



# Investigating the Effects of Polyimido Amine Corrosion Inhibitors on Gas Hydrate Formation in Gas Pipelines

S. Isaiah<sup>1</sup>, U. Osokogwu<sup>2</sup>

<sup>1</sup>Department of Petroleum and Gas Engineering, University of Port Harcourt, P.M.B. 5323, Port Harcourt, Nigeria

<sup>2</sup>Department of Petroleum and Gas Engineering, University of Port Harcourt, P.M.B. 5323, Port Harcourt, Nigeria

\*Corresponding author: Samuel Isaiah, Email address: [samuel.isaiah@uniport.edu.ng](mailto:samuel.isaiah@uniport.edu.ng)

\*\*Corresponding author: Uche Osokogwu, Email address: [uche.osokogwu@uniport.edu.ng](mailto:uche.osokogwu@uniport.edu.ng)

Received 27 Aug 2022,  
Revised 15 Oct 2022,  
Accepted 21 Oct 2022

## Keywords

- ✓ Corrosion inhibitors
- ✓ Concentrations,
- ✓ Hydrate formation,
- ✓ Diethylenetriamine,
- ✓ Ethylenediamine,
- ✓ Pipelines.

[samuel.isaiah@uniport.edu.ng](mailto:samuel.isaiah@uniport.edu.ng)  
Phone: +2348024084233;

## Abstract

Corrosion and gas hydrate formation in natural gas pipelines are critical flow assurance problems confronting the oil and gas industry globally. Recent reports show that some corrosion inhibitors often create other flow assurance problems when applied for specific flow issues. Hence the need for thorough empirical analysis of oil field chemicals before they are applied in the field. This research work focuses on investigating the effects of polyimidoamine corrosion inhibitors on gas hydrate formation. The study found that the two corrosion inhibitors (Diethylenetriamine and Ethylenediamine) used had better hydrate inhibiting efficiency than Mono-ethylene glycol, thus serving as dual-functional inhibitors. Also, cost analyses for the inhibitors were done using their efficiency factor and monetary value for ease of inhibitor selection based on their dosage and required efficiencies.

## 1. Introduction

Inhibition of corrosion in gas transportation is one of the major investment problems in the oil and gas industry. It accounts for a huge portion of the production cost globally which amount to billions of dollars annually [1]. Most gas pipelines are made with steel materials due to their low cost [2]. These materials are prone to sweet and sour corrosion in the presence of water molecules; hydrogen sulphide (H<sub>2</sub>S) and carbon dioxide (CO<sub>2</sub>) within the flowing gas stream [3, 4], with CO<sub>2</sub> induced corrosion accounting for approximately 60% of oilfield failures [5]. In light of this, corrosion inhibitors are often injected into the gas flowing stream to inhibit or reduce the rate of corrosion of the pipeline [6]. Corrosion inhibitors are chemicals that are added in smaller doses to a corrosive environment to slow down the rate of corrosion of certain metals in that environment [7].

The corrosive environments in oil and gas producing wells undergo frequent variations due to changes in the composition of the produced fluids [8]. Thus, the need for periodic empirical testing to determine the efficiency of each chemical inhibitor before it is applied in the field [1]. There are several groups of corrosion inhibitors which include but not limited to the following: Amides and imidazolines (examples are Polyimido amines, Polypeptides, Slow-release formulation and Ampholytes), Nitrogen quaternaries, Nitrogen heterocyclics, Lignin amines and Amido amine salts, etc [9]. The properties of corrosion inhibitors such as the length of the hydrocarbon chain, ring size, functional group, contact angle and nature of bond formed determine their effectiveness [10]. The

inhibitors of interest in this research work are Diethylene-triamine and Ethylenediamine which are examples of polyimido amine corrosion inhibitors, a sub-set of the amides and imidazolines group of corrosion inhibitors. Polyimido amines corrosion inhibitors are made from the condensation reaction of poly-amines with maleic or styrene anhydride (SA) copolymer. The resultant product is a film-forming polyimido amine corrosion inhibitor. The film forming corrosion inhibitors precipitate a stable protective corrosion film on the surface of the pipeline [11], and are ideal for high acidic environments [9].

It has been established from literature that some corrosion inhibitors do improve hydrate inhibition, while some promote hydrate formation when applied to inhibit corrosion. The influence of corrosion inhibitors on hydrate formation temperature along the subsea natural gas pipelines was researched using five corrosion inhibitors (2-Mercapto pyrimidine (MP), Cetyl pyridinium chloride (CPC), Dodecyl pyridinium chloride (DPC), Thiobenzamide (TB) and Benzyl dimethyl hexadecyl ammonium-chloride (BDHC)). The various corrosion inhibitors were applied at varying concentrations (0 - 10,000 ppm) and pressures (50 -150 bar) to different samples (natural gas and water) in a cryogenic sapphire cell under the same operating conditions. It was discovered that the corrosion inhibitors promoted hydrate formation at different rates in this order DPC, BDHC, MP, CPC and TB respectively with TB having the least influence [12]. The effect of N-methyl-diethanolamine (MDEA) and film forming corrosion inhibitor (FFCI) on gas hydrate formation was researched using a magnetic stirrer and a high-pressure PVT cell with computer aided temperature and pressure capturing devices. It was discovered that the combination of KHI + FFCI, MDEA + MEG and FFCI + MEG showed improved hydrate inhibitory performance, but the combination of MDEA with KHI revealed an increase in hydrate induction time [13].

The interactions between a commercial KHI (Kinetic Hydrate Inhibitor) and three different CIs (Corrosion Inhibitors), was also researched by subjecting the KHI and the CIs to critical micelle concentration (CMC) and Surface tension tests prior to their corrosion and hydrate testing. The result of the test showed a trend of incompatibility between the KHI and two of the CI samples with a 50% reduction in hydrate induction time, while the third had a slight improvement in inhibiting corrosion and hydrate [14]. Similar research was also conducted on the interaction of KHI and four CIs using linear polarized resistance (LPR) and pressurized rocking cells. The result showed that out of four corrosion inhibitor samples, only one of the sample (sample D) was compatible with the KHI and was also effective in inhibiting corrosion and hydrate formation, while the other three samples (sample A, B and C) had adverse interaction with the KHI which resulted in an increase in hydrate formation [15].

The Kinetic Hydrate Inhibition Performance of Poly (vinyl caprolactam) modified with Corrosion Inhibitor Groups (PVCap-co-AA, PVCap-co-ATCH, and PVCap-co-APIM) was also researched to determine the hydrate onset time, growth rate, and resistance-to-flow using a high pressure autoclave. The experimental results show that PVCap-co-APIM and PVCap-co-ATCH were able to delay hydrate nucleation; however, PVCap-co-APIM was better than PVCap-co-ATCH. The performance of the new KHICs (Kinetic Hydrate and Corrosion Inhibitors) was compared with a commercial KHI (Luvicap) at different cooling rates. At higher cooling rates, Luvicap was able to delay the nucleation of hydrate for a longer period than did the new KHICs, while KHIC of PVCap-co- APIM performed better than KHIC of PVCap-co-ATCH and the commercial KHI (Luvicap) at lower cooling rates [16].

The Effects of Thermally Degraded Monoethylene Glycol (MEG) with Methyl Diethanolamine (MDEA) and a Film-Forming Corrosion Inhibitor on Gas Hydrate Kinetics was investigated using a PVT sapphire cell unit and autoclave apparatus. The study revealed that a thermally degraded MEG with MDEA and/or FFCI inhibited hydrate formation more efficiently than thermally degraded MEG without MDEA and/or FFCI, with sample C (MEG-MDEA-FFCI) showing the best hydrate inhibition performance, because of the additional synergistic hydrate inhibition effect of both MDEA and FFCI, followed by sample A (MEG-MDEA), and lastly sample B (MEG-FFCI). Sample A showed better inhibition compared to B because of the higher hydrate inhibition effect of MDEA compared to FFCI [17].

Some oil and gas facilities are situated offshore where oil and gas are produced and transported under conditions that enhance gas hydrate formation and other flow assurance issues [18, 19]. Gas hydrates are crystal compounds consisting of molecules of gases encapsulated by water molecules and held by hydrogen bonding at high-pressure and low-temperature [20, 21]. Research shows that hydrate formation occurs at the water-gas interface, which eventually grows by agglomeration of the hydrate nuclei into larger sizes [22] and can result to pipeline blockage leading to explosion, production down-time and severe economic losses [23, 24]. Hydrate inhibitors are usually injected into the gas flow line to inhibit hydrate nucleation or agglomeration [25]. They exist in various forms such as Thermodynamic Hydrate Inhibitors (THI), Low Dosage Hydrate Inhibitors (LDHI) (comprising Anti Agglomerate (AA) and Kinetic Hydrate Inhibitors (KHI)), and Kinetic hydrate and corrosion inhibitors (KHCI) [9].

There are several research work and literature on the types, operating mechanisms and efficiencies of various corrosion and hydrate inhibitors but there are relatively few existing research works and literatures on the compatibility of these inhibitors and their ability to pose other flow assurance problems [12]. This study is to evaluate experimentally the effect of Diethylene-triamine and Ethylenediamine polyimido amine-based corrosion inhibitors on gas hydrate formation in gas pipelines system using a horizontal hydrate flow loop and also to select the most cost-effective corrosion inhibitors based on their doses and their effect on hydrate inhibition or formation. The two corrosion inhibitors selected for this research work are Diethylene-triamine and Ethylenediamine based on their frequent usage and better efficiency in high acidic environments [9]. This is to ensure that while they are applied to inhibit corrosion that they do not induce hydrate formation. The resultant inhibiting effect of the two corrosion inhibitors shall be compared with the inhibiting efficiency of MEG, a commonly used thermodynamic hydrate inhibitor based on its low volatility [26-27] and high recovery efficiency.

## **2. Methodology**

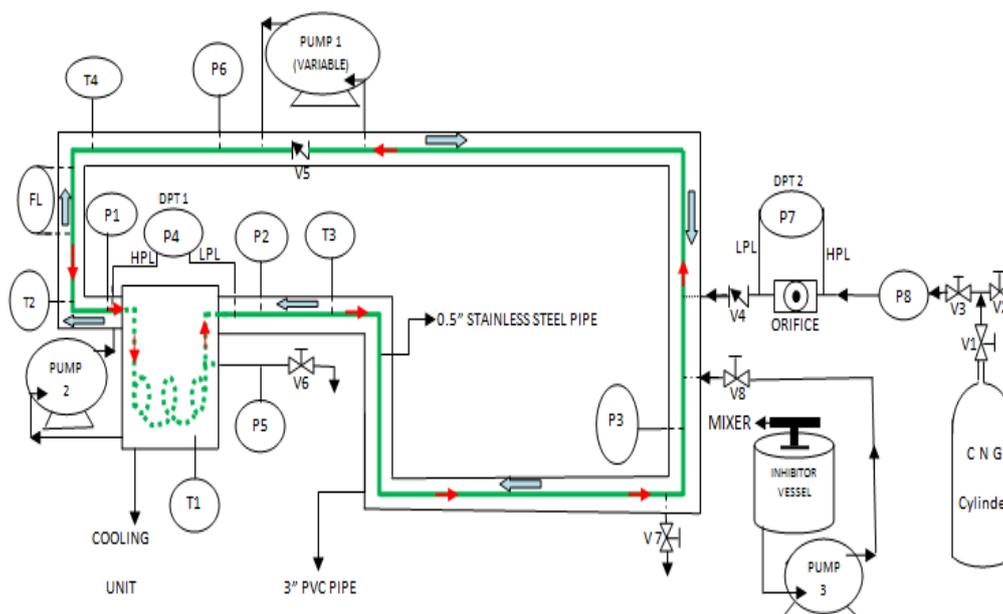
The research experiments were conducted using hydrate flow loop equipment in the Production Engineering Laboratory in the Petroleum Engineering Department, University of Port Harcourt.

### ***2.1 Equipment and materials used in experimenting***

#### ***2.1.1 Hydrate mini flow loop description***

The equipment used for this project is a closed mini hydrate flow loop which was used to simulate an offshore gas pipeline operating under gas hydrate formation conditions (of low temperatures and high pressures). The flow loop consists of the following parts; a control panel, refrigerator, electrical pumps, compressed natural gas cylinder, temperature sensors, inhibitor vessel, pressure sensors, differential pressure gauge, flow meter and a stainless steel tubing of measured length 45 feet with

0.5 inches outer diameter and 0.4 inches internal diameter. The stainless steel is enclosed in an insulated 3 inches internal diameter polyvinyl chloride (PVC) pipe for water circulation at regulated or controlled temperatures. The flow loop was designed to operate at temperatures ranging from -1.5 °C to 35 °C and at a pressure of 150 psi. The schematic diagrams of the mini gas hydrate flow loop used for this research work is as shown in [Figure 1](#).



**Fig. 1** Schematic diagram of the hydrate flow loop (Petroleum and Gas Engineering Department, University of Port Harcourt, Nigeria).

### 2.1.2. Materials used for the experiment

**a. Compressed natural gas (CNG):** This consists of methane, ethane, propane, butane and carbon dioxide in trace amounts. Natural gas is used as a gas feed for the hydrate flow loop.

**Table 1.** Composition of compressed natural gas

Gas	Structural Formula	% composition
Methane	CH <sub>4</sub>	98.44
Ethane	C <sub>2</sub> H <sub>6</sub>	1.13
Propane	C <sub>3</sub> H <sub>8</sub>	0.17
Butane	C <sub>4</sub> H <sub>10</sub>	0.06
Carbon dioxide	CO <sub>2</sub>	0.14

**b. Inhibitors:** Corrosion and Hydrate Inhibitors

**Table 2.** Inhibitors, molecular formula and weight

List of inhibitors	Abbreviation	Molecular formula	Mol.wt. (g/mol)
<b>Corrosion Inhibitors</b>			
Ethylene-di-amine	EDA	C <sub>2</sub> H <sub>5</sub> NH <sub>2</sub>	45.080
Diethylene triamine	DETA	C <sub>4</sub> H <sub>13</sub> N <sub>3</sub>	103.169
<b>Hydrate Inhibitor</b>			
Mono Ethylene Glycol	MEG	C <sub>2</sub> H <sub>6</sub> O <sub>2</sub>	62.070

## 2.2 Experimental procedure

The experiment was preceded by the flushing of the loop using water to remove any trace of leftover inhibitors or rust that might be present in the loop. The inhibitor mixer vessel was cleaned and filled with water which was pumped into the loop with the aid of pump 3 and circulated with the aid of pump 1. The circulated water was let out through valves 6 and 7 at separate intervals. The flushing process was repeated until there was no more trace of rust in the inner line of the 0.5-inch diameter loop.

Before the application of inhibitors, the experiment was conducted using only CNG and water to serve as a control. 4 liters of water was poured into the mixer vessel and pumped into the loop with the aid of pump 3 and valve 4 till the loop attains a pressure of 25 Psi. Valve 1 and the orifice were opened and with the aid of valve 3, CNG gas was flowed into the loop to raise the internal pressure of the loop from 25 Psi to 150 Psi. Pump 1 was turned on to circulate and induce agitation of the water and gas in the loop. Pump 2 was also turned on to pump water from the refrigerating unit and circulated round within the 3 inches PVC pipe which encloses the 0.5-inch stainless steel meant for chilling of the loop. Ice blocks were intermittently added into the refrigerating unit of the flow loop until it gets to its lowest temperature of  $-1.5^{\circ}\text{C}$ .

The experimental process lasted for 2 hours and readings were obtained every 2 minute from all the pressure gauges (P1 to P6) and thermometers (T1, T2, and T3) throughout the 120 minutes (2 hours) duration of the experiment. The result of the experiment gotten from the sample of gas and water only serve as control. The process was repeated for 0.05 Vol.%, 0.1 Vol.%, 0.2 Vol.% and 0.3 Vol.% concentrations of Ethylenediamine (EDA) and Diethylenetriamine (DETA) corrosion inhibitors (CIs) in water. The average flow rate of the loop was maintained at 2 GPM in the course of the experiment. At the end of the 120 minutes duration of the experiment, while the equipment is still on, valve 6 was opened for collection of samples to check for hydrate formation and the nature of hydrates formed in difference between the pressure drop for the uninhibited sample and the inhibited sample ( $\Delta P_a - \Delta P_b$ ) to that of the inhibited samples ( $\Delta P_b$ ) gives the inhibitor efficiency.

Where;

$$\Delta P_a = P_a - P_b \quad \text{Eqn. 3.1}$$

$$\Delta P_b = P_i - P_b \quad \text{Eqn. 3.2}$$

$P_i$  = Initial pressure reading of the system at the commencement of the experiment for both inhibited and uninhibited = 150 Psi.

$P_b$  = the last pressure for the uninhibited sample

$P_a$  = the last pressure reading for each of the inhibited samples.

The inhibition Efficiency ( $\eta$ ) is determined using the equation below

$$\eta = \frac{\Delta P_a}{\Delta P_b} \quad \text{Eqn. 3.3}$$

terms of its color and foam (if any) noted and recorded. Finally, the loop was flushed to remove all traces of hydrates (if any) and inhibitors using the flushing procedure discussed earlier.

## 2.3 The efficiencies of the inhibitors

The performance of the inhibitors used for this research work can be evaluated by determining the efficiency of each inhibitor concentration used. This is done by determining the pressure drop for the uninhibited sample ( $\Delta P_a$ ) and that of the inhibited samples ( $\Delta P_b$ ) at each concentration. The ratio of

the the difference between the pressure drop for the uninhibited sample and the inhibited sample ( $\Delta P_a - \Delta P_b$ ) to that of the inhibited samples ( $\Delta P_b$ ) gives the inhibitor efficiency.

Where;

$$\Delta P_a = P_a - P_b \quad \text{Eqn. 3.1}$$

$$\Delta P_b = P_i - P_b \quad \text{Eqn. 3.2}$$

$P_i$  = Initial pressure reading of the system at the commencement of the experiment for both inhibited and uninhibited = 150 Psi.

$P_b$  = the last pressure for the uninhibited sample

$P_a$  = the last pressure reading for each of the inhibited samples.

The inhibition Efficiency ( $\eta$ ) is determined using the equation below

$$\eta = \frac{\Delta P_a}{\Delta P_b} \quad \text{Eqn. 3.3}$$

#### 2.4 Efficiency factor of inhibitors

The Efficiency factor ( $\eta_f$ ) of the Inhibitor is the efficiency of the inhibitor per unit volume. The higher the efficiency factor, the lower its cost. Hence, the inhibitor with the highest efficiency factor has the lowest cost per unit volume. It is given by the equation;

$$\eta_f = \left( \frac{\eta}{V} \right) \quad \text{Eqn. 3.4}$$

Where;

$V$  = Volume of inhibitor used in  $\text{cm}^3$

$\eta$  = Efficiency of the inhibitor used

#### 2.5 Monetary cost of inhibitor used based on their efficiency ( $E_c$ )

This is the monetary cost of each inhibitor volume used and its efficiency. The lower it is the cheaper the inhibitor in terms of monetary value. It is given by the equation;

$$E_c = \left( \frac{C * V}{\eta * 1000} \right) \quad \text{Eqn. 3.5}$$

Where;

$E_c$  = Monetary Cost of Inhibitor used based on their Efficiency

$C$  = Cost of Inhibitor per Liter ( $1000 \text{ cm}^3$ )

$\eta$  = Efficiency of inhibitor

$V$  = Volume of inhibitor used

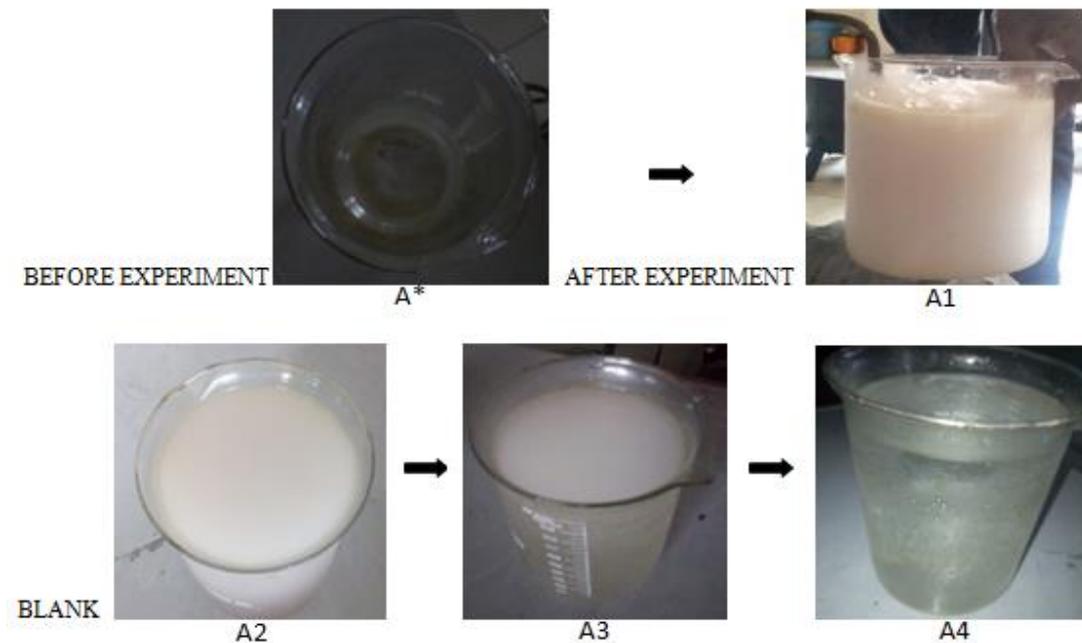
### 3. Results and Discussion

Result analysis of the effects of polyimido amine corrosion inhibitors on gas hydrate formation. The experiment was conducted with an initial pressure of 150 psi and a gradual temperature reduction from 30 °C to 6 °C.. The experimental data obtained were used to plot several graphs of temperature versus time, pressure versus time, and temperature and pressure versus time. The various plotted graphs were used to analyze all the results from the experiment.

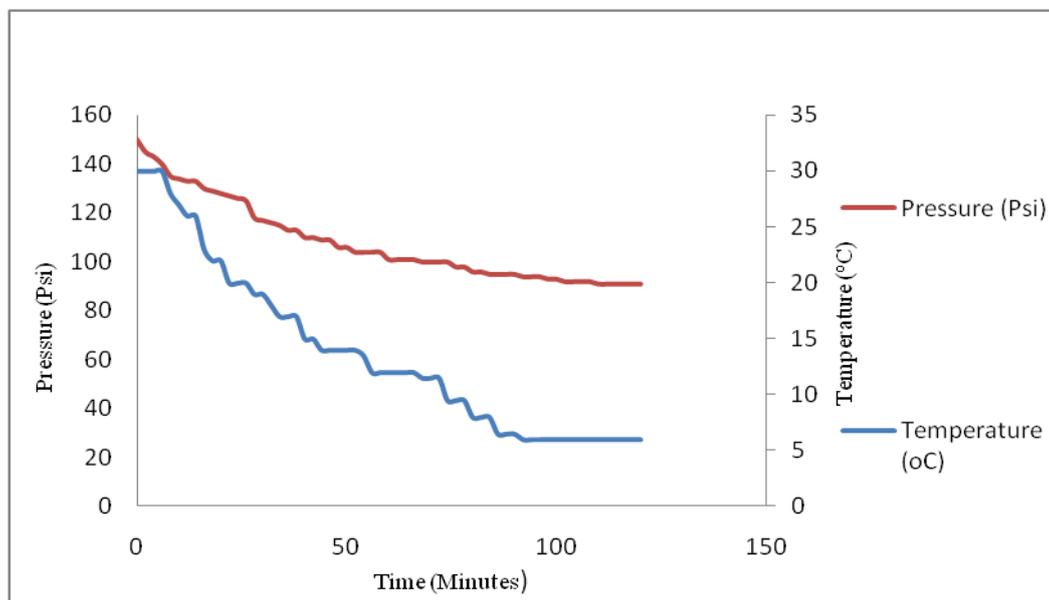
#### 3.1 Analyses of gas hydrate formation plot for uninhibited (control) sample

[Figure 2b](#) is a graph of pressure (psi) and temperature (°C) against time (minutes) for uninhibited sample (consisting of water and compressed natural gas (CNG) only). From the graph, it was observed that the system had a pressure drop of 59 Psi (from 150 psi to 91 Psi) as the temperature

dropped from 30 °C to 6 °C. The drop in pressure as the temperature of the flow-loop dropped to 6 °C is an indication that some of the gases have been encapsulated by the surrounding water molecules resulting to hydrate formation. The sample collected from valve 6 at the end of the experiment shows a white cloudy coloration which confirms that the drop in pressure was not due to gas solubility but rather due to hydrate formation at its nucleation stage. The white cloudy coloration gradually and completely disappears after 2 minutes due to sudden pressure reduction and increase in temperature when exposed to atmospheric conditions as shown in [Figure 2a](#).



**Fig. 2a** Blank Sample effluent collected after the experiment for 0.0 V/V %



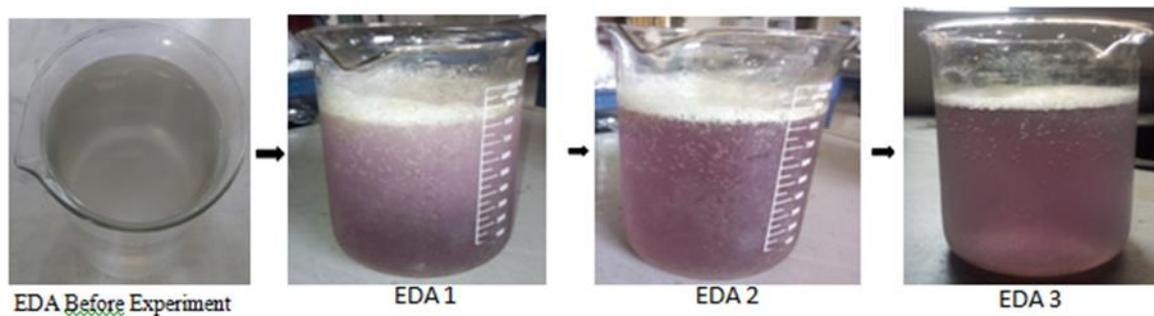
**Fig. 2b** Pressure and temperature against time graph for uninhibited (control) sample

### 3.2 Analyses of the effect of Ethylenediamine (EDA) on gas hydrate formation

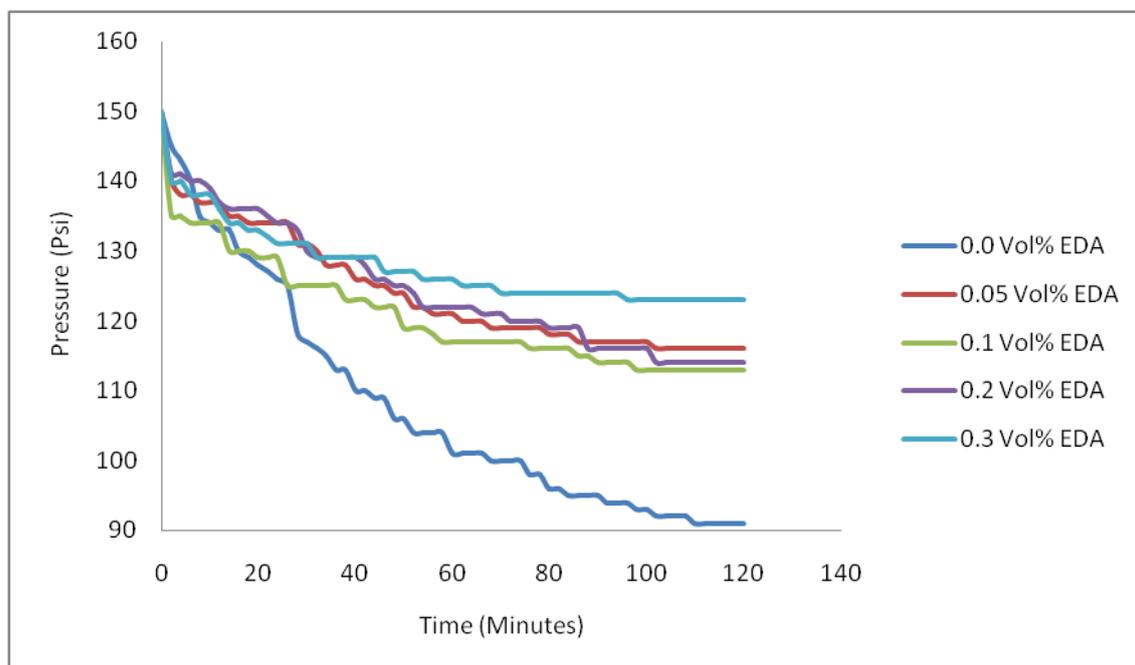
#### a. Temperature vs time plots analysis for EDA

[Figure 3b](#) is a graph of temperature against time for EDA corrosion inhibitor at different concentrations. The graph shows a similar pattern for all the plots and no significant difference in

temperature drop was observed for both the uninhibited and the various concentrations of the EDA corrosion inhibitors. They all have temperature drop of 24 °C (30 °C to 6 °C). This uniform drop in temperature for the various EDA corrosion inhibitor concentrations without a commensurate drop in pressure when compared to that of the uninhibited sample which also had the same temperature drop from 30 °C to 6 °C but with a greater pressure drop indicates that there was inhibition of hydrate formation.



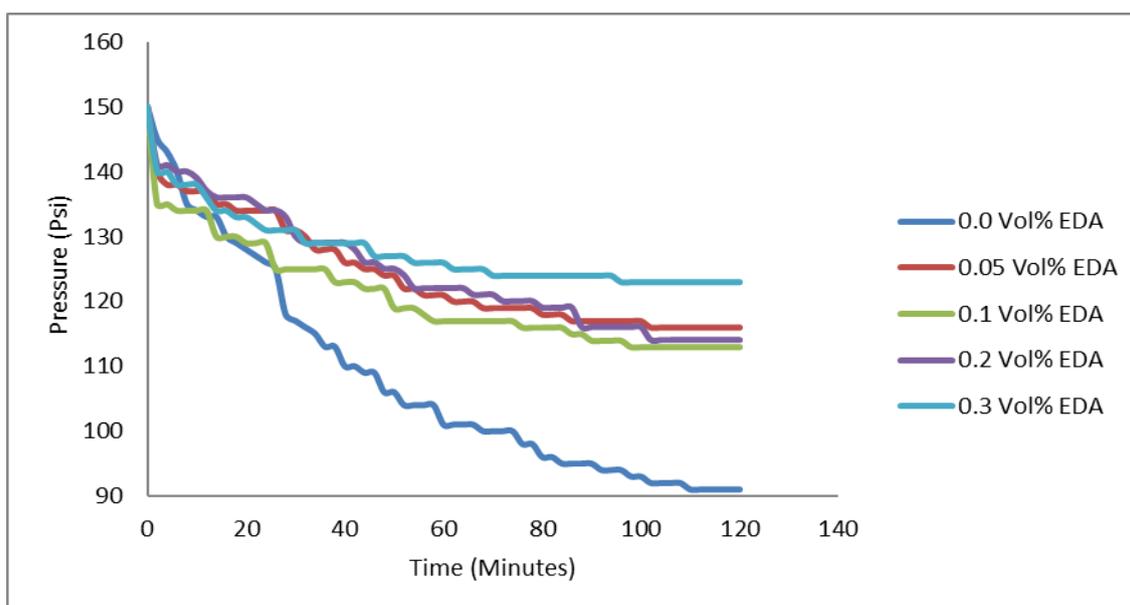
**Fig. 3a** EDA Sample effluent collected after the experiment for 0.1 V/V %



**Fig. 3b** Temperature against time graph for EDA samples

**b. Pressure vs time plots analysis for EDA corrosion inhibitor**

**Figure 3c** is a graph of pressure (psi) against time (minutes) for the EDA corrosion inhibitor at different concentrations. The graph shows a lesser pressure drop for all the inhibited samples compared to that of the uninhibited sample. The difference in pressure drop between the inhibited samples and the uninhibited sample indicates some degree of hydrate inhibition. The results obtained from the experiment shows that the various samples with 0.05 Vol.%, 0.1 Vol.%, 0.2 Vol.% and 0.3 Vol.% concentration of EDA had pressure drops of 34 Psi, 37 Psi, 36 Psi and 27 Psi respectively, while the un-inhibited (control) sample had a total pressure drop of 59 Psi. This shows different degree of hydrate inhibition by the various concentrations of the EDA which is also an established corrosion inhibitor, thus, serving a dual function of inhibiting both corrosion and hydrate formation with 0.3 Vol.% concentration having the highest inhibition.



**Fig. 3c** Pressure against Time graph for EDA Corrosion Inhibitor

At the end of the experiment, the sample collected from valve 6 shows a purple accent, light coloration and was foamy. The foam and hydrate gradually and completely disappear after 50 seconds of exposure to atmospheric condition as shown in [Figure 3a](#).

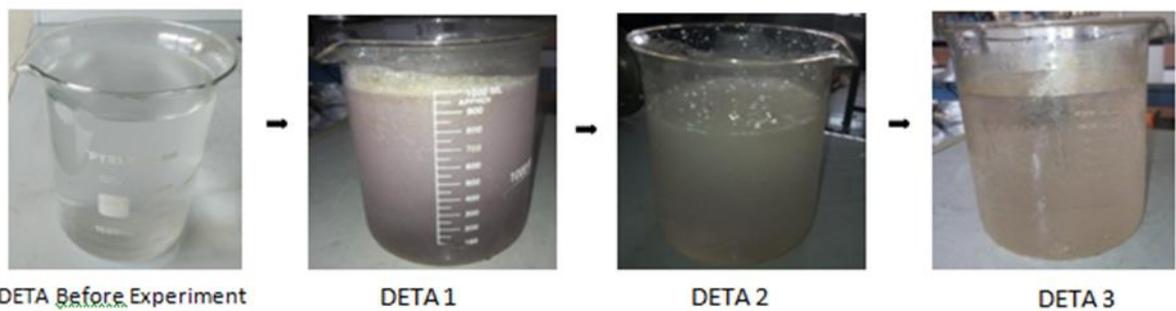
### 3.2 Analyses of the effect of Diethylenetriamine (DETA) on gas hydrate formation

#### a. Temperature vs time plots analysis for DETA

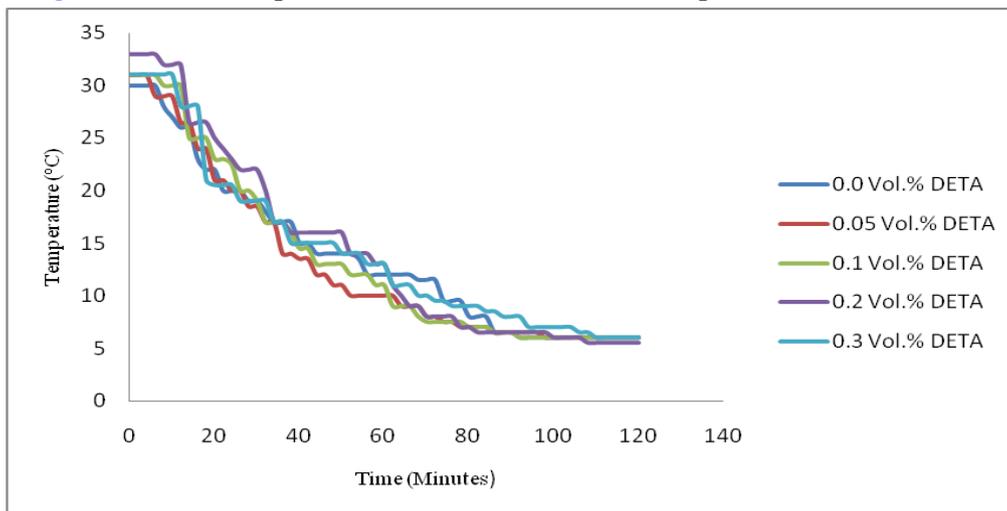
[Figure 4b](#) is a graph of temperature against time for DETA corrosion inhibitor at different concentrations. The graph shows a similar pattern for all the plots and that there is no significant difference in temperature drop for the various concentrations of the DETA corrosion inhibitors from 30 °C to 5.5 °C. This drop in temperature for the various DETA corrosion inhibitor concentrations without a commensurate drop in pressure when compared to that of the uninhibited sample which had about the same temperature drop from 30 °C to 6 °C but with a higher pressure drop indicates some degree of hydrate inhibition.

#### b. Pressure vs time plots analysis for DETA corrosion inhibitor

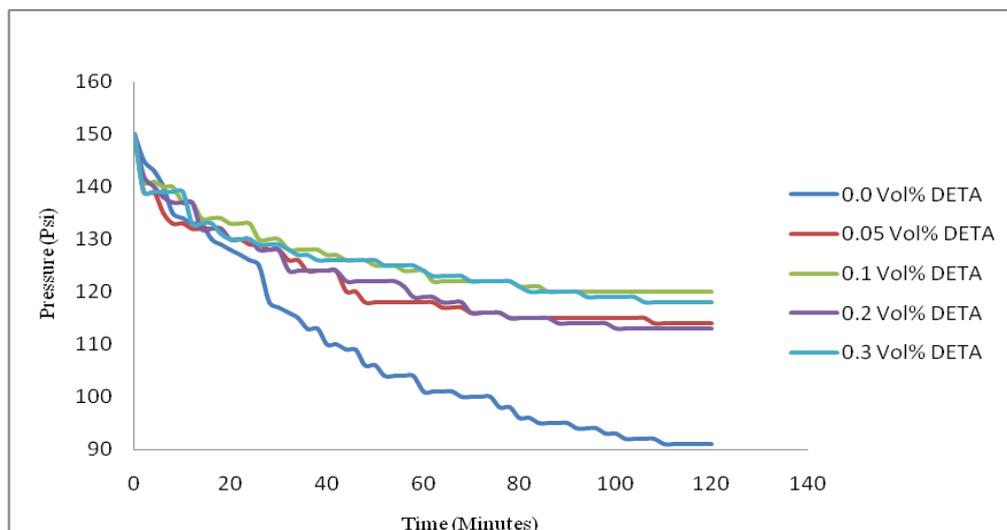
[Figure 4c](#) is a graph of pressure (Psi) against time (minutes) for the DETA corrosion inhibitors at different concentrations. The graph shows a lesser pressure drop on all samples inhibited with DETA corrosion inhibitors compared to the un-inhibited sample (control sample). This difference in pressure drop between the inhibited samples and the uninhibited sample indicates that hydrate is inhibited. At the end of the experiment, the DETA samples with 0.05 vol.%, 0.1 vol.%, 0.2 vol.% and 0.3 vol.% concentration had pressure drop of 36 Psi, 30 Psi, 37 Psi and 32 Psi respectively, while the un-inhibited sample (0.0 Vol.%) had a pressure drop of 59 Psi. This indicates that increasing the concentration of DETA did not transcend to an increase in gas hydrate inhibition, though inhibition occurred in all concentrations of the DETA used. Hence, DETA which is an established corrosion inhibitor serves a dual function of inhibiting both corrosion and hydrate formation with the sample concentration of 0.1 Vol.% performing better than the rest. At the end of the experiment, the effluent sample collected from valve 6 had an orange accent, light coloration and was foamy. The foam and hydrate gradually and completely disappear after 35 seconds of exposure to atmospheric condition as shown in [Figure 4a](#).



**Fig. 4a** DETA Sample effluent collected after the experiment for 0.1 V/V %



**Fig. 4b** Temperature against Time graph for DETA Corrosion Inhibitor



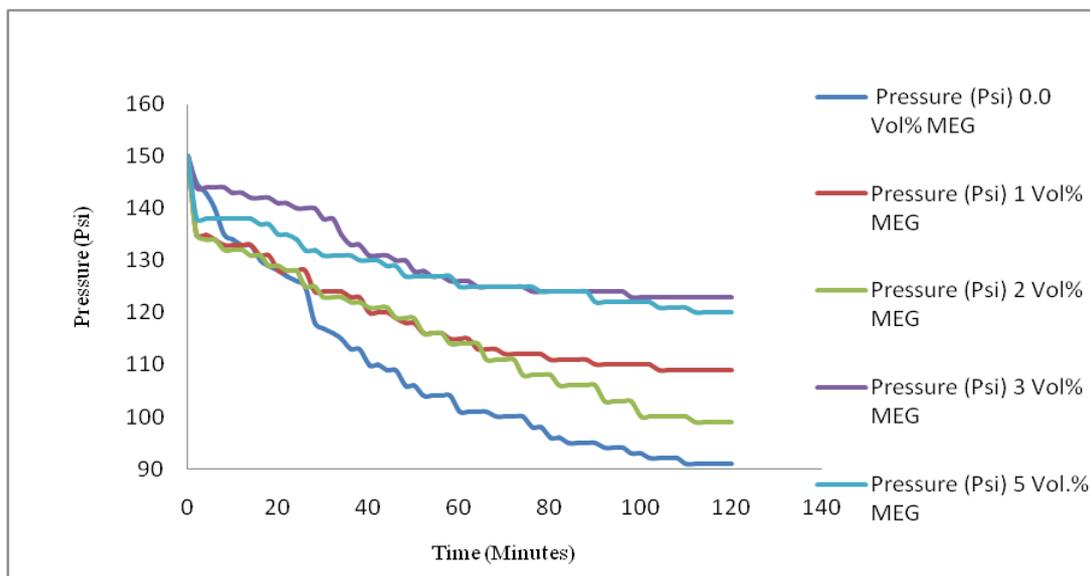
**Fig. 4c** Pressure against time graph for DETA corrosion inhibitor

### 3.4 Pressure vs time for Monoethylene glycol (MEG) hydrate inhibitor

**Figure 5** is a graph of pressure (psi) against time (minutes) for MEG hydrate inhibitor at different concentrations. The plots show a lesser pressure drop on all samples inhibited with MEG hydrate inhibitors compared to the un-inhibited sample (control sample). From the plots, it was observed that the various concentrations of the inhibitors 0.0 Vol.%, 1 Vol.% MEG, 2 Vol.% MEG, 3 Vol.% MEG and 5 Vol.% MEG, had a corresponding pressure drop of 59 Psi, 41 Psi, 27 Psi, 51 Psi, 27 Psi and 30 Psi.

### 3.5 Efficiencies of the different inhibitors concentrations used during the experiment

In [Table 3](#), the EDA concentration of 0.3 Vol.% had the highest inhibiting efficiency of 54.24% as the other lower EDA concentration of 0.05 Vol.%, 0.1 Vol.% and 0.2 Vol.% could not inhibit hydrate as much as the 0.3 Vol.%. For the DETA, the 0.1 Vol.% concentration had the highest efficiency of 49.15% inhibition, as the other concentrations both higher and lower could not perform as much as 0.1 Vol.%.



**Fig. 5** Pressure against time graph for MEG hydrate inhibitor

**Table 3.** Efficiencies of the different inhibitors concentrations used

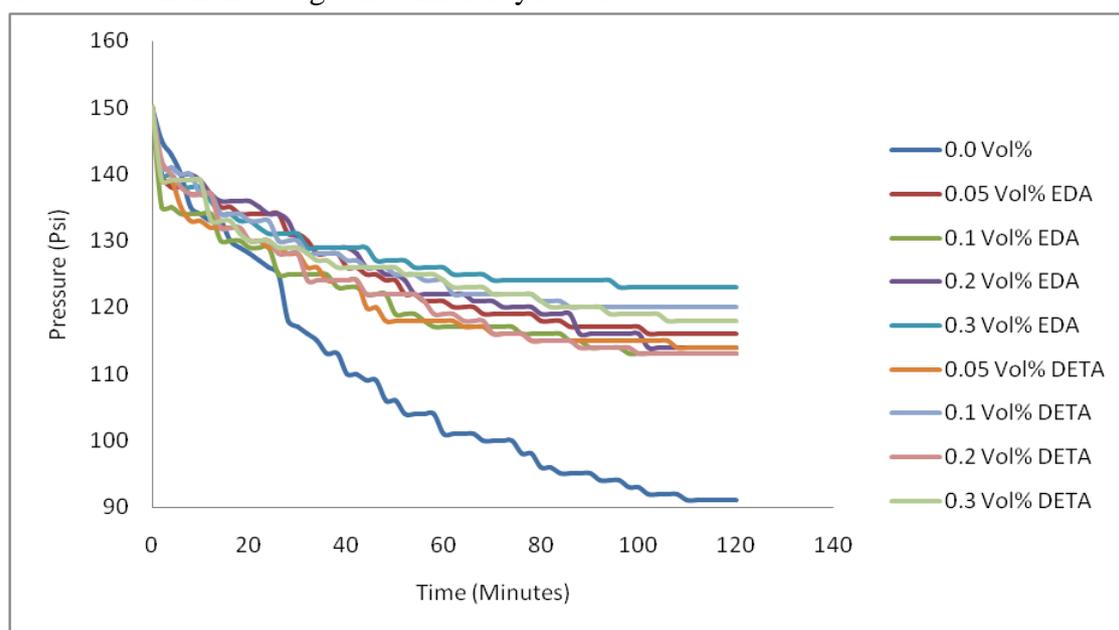
Names of Inhibitors	Vol.% of Inhibitors	$P_i$ (Psi)	$P_a$ (Psi)	$P_b$ (Psi)	$\eta = \frac{\Delta P_a}{\Delta P_b}$	$\eta * 100(\%)$
EDA	0.05	150	116	01	0.4237	42.37
EDA	0.10	150	113	91	0.3729	37.29
EDA	0.20	150	114	91	0.3898	38.98
EDA	0.30	150	123	91	0.5424	54.24
DETA	0.05	150	114	91	0.3898	38.98
DETA	0.10	150	120	91	0.4915	49.15
DETA	0.20	150	113	91	0.3729	37.29
DETA	0.30	150	118	91	0.4576	45.76
MEG	1.00	150	109	91	0.3053	30.53
MEG	2.00	150	99	91	0.1356	13.56
MEG	3.00	150	123	91	0.5424	54.24
MEG	5.00	150	120	91	0.4915	49.15

### 3.6 Pressure (Psi) and time (minutes) readings for both EDA and DETA concentrations

[Figure 6](#) is a graph of pressure (Psi) against Time (Minutes) for the most effective three concentrations of EDA and DETA corrosion inhibitors. From the plots, it was observed that the various concentrations of the inhibitors 0.0 Vol.%, 0.05 Vol.% EDA, 0.1 Vol.% EDA, 0.2 Vol.% EDA 0.3 Vol.% EDA, 0.05 Vol.% DETA, 0.1 Vol.% DETA, 0.2 Vol.% DETA and 0.3 Vol.% DETA, had corresponding pressure drop of 59 Psi, 34 Psi, 36 Psi, 37 Psi, 27 Psi, 36 Psi, 30 Psi, 37 Psi and 32 Psi.

### 3.7 Efficiency factor of inhibitors used

The efficiency factor of inhibitors used is ascertained by the ratio of their efficiency to their volume as shown in [Eqn. 3.4](#). From [Table 3](#), 0.05 Vol.% concentration for both corrosion inhibitors has the highest efficiency factors of 0.8474 and 0.7796 for EDA and DETA respectively. The 0.05 Vol.% concentrations are preferred because of their low dosage and higher efficiency factors since the DETA and the EDA are often applied as low dosage corrosion inhibitors of less than 1000ppm. Though all the applied concentrations of both corrosion inhibitors inhibited hydrate formation, the higher efficiency of the other higher concentrations (> 0.05 Vol.%) is made insignificant by their higher dosage and lower efficiency factors. From the efficiency factor in [Table 4](#) and [Figure 7](#), the 0.05 Vol.% concentration of EDA is better and most efficient of the two corrosion inhibitors when considered based on their dosage and efficiency factor.



**Fig. 6** Pressure (Psi) against time (minutes) graph for EDA and DETA.

### 3.8 A graph of inhibition efficiency and efficiency factor versus concentration (Vol.%) for DETA, EDA and MEG

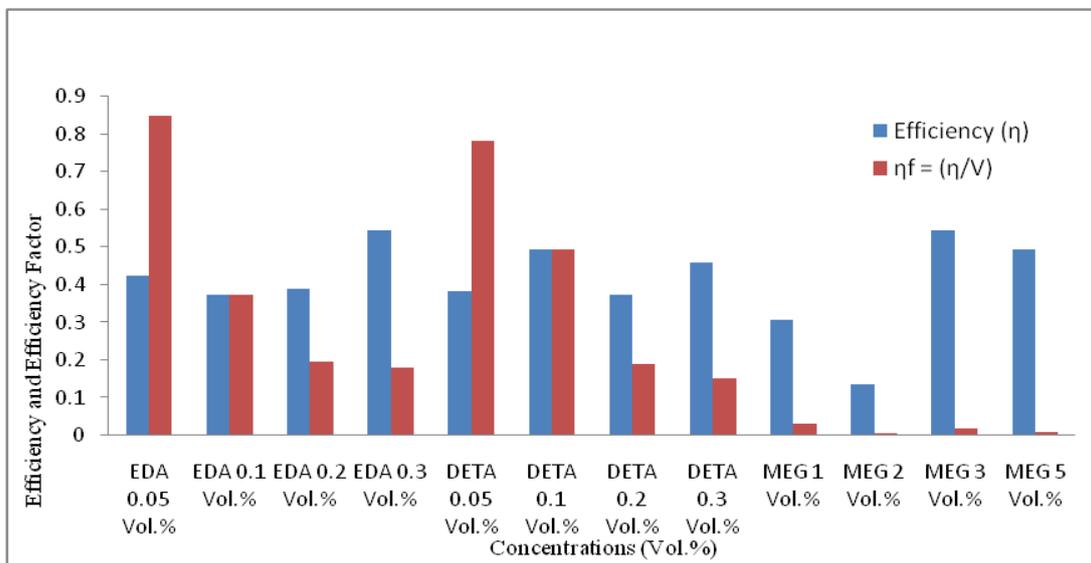
[Table 4](#) and [Figure 7](#) shows a comparison of the inhibition efficiencies and efficiency factors of EDA, DETA and MEG at different concentrations. It is observed that both corrosion inhibitors (EDA and DETA) have better efficiency factors than MEG in inhibiting hydrate in all concentrations applied, despite the higher doses of MEG.

### 3.9 Monetary cost of inhibitor used based on their efficiency ( $E_c$ )

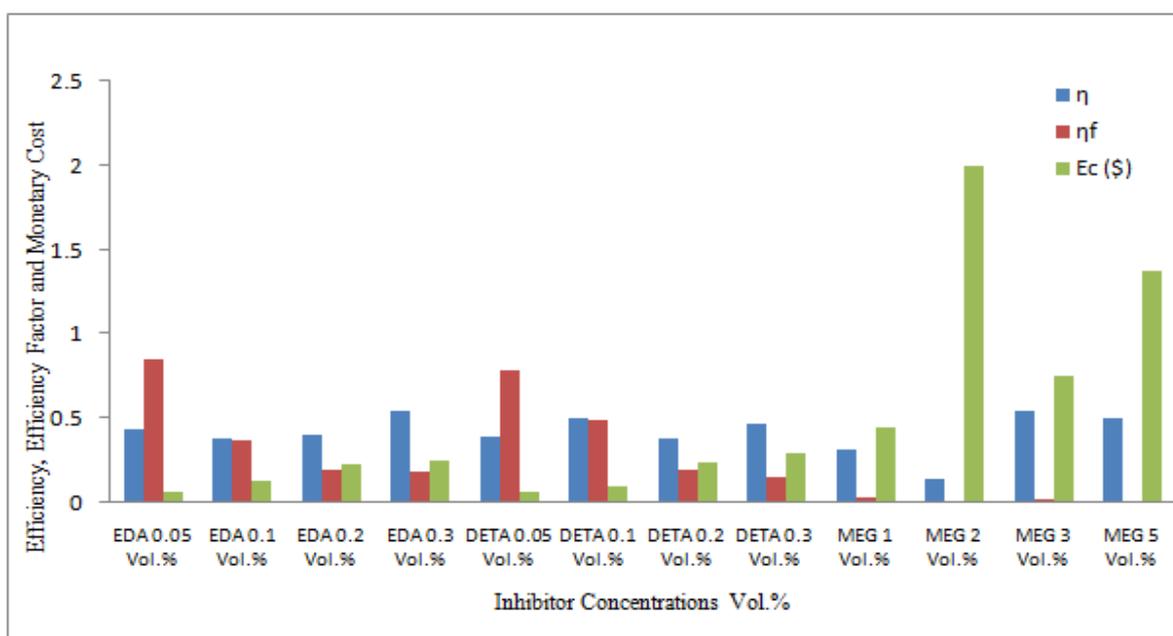
This is the monetary cost of using each inhibitor based on their used volume (dosage) and their efficiency. [Table 5](#) and [Figure 8](#) show a comparison of efficiency, efficiency factor and monetary cost of DETA, EDA and MEG. It is observed that both DETA and EDA corrosion inhibitors inhibited hydrate better than MEG in all the applied concentrations in terms of their efficiency factor and are also cheaper than MEG in terms of monetary cost which is a key factor in every business. With the aid of the inhibitor's efficiency, efficiency factor and monetary cost tables and charts, selection of inhibitors based on their required efficiency, usage boundary or maximum allowable concentration can easily be done by glancing through their charts and tables.

**Table 4.** Efficiency factors of inhibitors based on their volume

Inhibitor	Vol. of Inhibitor (cm <sup>3</sup> ) Per Liter of Water	Efficiency ( $\eta$ )	$\eta_f = \left(\frac{\eta}{V}\right)$
EDA	0.5	0.4237	0.8474
EDA	1.0	0.3729	0.3729
EDA	2.0	0.3898	0.1949
EDA	3.0	0.5424	0.1808
DETA	0.5	0.3898	0.7796
DETA	1.0	0.4915	0.4915
DETA	2.0	0.3729	0.1880
DETA	3.0	0.4576	0.1525
MEG	10.0	0.3053	0.0305
MEG	20.0	0.1356	0.0068
MEG	30.0	0.5424	0.0181
MEG	50.0	0.4915	0.0098

**Fig. 7** Inhibition efficiency and efficiency factor versus concentration (Vol.%) for DETA, EDA and MEG.**Table 5.** Monetary cost of inhibitors used based on their efficiency

Inhibitor	Vol. of Inhibitor (cm <sup>3</sup> ) Per Liter of Water	Efficiency ( $\eta$ )	$\eta_f = \left(\frac{\eta}{V}\right)$	C (\$)	$E_c = \left(\frac{C * V}{\eta * 1000}\right)$ (\$)
EDA	0.5	0.4237	0.8474	43.8	0.052
EDA	1.0	0.3729	0.3729	43.8	0.117
EDA	2.0	0.3898	0.1949	43.8	0.225
EDA	3.0	0.5424	0.1808	43.8	0.242
DETA	0.5	0.3898	0.7796	43.8	0.058
DETA	1.0	0.4915	0.4915	43.8	0.089
DETA	2.0	0.3729	0.1880	43.8	0.235
DETA	3.0	0.4576	0.1525	43.8	0.287
MEG	10.0	0.3053	0.0305	13.5	0.442
MEG	20.0	0.1356	0.0068	13.5	1.991
MEG	30.0	0.5424	0.0181	13.5	0.747
MEG	50.0	0.4915	0.0098	13.5	1.373



**Fig. 8** Graph of efficiency, efficiency factor and monetary cost against EDA, DETA and MEG inhibitor concentrations

## Conclusion

In conclusion, chemical inhibitors incompatibility and their ability to create other flow assurance problems when applied to solve some specific flow issues have made empirical analyses imperative in chemical inhibitor selection to ensure that the inhibitor with the highest efficiency at the least cost is selected. The two corrosion inhibitors (DETA and EDA) that were used for this research work, positively contributed to hydrate inhibition in all the concentrations applied even though they are established corrosion inhibitors, thus, serving as dual-functional inhibitors. From the Efficiency factor and Monetary Cost Table and Chart for the inhibitors, the 0.05 Vol.% concentration of both corrosion inhibitors is the most efficient based on their efficiency, low dosage and minimal cost. Through the cost and empirical analyses of the inhibitors, it can be inferred that the application of DETA and EDA corrosion inhibitors for mitigating flow assurance problems associated with corrosion and hydrate formation in the field will help reduce the problem of space for the installation of hydrate inhibitor vessels and chemical incompatibility, especially in offshore production facilities. This will lead to reduced CAPEX, OPEX and increased revenue for investors.

**Acknowledgement:** The authors thank the staff and management of the Department of Petroleum and Gas Engineering, the University of Port Harcourt for granting permission for the use of their laboratory facilities and also providing technical assistance in support of this research work.

**Disclosure statement:** *Conflict of Interest:* The authors declare that there are no conflicts of interest.

*Compliance with Ethical Standards:* This article does not contain any studies involving human or animal subjects.

## References

- [1] M. Finšgar, J. Jackson, Application of corrosion inhibitors for steels in acidic media for the oil and gas industry: A review, *Corrosion Science Journal-Elsevier*, 86 (2014) 17-41. <https://doi.org/10.1016/j.corsci.2014.04.044>

- [2] M. Oberndorfer, K. Thayer, W. Havlik, Corrosion control in the oil and gas production – 5 successful case histories, Proceedings from the *National Association of Corrosion Engineers (NACE) International Conference and Exposition*, held in Nashville, Tennessee, 2007. [NACE-07317  
https://www.academia.edu/35135764/CORROSION\\_CONTROL\\_IN\\_THE\\_OIL\\_AND\\_GAS\\_PRODUCTION\\_5\\_SUCCESSFUL\\_CASE\\_HISTORIES](https://www.academia.edu/35135764/CORROSION_CONTROL_IN_THE_OIL_AND_GAS_PRODUCTION_5_SUCCESSFUL_CASE_HISTORIES)
- [3] Y. Bai, Q. Bai, Subsea Engineering Handbook Book, 2<sup>nd</sup> edition, (2018). [https://www.academia.edu/42103257/SUBSEA\\_ENGINEERING\\_HANDBOOK\\_YONG\\_BAI\\_QIANG\\_BAI\\_Gulf\\_Professional\\_Publishing\\_is\\_an\\_imprint\\_of\\_Elsevier](https://www.academia.edu/42103257/SUBSEA_ENGINEERING_HANDBOOK_YONG_BAI_QIANG_BAI_Gulf_Professional_Publishing_is_an_imprint_of_Elsevier)
- [4] S. Papavinasam, A. Doiron, T.Panneerselvam, R.W. Revie, The effects of hydrocarbons on the internal corrosion of oil and gas pipelines, *Corrosion*, 63(7) (2007) 704-712. <http://dx.doi.org/10.5006/1.3278419>
- [5] T.E. Perez, Corrosion in the Oil and Gas Industry An Increasing Challenge for materials, *JOM*, 65(8) (2013) 1033–1042. <https://sci-hub.se/10.1007/s11837-013-0675-3>
- [6] J. Hobbs, Reliable corrosion inhibition in the oil and gas industry, (2014). <https://www.hse.gov.uk/research/rrhtm/rr1023.htm>
- [7] B.U. Oreko, B. Samuel, Assessment of Inhibitive Drugs for Corrosion Inhibition Applications in Petrochemical Plants- A Review, *Saudi Journal of Engineering Technology-ResearchGate*, 7(5) (2022) 201-210. <https://doi.org/10.36348/sjet.2022.v07i05.001>
- [8] L. Popoola, A. Grema, G. Latinwo, B. Gutti, A. Balogun, Corrosion problems during oil and gas production and its mitigation, *International Journal of Industrial Chemistry*, 4(1) (2013) 35. [doi:10.1186/2228-5547-4-35](https://doi.org/10.1186/2228-5547-4-35)
- [9] J.K. Fink, Corrosion Inhibitors, in *Petroleum Engineer's Guide to Oil Field Chemicals and Fluids*, (2<sup>nd</sup> ed.), Ch. 6, (2012) 217-252. <https://doi.org/10.1016/B978-0-12-383844-5.00006-4>
- [10] S.M. Shaban, A. Saied, S.M. Tawfik, A. Abd-Elaal, I. Aiad, Corrosion inhibition and biocidal effect of some cationic surfactants based on Schiff base, *Journal of Industrial and Engineering Chemistry*, (2013).
- [11] M.N. Lehmann, A. Lamm, H.M. Nguyen, C.W. Bowman, W.Y. Mok, M. Salasi, R. Gubner, Corrosion inhibitor and oxygen scavenger for use as MEG additives in the inhibition of wet gas pipelines, proceedings from the *Offshore Technology Conference*, held in Asia, (2014). <https://doi.org/10.4043/25070-MS>
- [12] E.O. Obanijesu, R. Gubner, A. Barifcani, V. Pareek, M.O. Tade, The influence of corrosion inhibitors on hydrate formation temperature along the subsea natural gas pipelines, *Journal of Petroleum Science and Engineering*, 120 (2014) 239–252.
- [13] K. Alef, A. Barifcani, Effect of N-methyl-diethanolamine and film forming corrosion inhibitor on gas hydrate, and empirical modeling for degradation, (2020).
- [14] K. Woie, A study of the interaction between a kinetic hydrate inhibitor and selected corrosion inhibitors, *Master Thesis, University of Stavanger, Norway*. (2011).
- [15] C.M. Menendez, J. Jardine, W.Y. Mok, S. Ramachandran, V. Jovancicevic, A. Bhattacharya, New Sour Gas Corrosion Inhibitor Compatible with Kinetic Hydrate Inhibitor, *International Petroleum Technology Conference, IPTC 17440*, held in Doha, Qatar (2014).
- [16] J. Park, H. Kim, Q. Sheng, C.D. Wood, Y. Seo, Kinetic Hydrate Inhibition Performance of Poly (vinyl caprolactam) Modified with Corrosion Inhibitor Groups, (2017).
- [17] K. AlHarooni, D. Pack, S. Iglauer, Effects of Thermally Degraded Monoethylene Glycol with Methyl Diethanolamine and Film-Forming Corrosion Inhibitor on Gas Hydrate Kinetics, (2017).

- [18] S. Cambell, L. Frostman, W. Li, V. Thieu, Corrosion and Hydrate Inhibition in High Shear, Low Temperature Conditions, Proceedings from the *National Association of Corrosion Engineers International Conference and Exposition*, held in Denver, Colorado, (2002) NACE-02290. <https://onepetro.org/NACECORR/proceedings-abstract/CORR02/All-CORR02/NACE-02290/114668>
- [19] K.S. Foo, O. Nashed, B. Lal, C.B. Bavoh, A.M. Shariff, R.D. Tewari, The Effect of Nonionic Surfactants on the Kinetics of Methane Hydrate Formation in Multiphase System, *Colloids Interfaces*, 6 (2022) 48. <https://doi.org/10.3390/colloids6030048>
- [20] Y. Seo, Hydrate Inhibitors and Their Interferences in Corrosion Inhibition, *In Corrosion Inhibitors in Oil and Gas Industry*, (1<sup>st</sup> ed.), Ch 17 (2020) 407-419. <https://doi.org/10.1002/9783527822140.ch17>
- [21] A. Qasima, M.S. Khan, B. Lal, A.M. Shariff, A perspective on dual purpose gas hydrate and corrosion inhibitors for flow assurance, *Journal of Petroleum Science and Engineering*, 183 (2019) 106418. <https://doi.org/10.1016/j.petrol.2019.106418>
- [22] E.D. Sloan, C.A. Koh, Clathrate Hydrates of Natural Gases *CRC Press/Taylor and Francis*, (2007). <https://doi.org/10.1201/9781420008494>
- [23] J.J. Carroll, Natural Gas Hydrates: A Guide for Engineers, Gulf Professional Publishing, (2014). <https://www.elsevier.com/books/natural-gas-hydrates/carroll/978-0-12-821771-9>
- [24] A. Farhadian, M.A. Varfolomeev, A. Rahimi, R.I. Mendgaziev, A.P. Semenov, A.S. Stoporev, S.S. Vinogradova, R. Karwt, M.A. Kelland, Gas Hydrate and Corrosion Inhibition Performance of the Newly Synthesized Polyurethanes: Potential Dual Function Inhibitors, *Energy Fuels*, 35 (2021) 6113–6124. <https://pubs.acs.org/doi/10.1021/acs.energyfuels.1c00101?ref=pdf>
- [25] J. Kim, H. Kim, Y.H. Sohn, D. Chang, Y. Seo, S.P. Kang, Prevention of methane hydrate reformation in transport pipeline using thermodynamic and kinetic hydrate inhibitors, (2017). <http://dx.doi.org/10.1016/j.petrol.2017.04.011>
- [26] Y. Seo, K.R. Seoul, H. Kim, MEG Recovery Apparatus and MEG Recovery Method, (2021). <https://patents.google.com/patent/US11052325B2/en>
- [27] U.S. Emmanuel, U. Osokogwu, Investigation of Local Inhibitor for Dissociating Hydrate Formation in Offshore Flow lines in Nigeria, *Journal of Energy and Natural Resources*, 11(3), (2022) 82-94. <https://doi:10.11648/j.jenr.20221103.12>

(2022) ; <http://www.jmaterenvirosci.com>