.03	0.04
-3.3	-0.06	-0.10	0.01
-6.2	-0.11	-0.15	-0.03
-8.2	-0.12	-0.16	-0.06
-11.2	-0.13	-0.17	-0.14
-13.3	-0.14	-0.19	-0.20
-16.2	-0.18	-0.23	-0.18
-18.3	-0.25	-0.30	-0.23

Table 12: Corresponding Temperature and Deviation Pressure of SNG A

Dew Point Pressure and Temperature for Synthetic Natural Gas B			
	Deviation Pressure – Pcal - Pexp (MPa)		
T (°C)	CSMGem	MultiFlash	Hysys
-7	-0.64	-0.68	-0.64
-10	-0.45	-0.49	-0.42
-13	-0.23	-0.27	-0.20
-15	-0.47	-0.51	-0.46
-18	-0.14	-0.18	-0.19
-20	-0.19	-0.23	-0.25

Table 13: Corresponding Temperature and Deviation Pressure of SNG B

a) Calculation of Average Absolute Deviation Percent (AAD_P)

By applying the formula below, AAD_P is calculated for each three set of prediction data in Table 12 and Table 13 for SNG A and SNG B respectively;

$$AADP\% = \frac{100}{n_p} \sum_1^{n_p} \left| \frac{P_{cal} - P_{exp}}{P_{exp}} \right|$$

n_p = number of components

P_{cal} = Calculated pressure from software prediction

P_{exp} = Experimental pressure from Fluid-Eval

Prediction Software	Average Absolute Deviation Percentage (%)	
	SNG A	SNG B
CSMGem	0.218	1.416
MultiFlash	0.315	1.576
HYSYS	0.145	1.442

Table 14: AAD_P for SNG A and SNG B with their respective software prediction

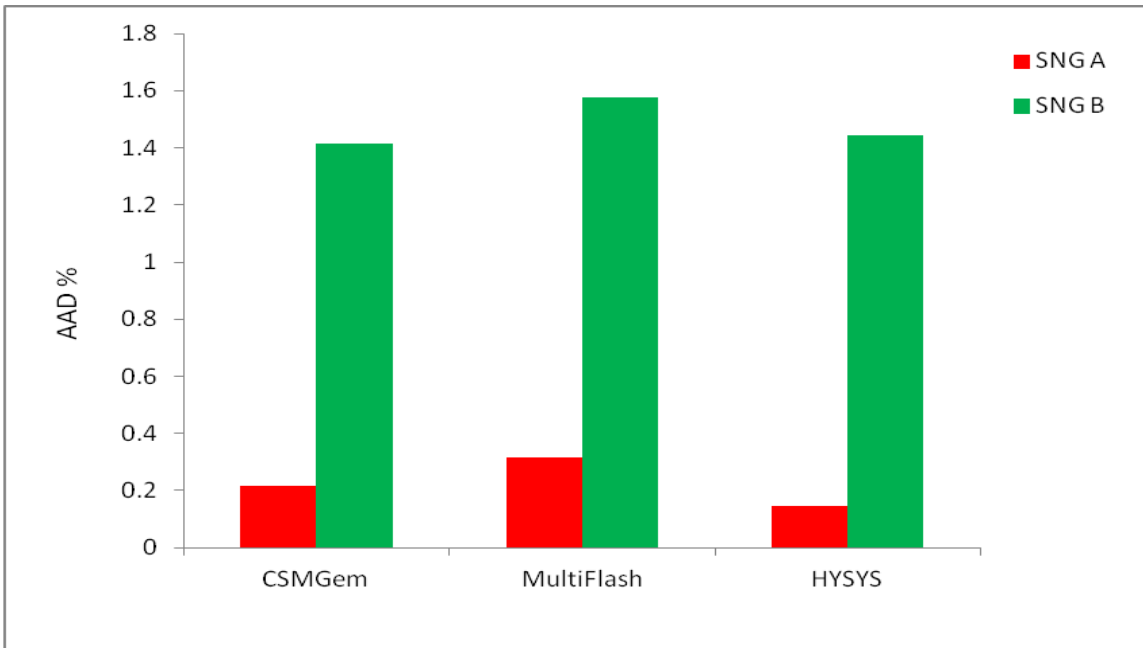


Figure 23 : Column Chart of AAD_P for SNG A and SNG B

The column charts in Figure 23 are constructed based on the data on Table 14. By observing at Figure 23, it is obvious that the AAD_P for SNG A in all the three software prediction are very much lower compared to SNG B. This definitely shows that there are very less deviations between the experimental data and prediction data for SNG A. Although, SNG B has slightly higher AAD_P between its software predictions, the deviations between the experimental and prediction data are acceptable and reasonable.

Moreover, HYSYS has the lowest AAD_P value, 0.145% for SNG A which greatly shows that the prediction data are very much reliable whereas, CSMGem has the lowest AAD_P value, 1.416% for SNG B which in turn shows that the prediction data are closely deviated from the experimental data.

b) Calculation of Percentage Deviation (% DEV)

By applying the formula below, % DEV is calculated for each three set of prediction data in Table 15 and Table 16 for SNG A and SNG B respectively;

$$\% \text{ DEV} = (P_{\text{cal}} - P_{\text{exp}}) / P_{\text{exp}} * 100\%$$

P_{cal} = Calculated pressure from software prediction

P_{exp} = Experimental pressure from Fluid-Eval

Experimental T (°C)	Calculated % DEV		
	CSMGem	MultiFlash	Hysys
1.8	3.01	2.67	4.17
-1.3	0.00	-0.54	0.72
-3.3	-1.14	-1.90	0.19
-6.2	-2.27	-3.10	-0.62
-8.2	-2.64	-3.52	-1.32
-11.2	-3.13	-4.10	-3.37
-13.3	-3.59	-4.87	-5.13
-16.2	-5.00	-6.39	-5.00
-18.3	-7.27	-8.72	-6.69

Table 15: Calculated % DEV for SNG A

Experimental T (°C)	Calculated % DEV		
	CSMGem	MultiFlash	Hysys
-7	-11.99	-12.73	-11.99
-10	-9.53	-10.38	-8.90
-13	-5.61	-6.59	-4.88
-15	-11.46	-12.44	-11.22
-18	-4.08	-5.25	-5.54
-20	-5.81	-7.03	-7.65

Table 16: Calculated % DEV for SNG B

Graph of % DEV versus temperature were plotted in Figure 24 and Figure 25 based on Table 15 and Table 16 respectively.

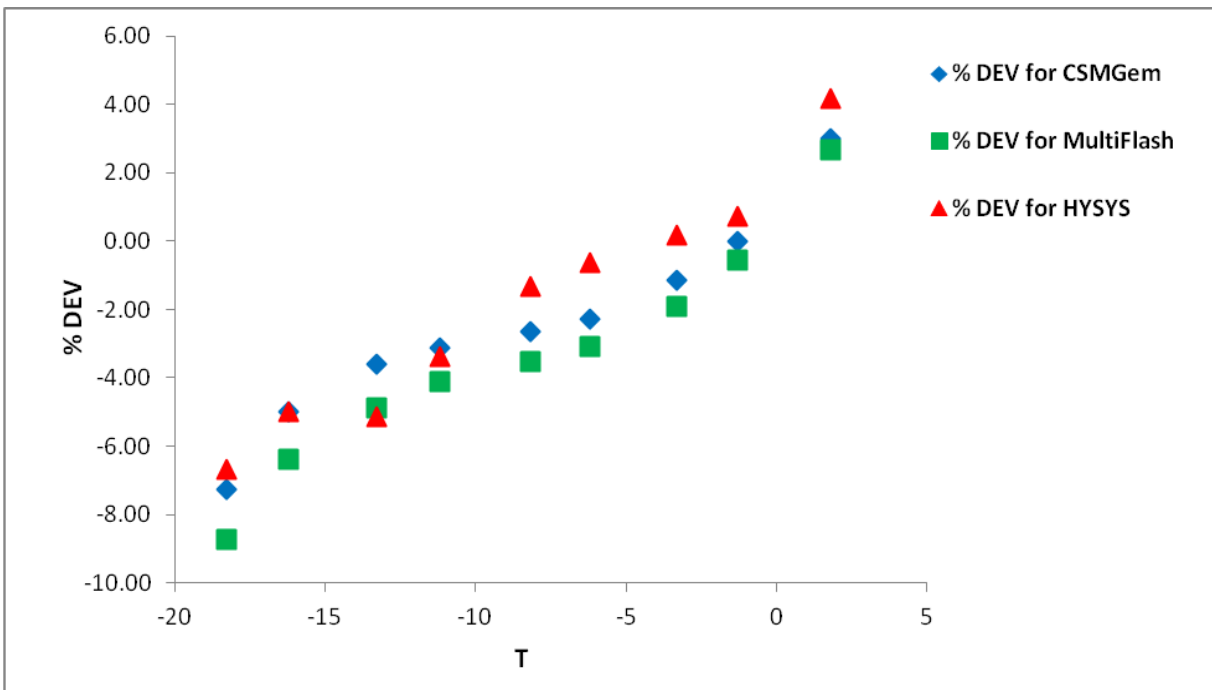


Figure 24: Graph of % DEV versus Temperature for SNG A

From Figure 24, it indicates that the most percentage deviations are in negative value starting from temperature below -3 degree Celsius for all the three software prediction. This was because all the three software over-predicted the dew pressures for SNG A under those temperatures of -3 degree Celsius below. However, the percentage deviations range from 4

percent till -8 percent which shows the predicted data and experimental data have a very close match between them.

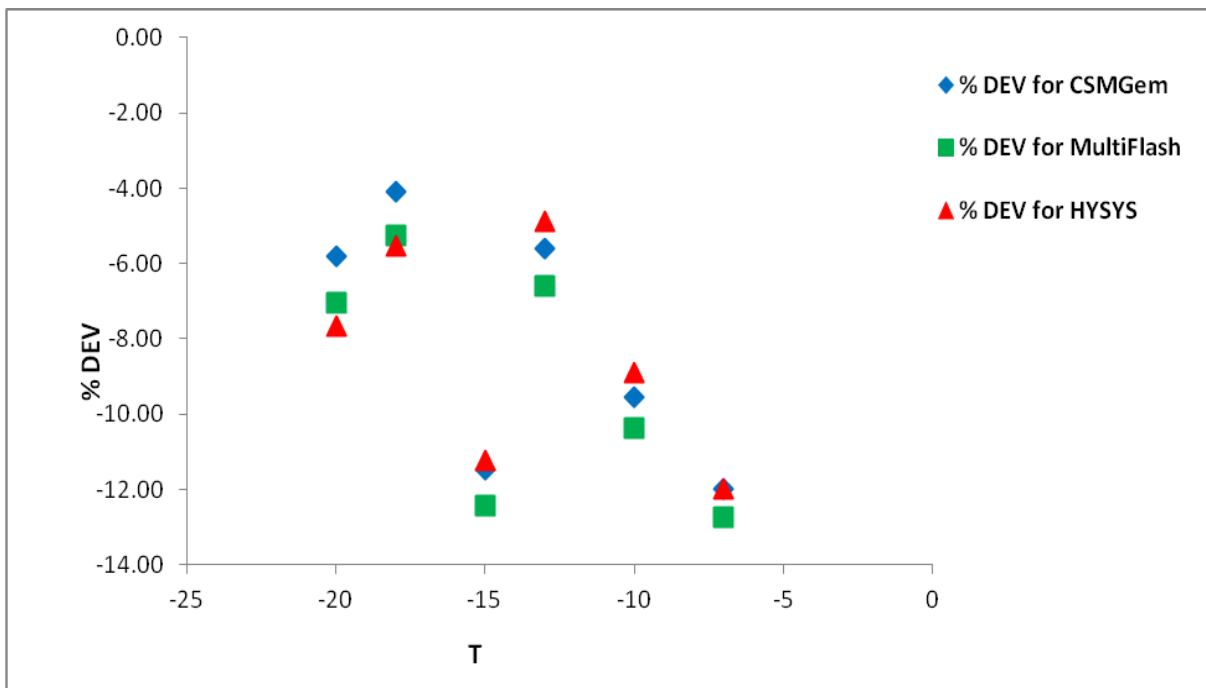


Figure 25: Graph of % DEV versus Temperature for SNG B

Based on Figure 25 above, it vividly shows that all the percentages deviations are in negative value for all the software predictions from the starting temperature of -7 till -20 degree Celsius. This was due to the commercial software, CSMGem, Multi Flash and HYSYS over-predicted the dew pressures for SNG B. In fact, the calculated pressure has a lesser value compared to the experimental pressure which results in the negative value of the percentage deviation.

Besides that, SNG B has only five gas components whereby the molecular interaction between them is much stronger and carbon dioxide compound has much stronger effect and influence on them compared to SNG A which has seven gas components. This explains why the SNG B experimental data has a slightly higher deviation with its prediction data compared to SNG A. Nevertheless, the prediction data and experimental data of SNG B are having fairly close match between them since the percentage deviations range from -12 till -4 percentages.

6. CONCLUSION AND RECOMMENDATIONS

6.1 Relevancy to Objectives

The aforementioned project activities, methodology, results obtained and the discussion done are directly related to the objectives of the project whereby the first objective is to study and get a deep knowledge on the phase behavior for high carbon dioxide natural gas. Secondly, to measure experimentally the dew points for high carbon dioxide natural gas using PVT Fluid-Eval equipment. Thirdly, to predict the dew points for high carbon dioxide natural gas using commercial software such as HYSYS, Multi Flash and CSMGem and lastly to compare experimental measurement data and prediction results.

Listed below would be a number of simple explanations on the relevancy of the work done to the objectives;

- Reading research papers and science journals for literature review relating to fluid phase behavior gives a very good understanding on how fluid behaves at different temperature and pressures. In addition, get to know many important technical terms such as critical point, cricondentherm and cricondenbar.
- Get to know the experimental procedures and the preparation of the PVT apparatus well before conducting the experimental measurement in a smooth and safe manner.
- Attended several lab sessions with the guidance of graduate assistant and conducted the experimental measurement of SNG A and SNG B. The experimental data is properly recorded and tabulated.
- Software such as HYSYS, CSMGem and MultiFlash were installed in my desk top to get familiarizes with the software features and did the dew point predictions for the same composition value of SNG A and SNG B. The prediction data is properly recorded and tabulated.
- Get to know the proper formula for calculating the average absolute deviation percent (AAD_P) and percentage deviation (% DEV) in order to compare and see how reliable and consistent of the prediction data to the experimental data.
- Calculated the AAD_P and % DEV values for both SNG A and SNG B and made appropriate comparisons between the experimental and prediction data.

6.2 Suggested Future Works for Expansion and Continuation

There are still much further works to be conducted for this project besides the experimental measurement of SNG A and SNG B that has been done for now. In order to bring the project to the next level for further expansion and continuation with much greater excellence, several suggested future works have been listed below;

a) Conduct experimental measurement of another SNG with higher CO₂

If time permits, experimental measurement of another SNG with higher CO₂ mole percentage than 69% should be conducted in order to study the dew point conditions for high carbon dioxide concentration in a more advanced manner.

b) Conduct experimental measurement with different PVT equipment

The dew points of SNG with higher CO₂ content should be experimental measured with other PVT equipments besides Fluid-Eval such as custom-made chilled mirror apparatus or other advanced PVT equipment which is available in the market. This is to ensure that the experimental measurement can be carried out in a much effective manner with better features.

c) Conduct experimental measurement of bubble point

Besides measuring the dew points for SNG A and SNG B, the bubble points should be experimental measured as well in order to study the phase envelope of both SNGs extensively and also to study the behavior of SNG during the bubble point conditions.

d) Conduct modeling of phase behavior for SNG A and SNG B

Developing a mathematical model based on fugacity approach to predict the phase behavior for SNG A and SNG B definitely will be a good idea plus challenging but certainly will take great deal of studies, effort and dedication to produce a good mathematical model.

7. REFERENCES

- [1] Odi,U.,El Hajj,H. and Gupta,A. 2012. Experimental Investigation of Wet Gas Dew Point Pressure Change with Carbon Dioxide Concentration. Paper SPE 161478 presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE, 11-14 November 2012.
- [2] Ahmed, T. (2001). *Reservoir Engineering Handbook*. Houston, Texas: Gulf Professional Publishing
- [3] Ø. Mørch, Kh. Nasrifar, O. Bolland , E. Solbraa , A.O. Fredheim, and L.H. Gjertsen,2006. Measurement and modeling of hydrocarbon dew points for five synthetic natural gas mixtures.Fluid Phase Equilibria 239, 138-145.
- [4] Antonin Chapoy, Hooman Haghghi, Bahman Tohidi. 2011. Development of Experimental Techniques, Equipment and Thermodynamic Modeling for Investigation Systems with High CO2 Concentrations. Paper SPE 145982 presented at the Gas Conference and Exhibition held in Jakarta, Indonesia, 20-22 September 2011.
- [5] O. Redlich, J.N.S. Kwong, Chem. Rev. 44 (1949) 233–244.
- [6] P.M. Mathias, T. Copeman, Fluid Phase Equilib. 13 (1983) 91–108.
- [7] G. Soave, Chem. Eng. Sci. 27 (1972) 1197–1203.
- [8] Kh. Nasrifar, M. Moshfeghian, Fluid Phase Equilib. 153 (1998) 231–242.
- [9] Kh. Nasrifar, Sh. Ayatollahi, M. Moshfeghian, Fluid Phase Equilib. 168 (2000) 71–90.
- [10] M.B Kermani and A. Morshed. 2003. Carbon Dioxide Corrosion in Oil and Gas Production – A Compendium. Corrosion. pp 2-5.
- [11] Vasiliki Loulia, Georgia Pappaa, Christos Boukouvalasa, Stathis Skourasb, Even Solbraab, Kjersti O. Christensenb, Epaminondas Voutsasa, Fluid Phase Equilibria 334 (2012) 1– 9.
- [12] V.Stephane, J.Jean-Noel, P.Jerome, D.Jean-Luc and B. Danielle, 2007. Bubble and Dew Points of Carbon Dioxide + a Five-Component Synthetic Mixture: Experimental Data and Modeling with the PPR78 Model. J. Chem. Eng. Data, 52, 1851-1855.
- [13] Malanowski, S., 1982. Experimental methods for vapour-liquid equilibria. II. Dew- and bubble-point method. Fluid Phase Equilibria, 9: 311-317.
- [14] Mario H. Gonzalez, and Anthony L. Lee, 1968. Dew and bubble points of simulated natural gases. J. Chem. Eng. Data, 13 (2), pp 172–176

- [15] M.F. Alfradique and M. Castier, 2007. Calculation of Phase Equilibrium of Natural Gases with the Peng-Robinson and PC-SAFT Equations of State. *Oil & Gas Science and Technology – Rev. IFP*, Vol. 62, No. 5, pp. 707-714.
- [16] Li-Sheng Wang and Jürgen Gmehling, 1999. Improvement of SRK Equation of State for Vapor-Liquid Equilibria of Petroleum Fluids. *AIChE Journal*, Vol. 45, No. 5, pp. 1125-1134.
- [17] Jayendra S. Parikh, Richard F. Bukacek, Lois Graham, and Stuart Leipziger, 1984. Dew and bubble point measurements for a methane-ethane-propane mixture. *J. Chem. Eng. Data*, 29 (3), pp 301–303.
- [18] Joseph A. Hudziak, Hassan Kahvand, Mehdi Yassaie, and Stuart Leipziger, 1984. Dew point measurements for nitrogen-propane and nitrogen-butane mixtures. *J. Chem. Eng. Data*, 29 (3), pp 296–301.
- [19] Khashayar Nasrifar, Miranda M. Mooijer-van den Heuvel and Cor J. Peters, 2008. Experimental Determination and Modeling of Bubble and Dew Points in the System $\text{CO}_2 + \text{CHF}_3$. *J. Chem. Eng. Data*, 53 (10), pp 2328–2332.
- [20] Julio C. Acosta, Edison Hevia, and Stuart Leipziger, 1984. Dew and bubble point measurements for carbon dioxide-propane mixtures. *J. Chem. Eng. Data*, 29 (3), pp 304–309.
- [21] Shuen-Cheng Hwang, Ho-Mu Lin, Patsy S. Chappellear, and Riki Kobayashi, 1976. Dew point study in the vapor-liquid region of the methane-carbon dioxide system. *J. Chem. Eng. Data*, 21 (4), pp 493–497.
- [22] S. Avila, A. Benito, C. Berro, S. T. Blanco, S. Oti'n, and I. Velasco, 2006. Dew-Point Curves of Natural Gas Measurement and Modeling. *Ind. Eng. Chem. Res*, 45, 5179-5184.