CO_2 Gas Hydrate Promotion With Acetone Solution

by

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16700

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Chemical Engineering)

May 2015

Universiti Teknologi PETRONAS,

32610, Bandar Seri Iskandar,

Perak

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Chemical Engineering Program

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Approved by,

____

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May 2015

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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HARIZ BIN ROSLAN

ABSTRACT

Impurities are common constituents in oil and gas production. One of the common impurity constituents is carbon dioxide. In South East Asia alone, gas reservoir regions are well known to have a CO_2 content more than 0.7 mole fraction of the gas production. One of the methods of carbon capture is the cryogenic method, or by using gas hydrate promoter. In the study presented here, the experimental dissociation data for carbon dioxide-methane mixture (70/30 in mol%) in a quaternary mixture of carbon dioxide, methane, water, and acetone (CO_2-CH4-H_2O-C_3H_6O) are analyzed with four (4) different concentrations of acetone solution (1 mol %, 3 mol %, 5 mol %, and 7 mol %) at three (3) different pressures of 30, 40, and 50 Bar using the T-cycling method. Based on the experimental data, as hydrate dissociation point increases, the concentration of acetone required increases along the buildup of pressure. In addition, according to the analyzed results, the optimum concentrations for gas hydrate promotion lie above 0.05 mol% as pressure increases above 30 bar.

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CHAPTER 1

INTRODUCTION

1.1 Background

Gas hydrates are the formation of a polyhydrous lattice which acts as a host and entraps guest molecules when thermodynamic equilibrium is achieved. Guest molecules may carry either a strong hydrophobic characteristics or no polarity, rendering both immiscible. This phenomena occurs due to the strong hydrogen bonding between the guest and host molecules. Adding to that, suitable conditions of extremely high pressure at relatively low temperatures provide more apparent hydrate formations.

Not all hydrophobic or non-polar molecules are able to be entrapped in hydrates. The majority of these ‘caged’ gases bear a low molecular weight. However, these hydrates do exist in multiple structures such as structure I (sI), structure II (sII), and structure H (sH) [1]. Its discovery was dated back in 1810 by Sir Humphry Davy as a scientific curiosity. It became the fundamental of phase change from gas-liquid to solid. The discovery continued its momentum of experiments until 1934, during then it was thought man-made gas hydrates would hinder the natural gas industry. Later in the mid-1960s, it was discovered that hydrate formations predates man’s discovery by millions of years. Gas hydrate is a common sight in deep oceans and permafrost regions [1]. Table 1.1 will be the summary of chemists worked on gas hydrates.

TABLE 1.1 Short summary of chemists worked on gas hydrates until the late 19th Century

Year	**Scientist**	**Event**
1810	Sir Humphrey Davy	• Chlorine hydrate discovery
1823	Davy corroborated with Michael Faraday	• Formulated water to chlorine ratio; Cl_2. $10H_2O$.
1884	Henry Louis Le Chatelier	• Slope change in Cl hydrate *P-T* curve at 273K.
1828	Carl Jacob Löwig	• Bromine hydrate discovery.
1888	Paul Ulrich Villard	• Obtained temperature dependence of H_2S hydrates.
1888	Paul Ulrich Villard	• Measured hydrates for methane, ethane, ethane, ethyne and dinitrogen oxide.
1890	Paul Ulrich Villard	• Suggested that adding molecular mass of guest molecule would decrease temperature at lower quad point.
1896	Paul Ulrich Villard	• First to use heat of formation data to get the water/gas ratio.

Roughly in the last century, a pivotal discovery has caused a prolific interest in gas hydrates. This discovery was the blockage of gas transmission lines by natural gas hydrates and resulted in the regulation of water content in gas pipelines [1]. This discovery also instigated the investigation of inhibitors for use on hydrates, which had been proven to be the factor of blockages. Unfortunately, the investigation was moving at a slow pace due to the lack of technology such as a chromatography which was in common use only in the early 1960s. Due to the oil boom in 1900s and the discovery of gas transmission lines' blockages, workers began treating gas hydrates as a nuisance in gas production. However, in a few decades, this 'nuisance' will later prove to be one of the low-cost and alternative methods to trap one of the main culprits for gas production declination and global warming; carbon dioxide (CO_2) gas.

As we venture into the 21st century, *environmental consciousness* and *natural gas production optimization* has become a critical topic in most public and political debate. This means the oil and gas industries need to mitigate and minimize the pollutants being emitted, especially carbon dioxide (CO_2) gas emissions in production of gas. As an example, according to Sabil, K. M. et al (2014), South East Asia gas reservoir regions are well known to have a CO_2 content more than 0.50 mole fraction of the gas production. Adding to that, in Malaysia's K5 field located offshore of Sarawak shows evidence of bearing more than 0.7 mole fraction CO_2 in its gas reserves [2].

Economically, the high CO_2 content in Malaysia's gas reserves proves the requirement of a CO_2 separation module to make our Natural Gas (NG) marketable or even suitable as feedstock for manufacturing [2]. However, the current gas separation technology is incapable both economically and technically to capture the large amounts of CO_2 from NG streams. One of the low cost alternative is to make use of **gas hydrates**. Since the mid-1990s until the present time, there has been a surplus of journals, articles and studies, both published and unpublished related to CO_2 separation using gas hydrates.

However, there are some drawbacks. Gas hydrates phase equilibrium window are restricted to only at high pressure and low temperature conditions. From there, researchers aim to introduce solvents that would act as a promoter. This promoter would aid in moderating gas hydrates at a relatively lower pressure and higher temperature than initially recorded. Moreover, the hydrate promoters would improve energy consumption by lowering process costs and encourage for its use commercially. Currently, acetone has shown good hydrate promotional effects which is supported by Maekawa's (2011) results [3]. However, the author proposes to acquire data at higher pressures and at higher acetone solution concentrations which will be discussed further in the 'Methodology' section.

1.2 Problem Statement

To maximize and optimize CO_2 hydrate formation in CO_2-CH_4 binary mixture with the presence of a solvent, acetone (C_3H_6O) solution.

1.3 Objectives

The objectives of this experiment are:

1. To observe the thermodynamic stability of CO_2 hydrate at a binary-phase equilibrium conditions using acetone (C_3H_6O) in a (CO_2-CH_4-H_2O-C_3H_6O) quaternary mixture;
2. To identify the optimum acetone solution's (C_3H_6O) concentration as a promoter for hydrate formation;

1.4 Scope of Study

The scope of study for this experiment only includes and only limited to the following:

1. Only carbon dioxide gas hydrate formation is analyzed and studied;
2. Hydrate chamber is presumed to have ideal experimental composition; no constituents other than the quaternary mixtures of carbon dioxide, methane, water, and acetone;
3. The work is limited to a small scale experiment (volume of liquid = 100 cm^3). Hence thermal equilibrium could be easily achieved within the closed system;
4. An isochoric condition is perfectly maintained throughout the period of experimentation.

1.5 Relevancy and feasibility

From the data collected, it should serve to aid in carbon capture within gas production lines. In commercial implications, carbon dioxide capture, or carbon capture, via hydrate formation occurs in a specially made hydrate tank after gas processing. A feasible target is required when the experiment is up scaled for commercial use. With 0.7 mole fraction of CO_2 in the K5 gas field, halving the CO_2 content would be a more realistic approach in which is easily achievable with the aid of the presented results in this experiment [2].

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Molecular Interactions

To understand hydrate formations, it is crucial to go in depth, yet brief, into molecular fundamentals. Gas hydrates exist in 2 different phases; solid for the host, and condensed gas for the guest. The host encages the gases by creating non-stoichiometric interactions between molecules. These interactions are called non-stoichiometric due to no transfer or sharing of electrons occur. Others, such as Atkins & De Paula (2010), define it as the attraction between closed-shell molecules, also known as Van Der Waals interaction [4]. These interactions are segregated into seven different interaction classifications. Table 2 shows the related molecular interactions along with the respective briefed definitions.

Due to these interactions, gas hydrates are easily formed and dissociated. Although the succession of gas hydrate formation is due to the combination of all interactions above, the main interaction that the author wishes to focus on is hydrogen bonding. According to Atkins & De Paula (2010, pp. 637), hydrogen bonding between H_2O molecules are predominant in liquid and solid water [4]. In addition, Smith, Van Ness & Abbott (2005) states that hydrogen bonding is when participating species combine to form new chemical entities during a manifestation of strong attractive interactions [5].

TABLE 2.1 Van Der Waals interactions along with the respective definitions [4, 5]

Type of interaction	**Brief Definition**
Potential energy of interaction;	➢ It is derived from the relative permittivity of a molecule. ➢ Permittivity is a quantitative value of Coulomb potential energy, ε ➢ Also apparent when two atomic charges are separated by a small distance in a vacuum
Dipole-dipole interactions;	➢ It is the potential energy of interaction between two dipoles in parallel.
Dipole-induced-dipole interactions;	➢ It is the interaction between a polar molecule with a polarizable molecule (ability to be polar under specific conditions)
Induced-dipole-induced-dipole interactions;	➢ It is the interaction between non-polar molecules which arose from the transient dipoles from the fluctuations of electron positions around the molecule.
Hydrogen Bonding;	➢ It is when a partial positive charge of hydrogen (H) and a partially negative charged particle.
Hydrophobic interaction; and,	➢ It occurs when nonpolar molecules are introduced in polar solvents, or in this case, water molecules. ➢ The entropy of water decreases, so the dispersal of the hydrocarbon in the water is entropy-opposed.
Total attractive interaction.	➢ It is the summation of all interactions above with the exclusion of hydrogen bonding.

2.2 Carbon Dioxide in Gas Production

With fundamentals aside, it is crucial as well to fathom the reasons behind promoting hydrate formations. Again, according to Sabil, et al (2014), South East Asia gas reservoir regions are well known to have a CO_2 content more than 0.70 mole fraction of the gas production [2]. Operators such as PETRONAS would favor the reduction of CO_2 content to produce marketable products.

Carbon Dioxide (CO_2) is known to be a Liquefied Natural Gas (LNG) or Natural Gas (NG) contaminant. According to Shimekit & Hilmi Mukhtar (2012), produced gas quality must be kept at a fixed standard, hence impurities are required to be removed [6]. One of the standards being monitored and maintained is calorific value of natural gas. Calorific values refers to the quantitative heat produced when ignited and combusted. For example, a CH_4-CO_2 gas mixture with a CH_4:CO_2 ratio of 9:1 would have a higher calorific value than the same mixture with a ratio of 6:1. Contaminants such as CO_2 do not pertain any combustible properties, therefore, a higher ratio of CO_2 in the said mixture would lower the calorific value. Besides calorie count, pipe corrosion factor and process bottle neck factor are also observed and regulated according to standard due to the notoriety of CO_2 being corrosive and exhibit low thermal equilibrium to form hydrates in production pipelines.

Ever since then, CO_2 reduction has been the key issue aim in LNG/NG processing. The issue needed to be tackled is to promote the hydrate formation of CO_2 which in turn reduces concentration before the liquefaction of natural gas. Multiple studies have been conducted to identify CO_2 thermodynamic equilibrium behavior by manipulating solvents such as customized surfactants by Karaaslan, U. & Parlaktuna, M. (2000) [7]. aqueous NaCl solution by Fan, S.S. & Guo, T.M. (1999) [8], gas hydrate process for recovery of CO2 from fuel gas by Kang, Seo & Jang (2009) [9], and solid carrier silica gel by Kang, S.P et al (2009) [9].

2.3 Carbon Dioxide Gas Hydrate Properties

Gas hydrates do pertain constructive traits. One of the traits mentioned is the ability for gas hydrates to store large quantities of gas per volume of hydrate. For example, Khokhar, Gudmundsson & Sloan (1998) tabulated that for every cubic meter (m^3) of gas hydrate, it could retain at least 56.02 m^3 of CH_4 gas at structure I (sI) in 12-faced-pentagons (5^{12}) and at most 200.93 m^3 of CH_4 gas at structure structure H (sH) in 12-faced-pentagons (5^{12}) along with 3-faced-squares-6-faced-pentagons-3-faced-hexagons ($4^3 5^6 6^3$) structures [10]. In layman's term, hydrates could specifically trap desirable molecules under certain favorable conditions.

It was inferred that different guest (*trapped molecules*) which inhabits the host (*ice-lattice*) will exhibit macroscopic hydrate formations when achieve thermodynamic equilibrium. For example, according to Qazi Nasir et al. (2014), CO_2 has higher tendency to form gas hydrate when compared with CH_4 gas in a (CO_2-CH_4) binary mixture [11]. In support of the latter statement, Long, Z. et al. (2014) mentioned that under the same PT (pressure & temperature), CO_2 has a higher chance of forming hydrates than CH_4, H_2, or N_2 gases [12]. The earlier inference is proven to be correct due to CO_2 hydrate has a higher equilibrium temperature when in comparison to the other hydrates such as CH_4 hydrates [2].

2.4 Acetone Promoting Properties

Promoters are classified into 2 types; kinetic and thermodynamic. Kinetic promoters are time-dependent and provide no equilibrium influences while thermodynamic promoters are time-independent and greatly affects equilibrium conditions [1]. According to Partoon & Javanmardi (2012), temperature and pressure of three phase boundaries of gas hydrate, liquid water, and free moving gases (the phase boundaries are also known as LHV) would be shifted to a higher and lower values respectively when thermodynamic promoters are introduced.[13] In the author's proposal, the solvent used to promote hydrate formation will be acetone solution.

Acetone is known to be an aprotic dipolar liquid. It is soluble in water at all concentrations. The studies of acetone suggested its tendency of hydrogen bonding with water by the carbonyl group (C=O). Liang et. al. (2004) found that C-H groups of acetone interacts with the oxygen atoms of free-water. Furthermore, the C-$H_{acetone}$---O_{water} weak hydrogen bonds and O-H_{water}---$O_{acetone}$ strong hydrogen bonds mutually cooperate in forming a stable solution [14].

This solution is experimented to locate an equilibrium structure for CO_2 hydrate formation at a lower thermodynamic conditions. Maekawa, T. (2011) reported that a hydrate structure II (more stable structure) was formed from structure I when 0.16 mass fraction of acetone solution was present in the mixture [3]. Despite the results by Maekawa, T., the author proposes to use a lower set of concentrations with different operating conditions for the proposed experiment to find an optimized phase equilibrium. No natural solvent has been commercially used for CO_2 gas hydrate promotion due to the unpredictability of hydrate formations at a commercial scale. However, with more introduction of these solvents into the industry, a lower separation cost is to be expected with a higher purity of natural gas being produced.

CHAPTER 3

METHODOLOGY

3.1 Experimental Material, Equipment and Procedure

3.1.1 Materials

The chemicals planned to be used will be as follow:

i. Distilled and deionized water;
ii. Premixed CO2-CH_4 (70:30) by Air Product Malaysia Sdn. Bhd.
iii. Acetone solution; concentration in weight % (10, 30, 50, 60 & 70) by Merck Malaysia.

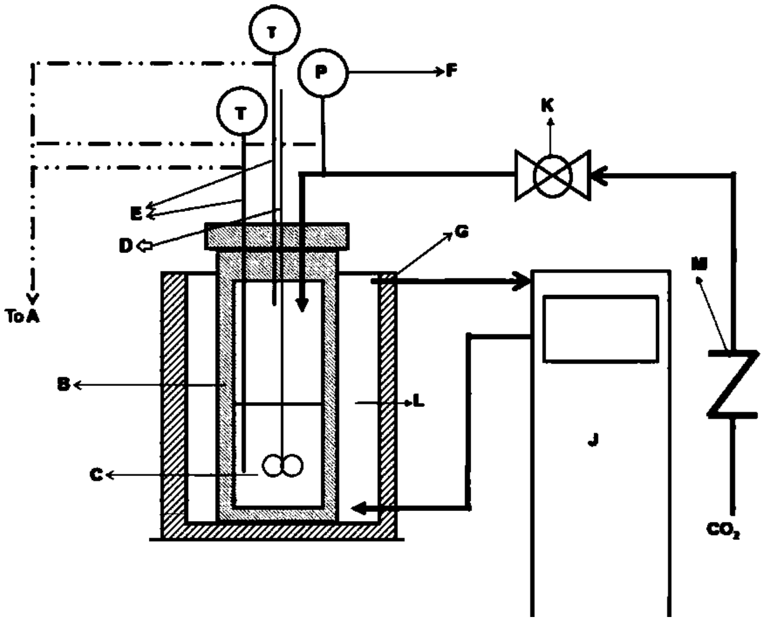


FIGURE 1.1 A simple schematic of the measurement equipment. A: Data Acquisition, B: High-Pressure Cell, C: Impeller, D: Rotating stainless steel shaft, E: Thermocouple, F: Pressure Gauge, G: Thermostatic Bath, J: Cryostat, K: Valve, L: Thermostat liquid, M: One-Way Valve

3.1.2 Equipment

The apparatus used is a custom built calorimeter. It has a cylindrical dimension, composed of a stainless-steel cell (B) with a volume of 500 cm^3. The cell used is jacketed by a steel casing and insulated with a Styrofoam-like polymer with an external heating coil wrapped around the steel casing. A water bath is stationed underneath the cell with piping in (G) and out of the steel jacket. Beside the water bath is a refrigeration unit and also a heating unit. An agitation unit is installed on the topside of the cell, with the shaft (D) running halfway through the cell ending at the impeller (C). The temperature and pressure is measured using a platinum resistance thermocouple (E) and a pressure gauge (F).

3.1.3 Procedures and Project Activities

The number of experiments planned to be conducted would be 15; which is comprised of 4 different solvent concentration at 3 different pressures per concentration, using the **T-Cycle method**. T-cycle method is the method of rapid cooling and step heating the desired mixture until it reaches the hydrate equilibrium/dissociation point within an isochoric system (constant volume). Pressure is initially fixed but will gradually reduce following the drastic temperature reduction as well. Figure 2 will be an example of T-cycle method data acquisition by the author.

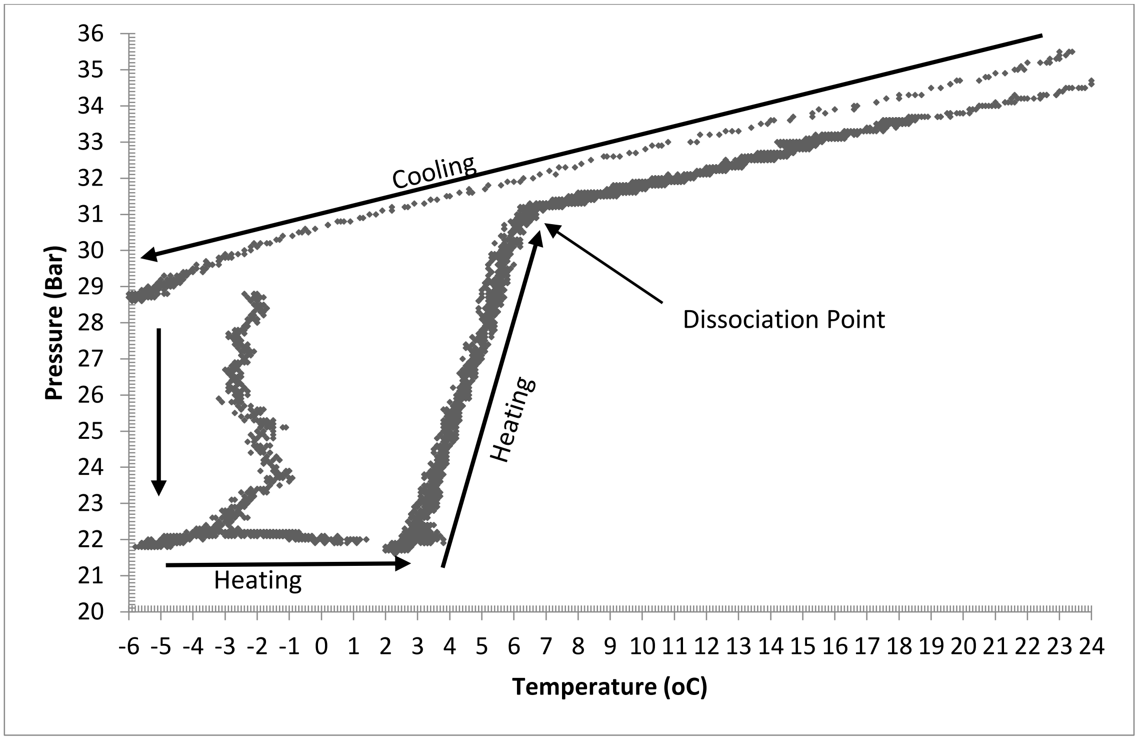


FIGURE 2.1 An example of a Pressure-Temperature (P-T) plot to explain a T-Cycle plotting.

The following will be the step by step procedures of the experiment:

1. The cell is vacuumed for any impurities and moisture;
2. 1 mol % of acetone solution is injected into the vacuumed cell;
3. Premixed gas is then injected;
4. The cell will be subdued with a pressure of 30 Bar (±0.05 Bar);
5. Temperature of 20^{o}C is then fixed within the cell initially. The holding up time for this step will be for at least 2 hours;
6. The system temperature is then drastically reduced to 0^{o}C or 273.15 K. The holding time for this temperature is for at least 2 hours;
7. The temperature is then raised by 3^{o}C with a holdup time of 2 hours. It is then reduced back to 0^{o}C for an additional holdup time of 2 hours. Force fluctuation of temperatures in small deviations assures gas hydrate formation occurring evenly within the system;

8. The mixture is then heated up by an average of 0.5±0.1 K every hour $(\frac{1\text{ K}}{hr})$ (temperature increment depending on concentration of acetone solution);
9. Once reached the equilibrium P-T point or the dissociation point, the data is recorded and the experiment is halted once the holding timer executes the last programmed command;
10. The experiment is then repeated with initial pressures set to 40 Bar and 50 Bar. After completing the cycles of 30, 40 and 50 bar for 1 mol % acetone solution, the acetone solution concentration is then changed to 3, 5, and 7 mol % for the respective pressures tested.
11. Experiment holding time ranges between 30 to 50 hours, depending on acetone concentration and other external factors.

To reiterate, induction time is not recorded due to acetone being a *thermodynamic promoter* which means any equilibrium changes are independent of time [1, 13]. Hence, to find an optimum acetone concentration, a wide set of low concentrations are required to both promote CO_2 hydrate as a carbon capture method for gas production. At the end of all experiments, a semi-logarithmic graph shall be plotted and an equilibrium phase boundary for the acetone would be determined.

3.2 Task Flow sheet and Project Timeline

Quantifying the gas hydrate phase equilibrium seems to be quite difficult at first glance. To achieve reputable results, firstly, apparent hydrate nuclei must be detected for validation of any thermodynamic shifts. Secondly, to produce a reliable conclusion the experiment must go through a number of repetitions with and without changes in solvent concentrations. Lastly, manipulation of thermodynamic conditions are definite to provide apparent comparisons between all the data recorded.[15] Throughout the project period, the Author will need to complete a number of tasks. The experimental tasks required to complete will be displayed in a flow sheet form, Figure 3.1.

Table 3 will be the Gantt chart in which displays an in depth look into the author's tasks and objectives needed to be completed with respect to the deadlines.

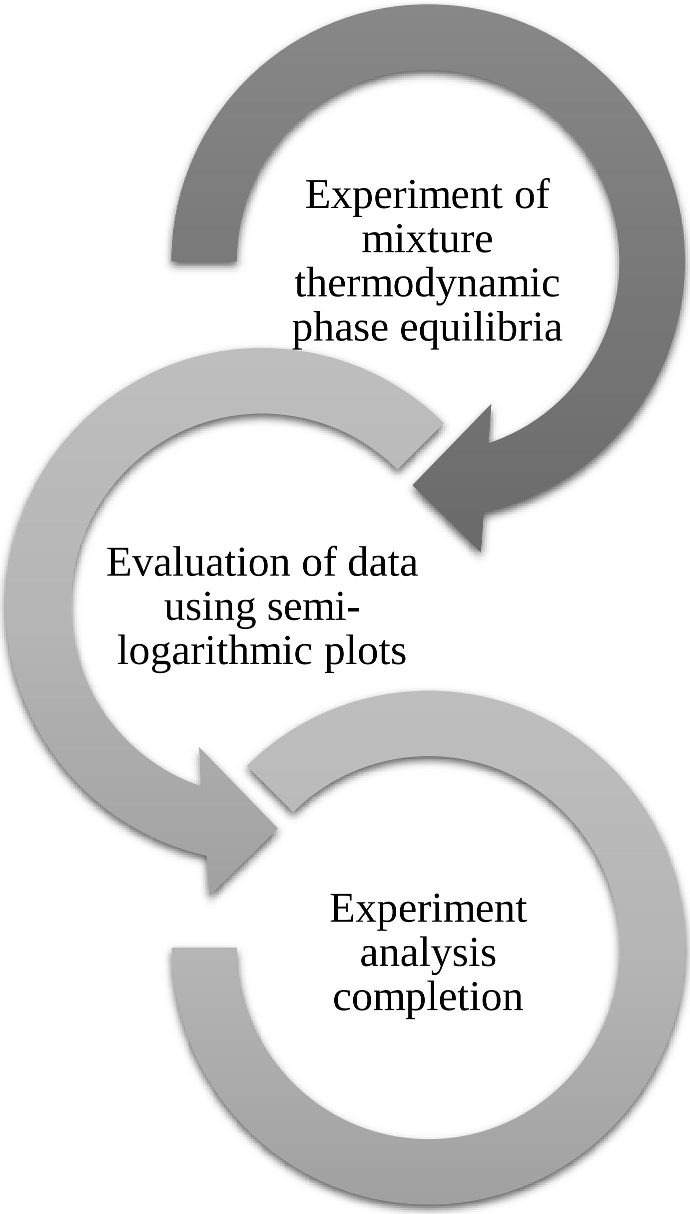
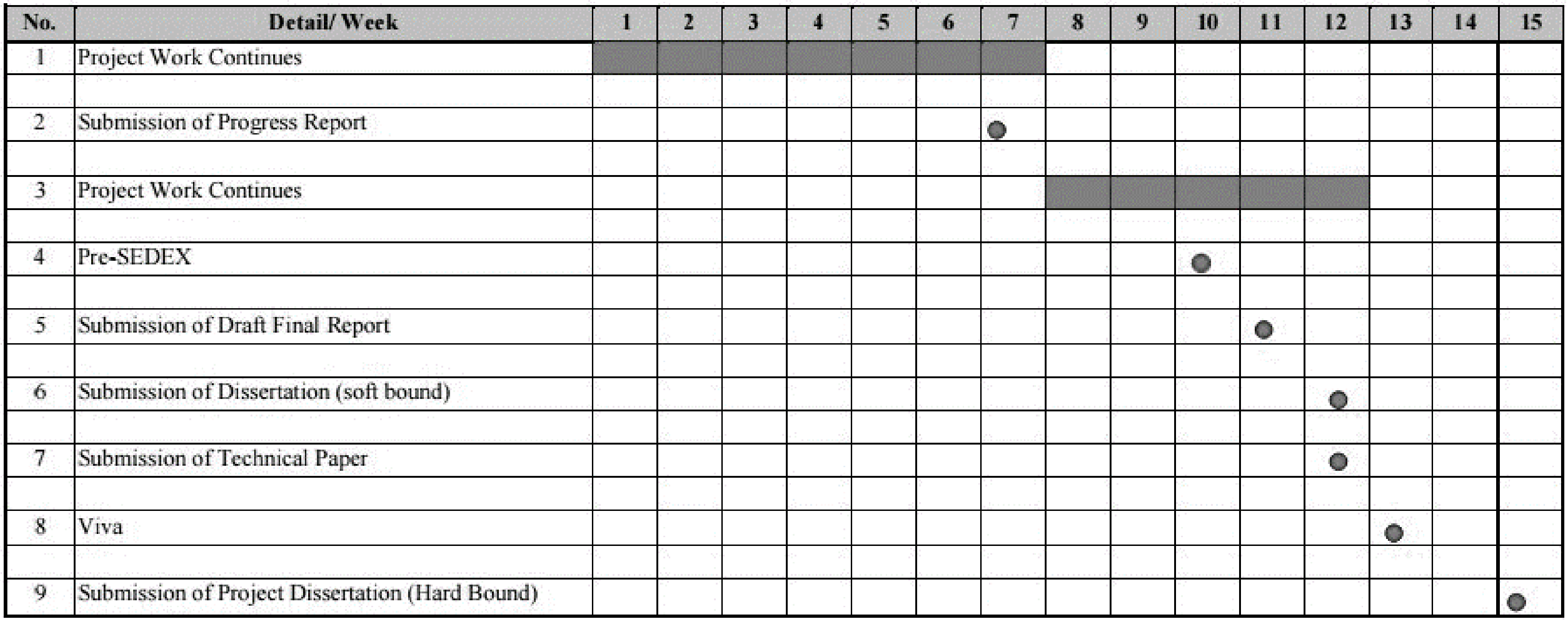


FIGURE 3.1 Flow Sheet of Project

TABLE 3.1 Project Timeline for Final Year Project 2



No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project Work Continues	▨	▨	▨	▨	▨	▨	▨								
2	Submission of Progress Report							●								
3	Project Work Continues								▨	▨	▨	▨	▨			
4	Pre-SEDEX										●					
5	Submission of Draft Final Report											●				
6	Submission of Dissertation (soft bound)												●			
7	Submission of Technical Paper												●			
8	Viva													●		
9	Submission of Project Dissertation (Hard Bound)															●

3.3 Early Project Progress

Two main issues were concentrated within week 5, 6, and 7 in reference to Table 3. These issues consist of the method of measuring the carbon dioxide miscibility in the quaternary system, and conducting a consistency test experiment. The latter was not achievable for the first 4 weeks of ‘experimental work’ period due to a malfunction of the stirrer’s motor.

For the former issue, CO_2 miscibility could be calculated and predicted by various thermodynamic models such as Gibbs ensemble Monte Carlo method (GEMC) and also recently published experimental data by Jodecke et. al and Urukova et al. [16, 17]. From the results in Jodecke et. al. and Urukova et. al., the author has resulted in the use of the conventional interpolation method for rough estimations.

After replacing the malfunctioned equipment, two (2) sample experiments had been conducted on 1 and 4 April 2015 with a reference sample of 3 mol % of acetone solution and 100% methane gas being used in both systems. The experiments ran for 40 hours straight and the result is tabulated into a graph and represented by Figures 3 and 4 below:

In reference to the Figure 3 and 4 below, the dissociation point is clearly visible at temperatures around 11.8 and 12.2 ^{o}C, and at pressures around 46.2 to 46.6 Bar. Both sample data lie within the region of consistency. From the latter confirmation, we could confidently conduct future experiments without the doubt of equipment errors such as inconsistencies.

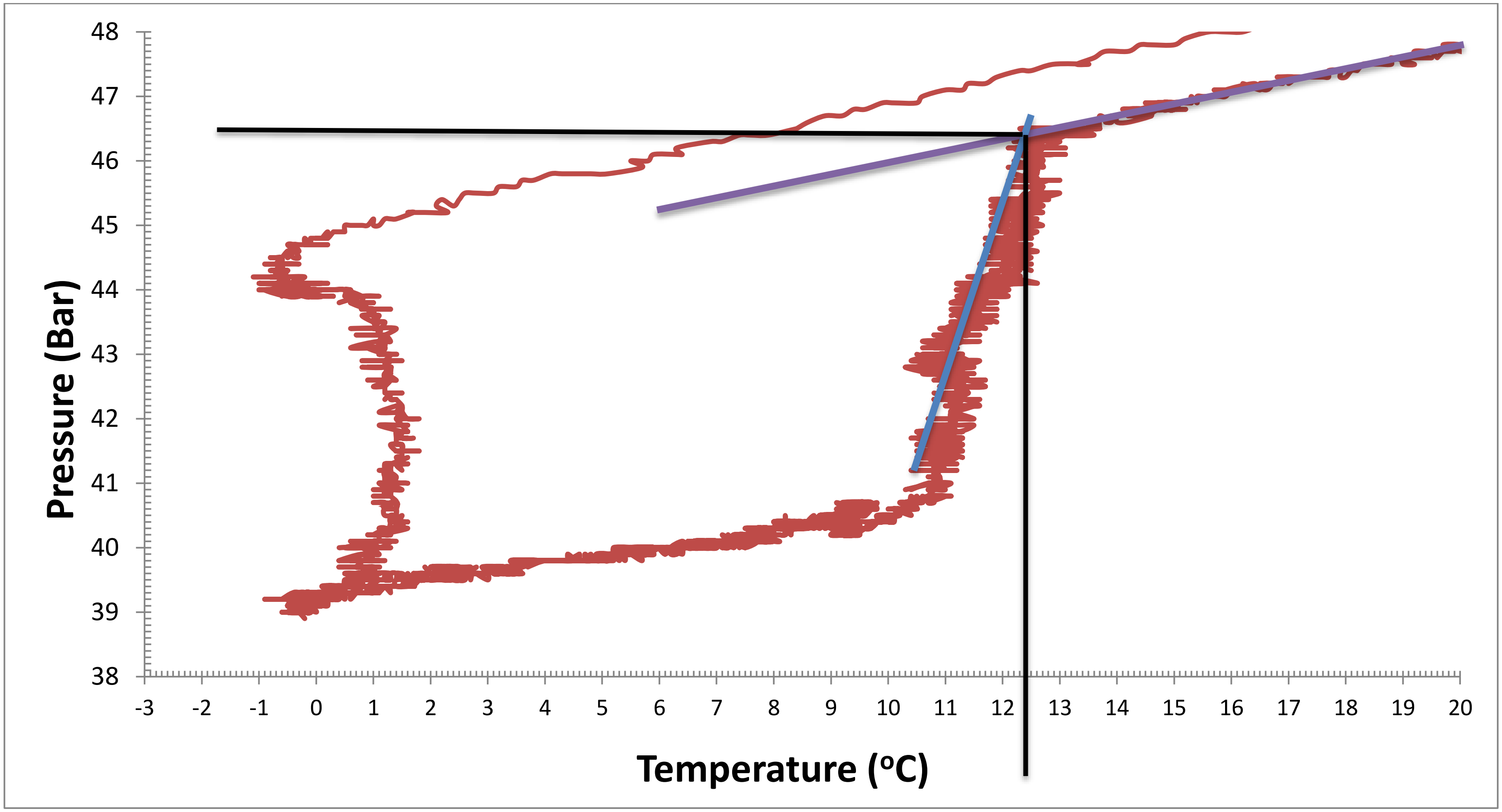


FIGURE 4.1 P-T Dissociation graph of Methane Gas Hydrate in 0.03 acetone solution at 50 Bar, Run 1

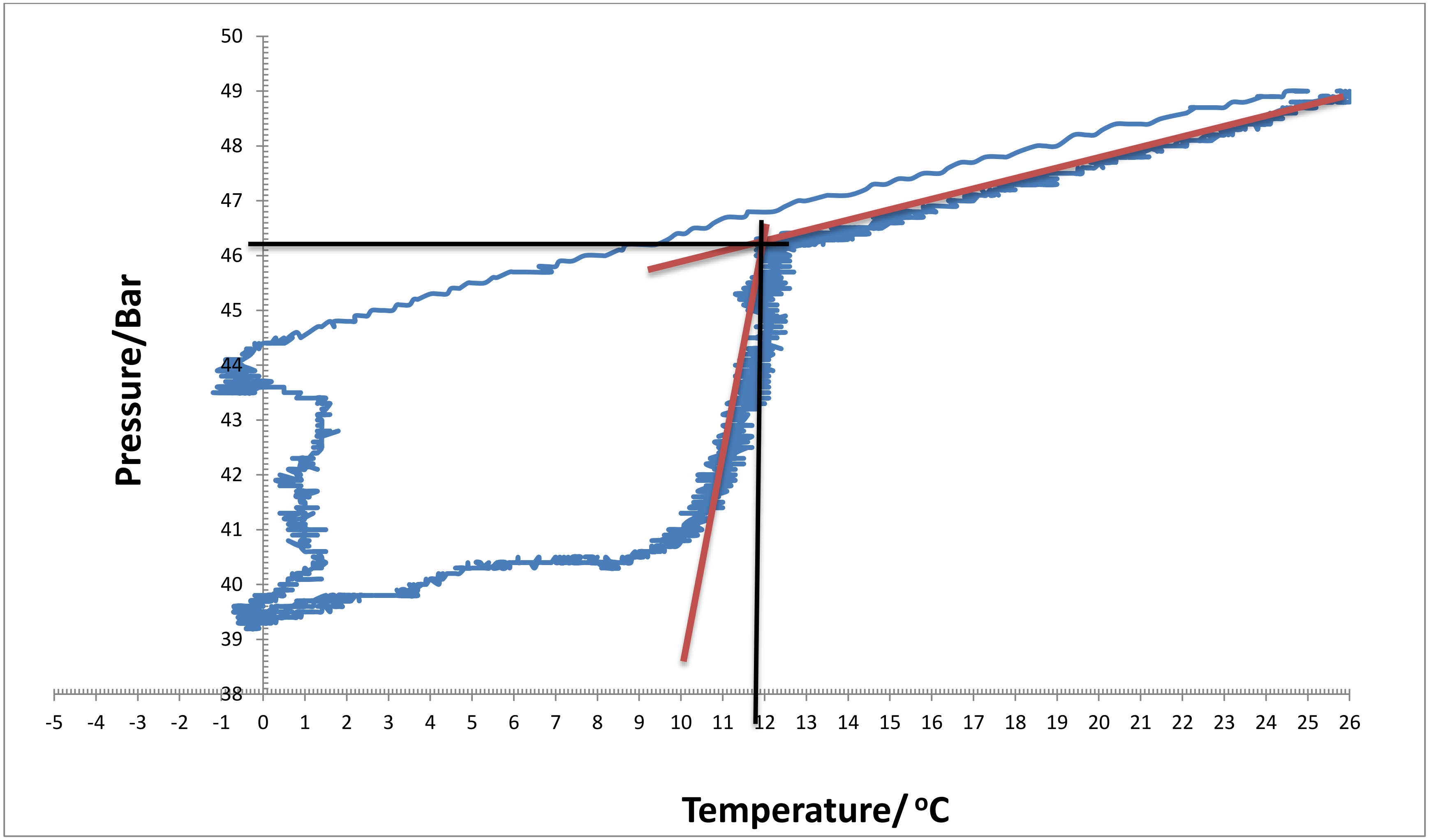


FIGURE 5.1 P-T Dissociation graph of Methane Gas Hydrate in 0.03 acetone solution at 50 Bar, Run 2

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

The dissociation points of CH_4-CO_2 hydrates obtained in the present study are tabulated in Table 1 below. Graphical representation of Table 1 is shown in Figure 4 using semi-logarithmic plots with scales on the vertical axis indicating pressure in bar (Bar) and on the horizontal axis indicating temperature in Kelvin (K). The data recorded are at 0.01, 0.03, 0.05 & 0.07 mole percent ('mol %' or simply '%').

TABLE 4.1 Tabulated Experimental Data

Solution (Experiment)	*Dissociation Point*	
	Temperature (K)	Pressure (Bar)
ACE|0.01%	279.23	32.01
	281.34	41.55
	283.16	52.89
ACE|0.03%	279.95	31.94
	281.07	37.20
	283.45	48.21
ACE|0.05%	280.70	33.20
	282.23	41.81
	282.96	50.49
ACE|0.07%	281.35	33.60
	282.17	42.25
	283.14	50.00

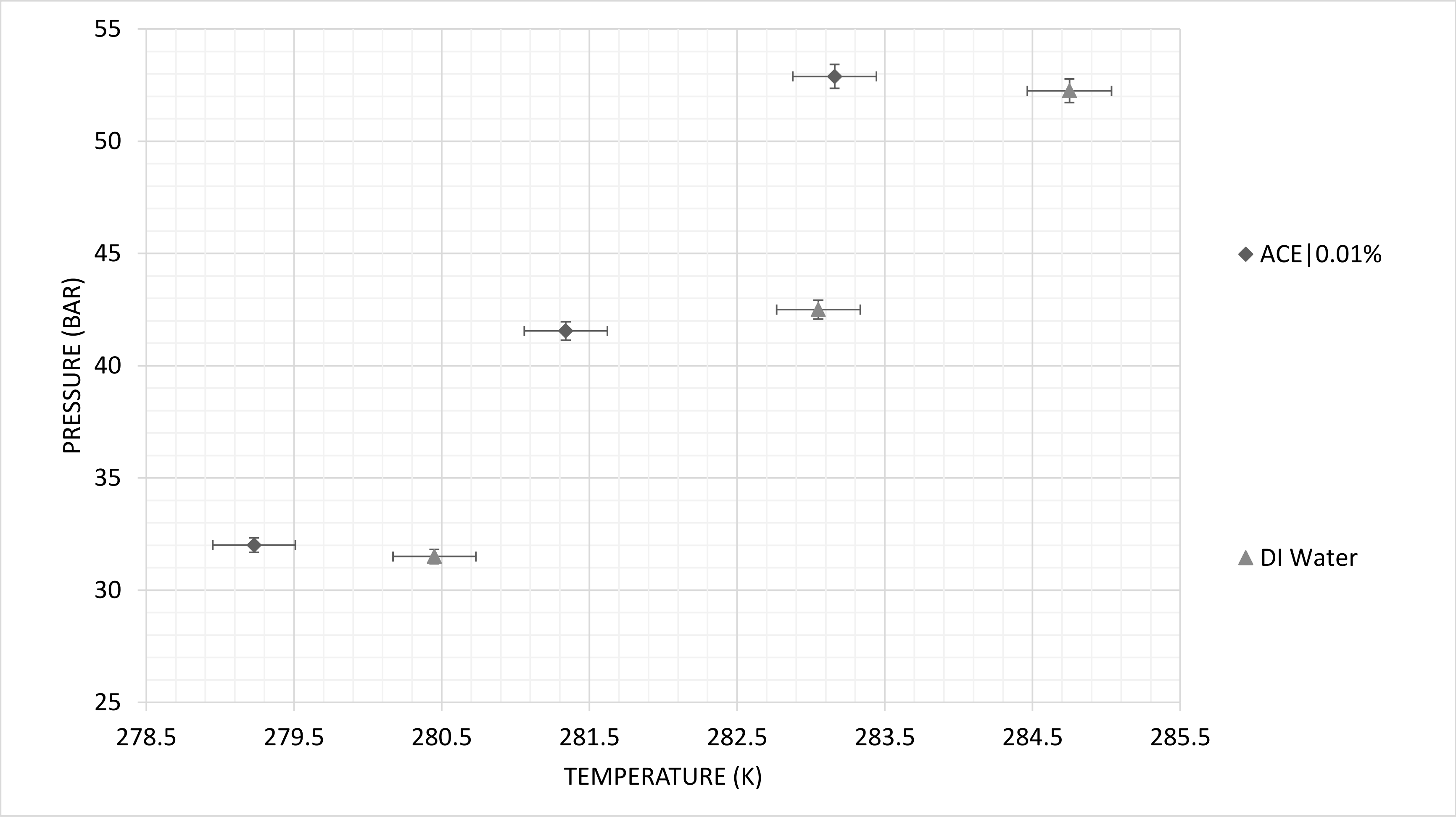


FIGURE 6.1 Acetone at 0.01 mol% concentration VS DI Water

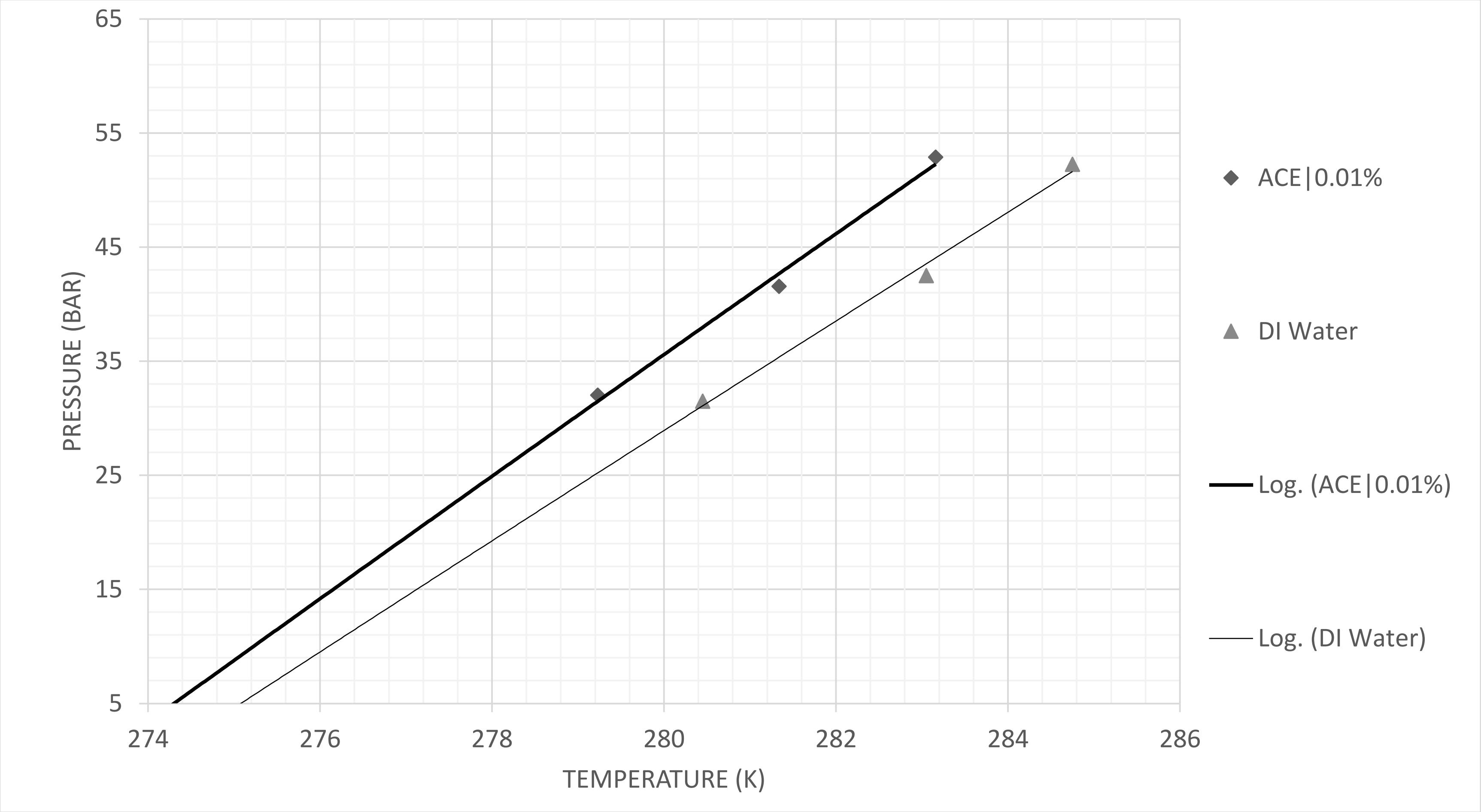


FIGURE 7.1   Trend lines of Acetone at 0.01 mol% concentration VS DI Water

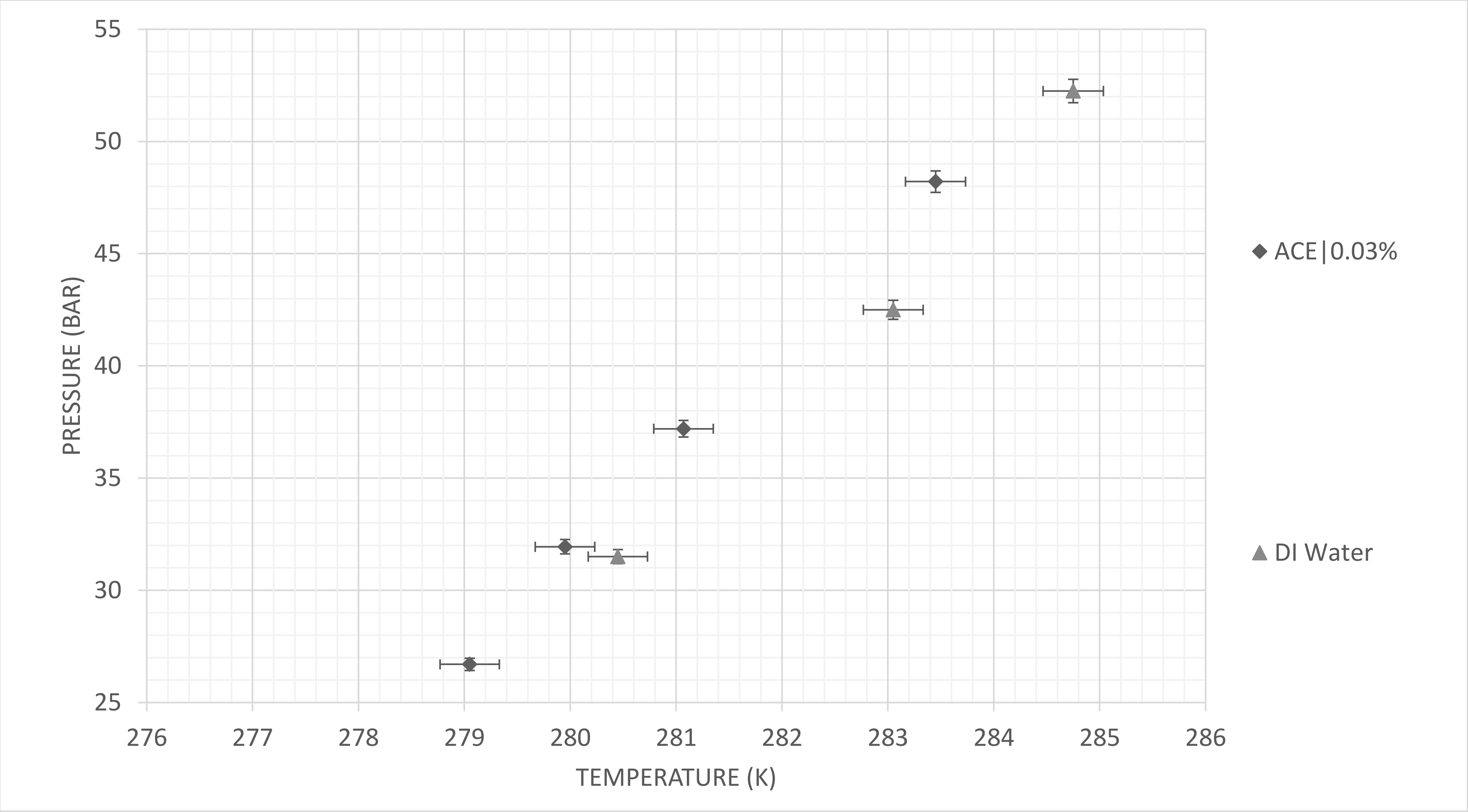


FIGURE 8.1 Acetone at 0.03 mol% VS DI Water

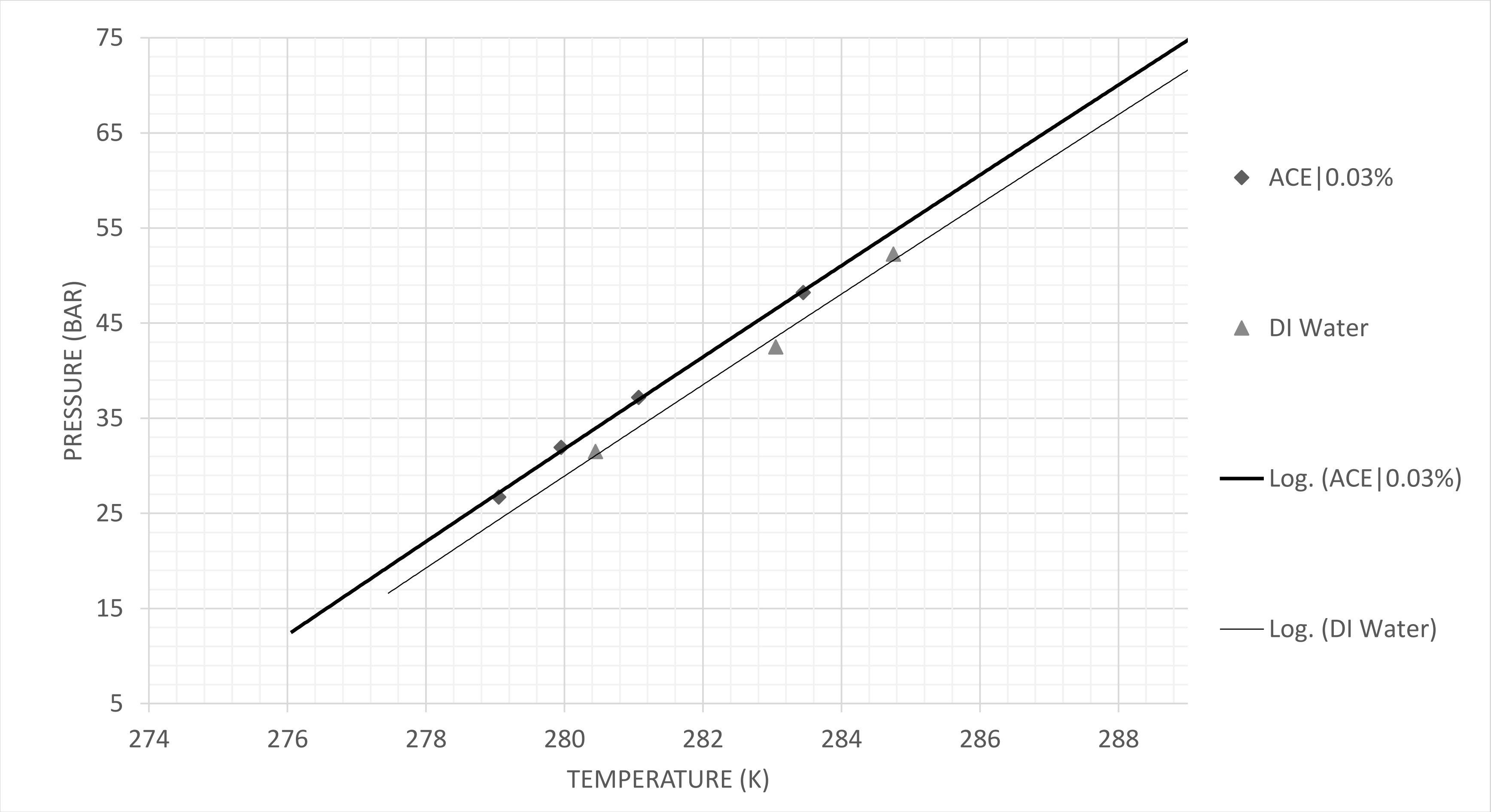


FIGURE 9.1 Trend lines of Acetone at 0.03mol% concentration VS DI Water

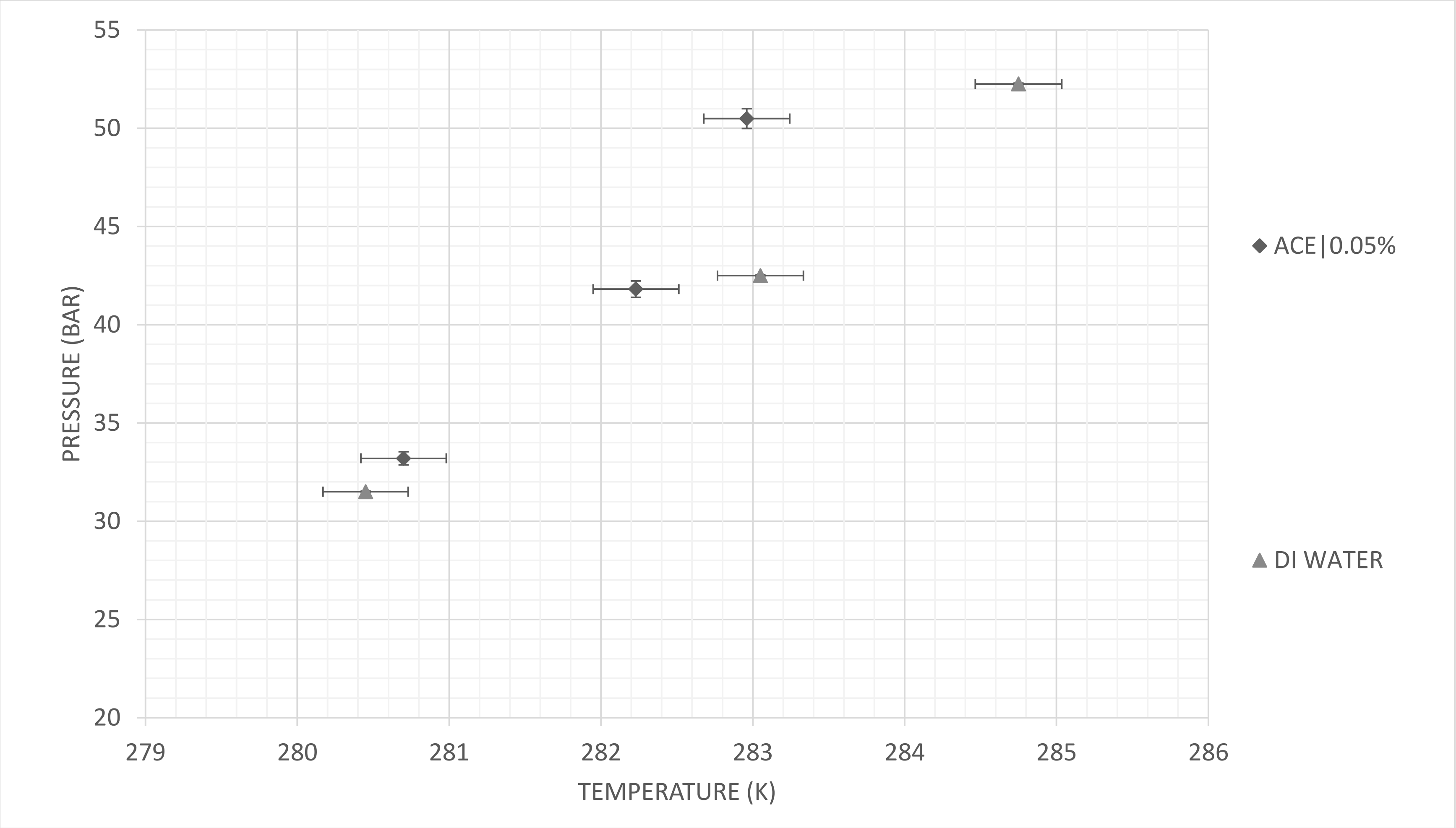


FIGURE 10.1 Acetone at 0.05mol% VS DI Water

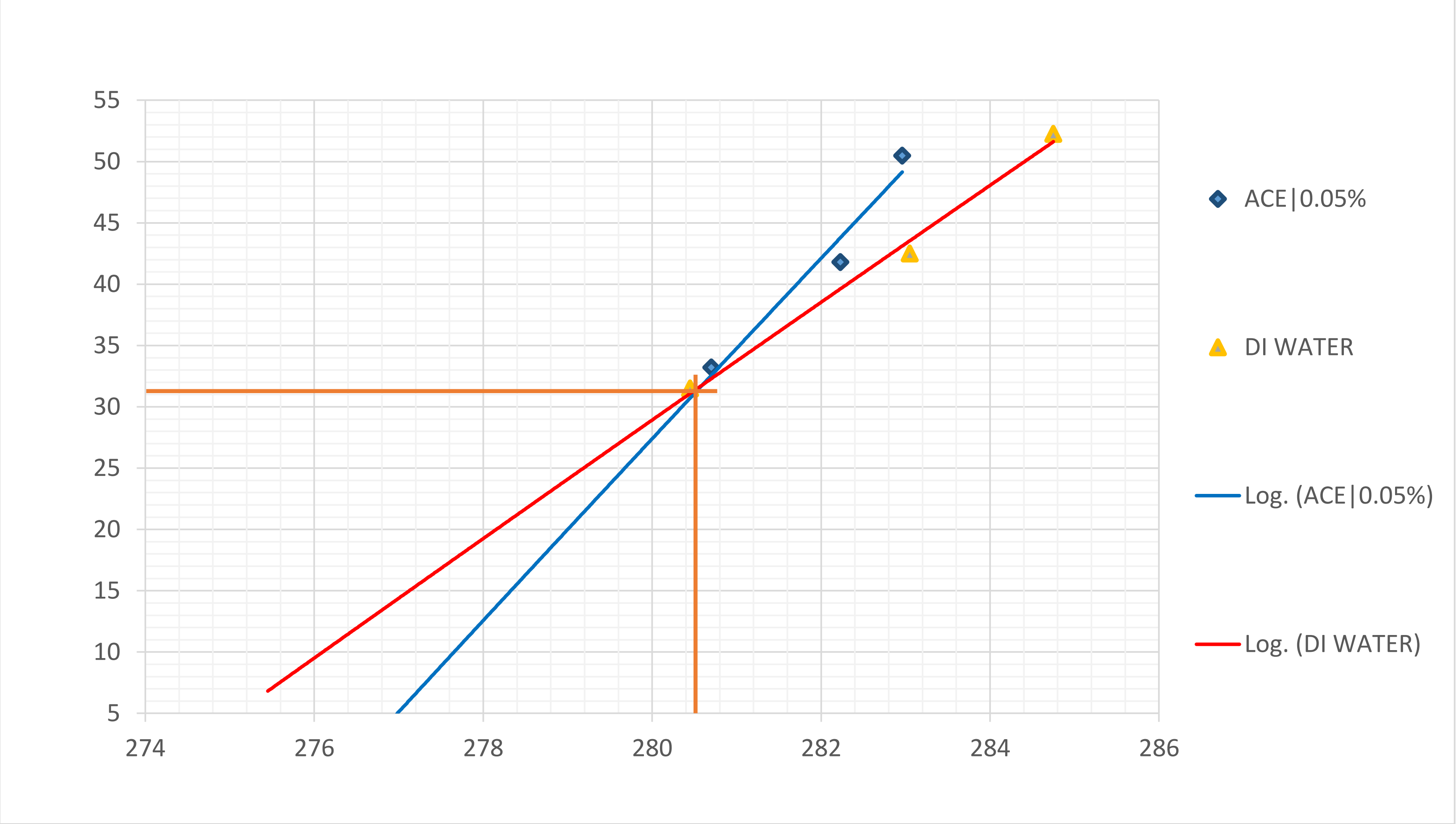


FIGURE 11.1 Expected convergence of Acetone at 0.05mol% concentration VS DI Water

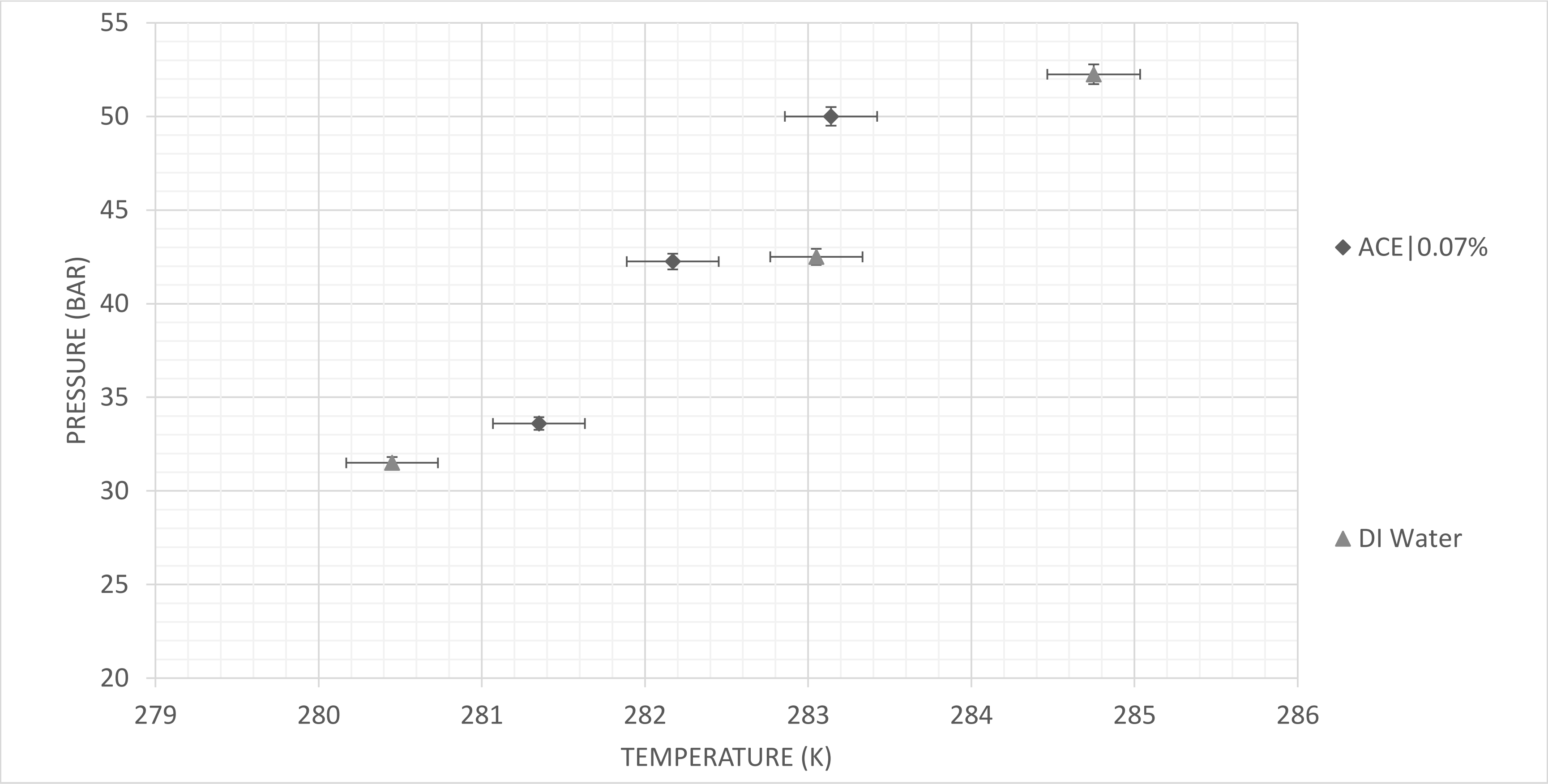


FIGURE 12.1 Acetone at 0.07mol% VS DI Water

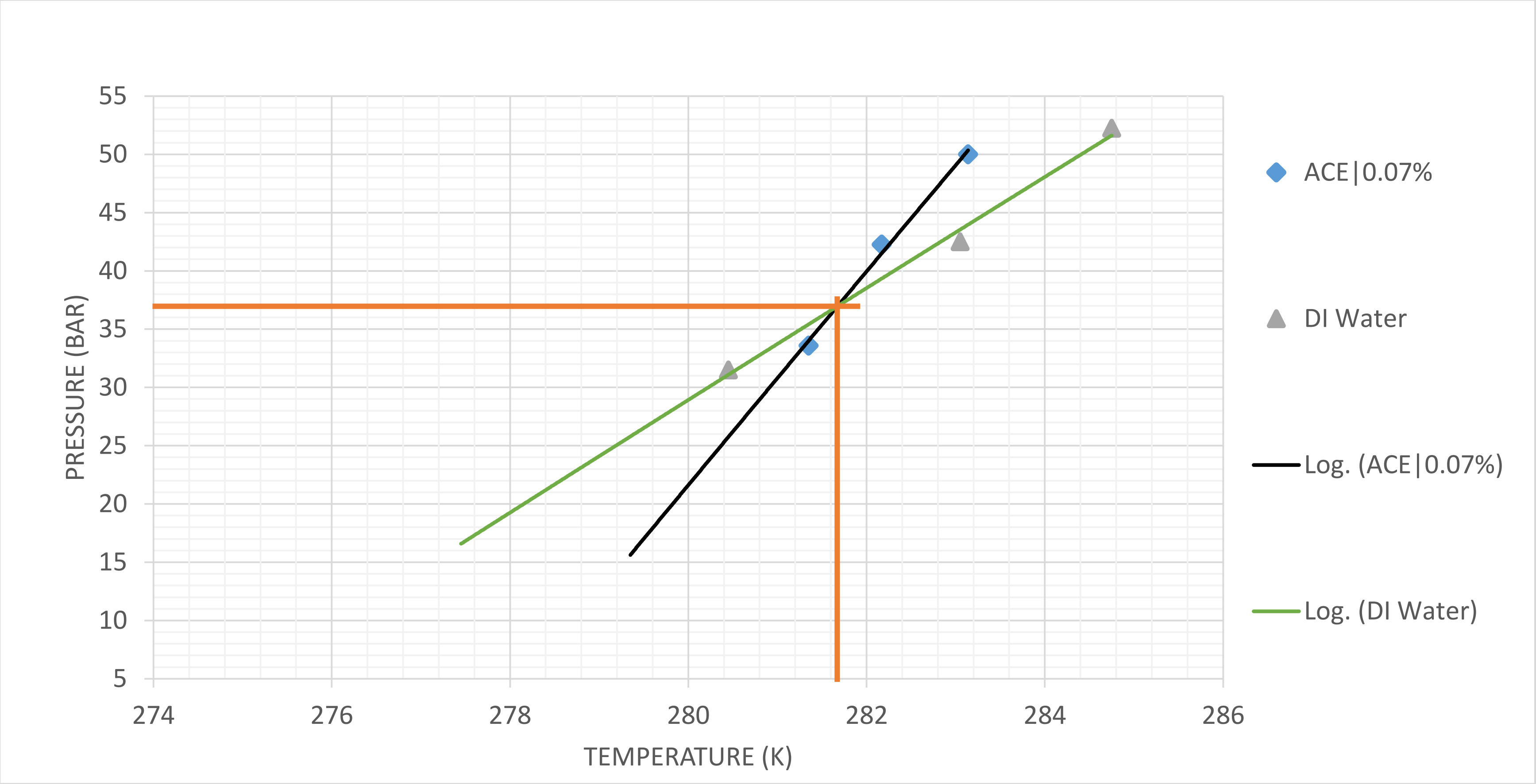


FIGURE 13.1 Expected convergence of Acetone at 0.07mol% concentration VS DI Water

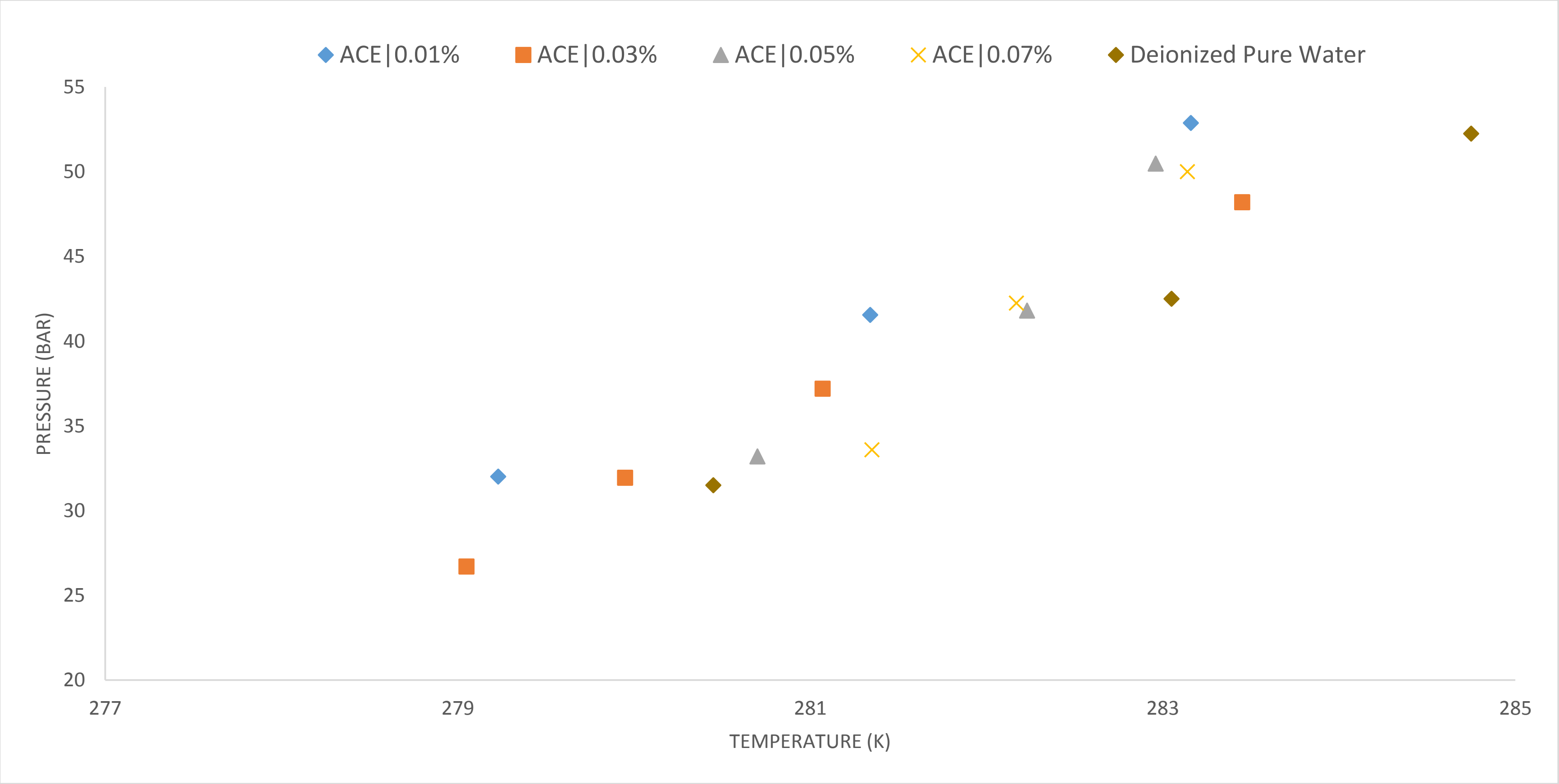


FIGURE 14.1Overall graphical interpretation of the tabulated data in Table 1. All percentages (%) are a representation of 'mol%'. ACE|(concentration) are experimental results by the author while ACE*|(concentration) are compared results.

4.2 DISCUSSION

Figure 13 offers an overall graphical interpretation of Figures 5 until 12. Figures 6, 8, 10, and 12 shows expected based on To simplify the visual representations, pressure regions are identified in multiples of 5 and denoted as $P_{x,}$ in which the subscript 'x' represents the pressures in Bar. The error labels for this experiment was determined to be at ±0.1% temperature (K) wise and ±1.0% pressure (Bar) wise.

In the author's experiment, under the pressure region between P_{30} & P_{35}, gas hydrates with ACE|0.07mol% solution has the highest dissociation point. At regions between P_{35} & P_{45}, and P_{45} & P_{55}, gas hydrates in pure DI water has the highest dissociation point. Figures 6, 8, 10, and 12 shows the extrapolated trend lines to predict optimum dissociation point at different acetone concentrations.

Figures 6 and 8 do not have any convergence of trend lines, hence at ACE|0.01% and ACE|0.03% do not enhance or improve in gas hydrate promotion and holding time. However, ACE|0.05% and ACE|0.07% trend lines intersect at (280.5 K, 31 Bar), and (281.7 K, 37 Bar) respectively.

These convergences displays the potential for acetone at 0.05 mol% and 0.07 mo l% of being an effective promoter below the convergence point e.g. *ACE|0.05% works as a gas hydrate promoter under the conditions either below 280.5K or below 31 Bar*. By observation, the author hypothesizes that *as the pressure increases, the concentration of acetone required to increase the hydrate dissociation point increases*.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

To reiterate, as hydrate dissociation point increases, the concentration of acetone required increases along the buildup of pressure. According to the convergences of Figure 10 and Figure 12, the optimum concentrations for gas hydrate promotion lie above 0.05 mol% as pressure increases above 30 bar.

5.2 Recommendation

The experiment conducted only used CO_2 gas, CH_4 gas, and deionized water (DI) as the constituents with acetone solution of 1 mol%, 3 mol%, 5 mol%, and 7 mol% being injected into the calorimeter. It is recommended that the experiment is to be conducted with higher acetone solutions and with more constituents such as hydrogen sulfide (H_2S).

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APPENDIX

APPENDIX 1.1

The actual equipment used as represented by Figure 1

APPENDIX 1.2

Pressure pump and booster to regulate pressure conditions and for gas input

APPENDIX 1.3

Water Deionizer Equipment