STUDY ON THE FOAMING TENDENCY OF IONIC LIQUIDS OF DIFFERENT ANION AND N-METHYLDIETHANOLAMINE (MDEA) FOR THE REMOVAL OF CARBON DIOXIDE.

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ABSTRACT

The removal of acid gases especially CO_2 is highly demand due to the fact that CO_2 can cause greenhouse effect and also corrosion along the pipeline and at equipment can lowering the heating value of natural gas. In industry most common absorption process is using the amine solution chemical absorbent. However, the use of amine as a solvent to capture CO_2 give some disadvantages which need to be stress in order to make efficient process for CO_2 capture such as foaming, corrosion of equipment and pipeline. In recent research, they found the new solvents that can perform better than amines in absorbing CO_2 which are ionic liquids (ILs). Foaming occurred due to few reasons such as the high gas and the presence of contaminants that enter the process or generated within the process. Since foaming is one of the severe problems in acid-gas removal process, therefore, in this work, two types of ionic liquids are used to study their foaming behavior at different temperature for the removal of CO_2. In this study, the ILs that is used were 1-n-butyl-3-methylimidazolium tetrafluoroborate ([bmim][BF_4]) and l-n-butyl-3-methylimidazolium chloride ([bmim] [Cl]) and amine used is N-methyldiethanolamine (MDEA) with temperature variation from 30ºC to 60ºC. 4M of MDEA and 2M of ILs in 100 ml of water of each ILs used was prepared. Carbon dioxide gas is then forced into the solution for 5 minutes prior to start the experiment. A constant nitrogen flow is allowed through the diffuser stone into the solution as the bubbling gas. The height of the foam and the time for foam to break until its original height is recorded as the experimental result. Based on the result, it shows that increasing the temperature has lowering the foam formation. Therefore, less foaming is recorded at temperature 60^oC compared to 30^0C. This is because the surface tension of the solution is decreasing at the same concentration used for MDEA while for [bmim][BF_4], it is due to the effect of poor foam stability and reduction of the bulk viscosity of the solution. It has also been found that, [bmim][BF_4] solution shows less foaming compared with [bmim][Cl] solution. As a conclusion, it can be said that [bmim][BF_4] solution is a very effective ionic liquids since its ability to capture CO_2 has been proved by researcher and that it also form less foaming compared to MDEA and [bmim][Cl] solution.

ABSTRAK

Penyingkiran asid gas terutamanya CO_2 amat tinggi permintaan kerana CO_2 boleh menyebabkan kesan rumah hijau dan juga hakisan di sepanjang saluran paip dan pada peralatan. Selain itu, CO_2 juga boleh menurunkan nilai pembakaran gas asli. Dalam industri proses penyingkiran CO_2 kaedah yang paling biasa digunakan adalah dengan menggunakan larutan amine. Walau bagaimanapun, dengan menggunakan amine sebagai pelarut untuk menyingkir CO_2, ternyata terdapat beberapa kelemahan yang perlu diberi penekanan. Dalam kajian baru-baru ini , mereka mendapati bahawa pelarut baru yang boleh menyingkirkan CO_2 dengan lebih baik berbanding amine adalah dengan menggunakan cecair ionik . Berbuih berlaku kerana beberapa sebab seperti gas yang tinggi dan kehadiran bahan cemar yang memasuki proses atau dihasilkan dalam proses tersebut. Berbuih adalah salah satu dalam proses penyingkiran asid gas. Oleh itu, dalam kajian saya pada kali ini, saya menggunakan cecair ionik sebagai satu langkah penyelesaian utk proses berbuih. Untuk meyiasat kesan berbuih terhadap cecair ionik saya mengkaji berdasarkan perubahan suhu. Dalam kajian ini, bahan kimia yang akan mengunakan 1-n-butyl-3-methylimidazolium tetrafluoroborate ([bmim][BF_4]) and l-n-butyl-3-methylimidazolium chloride ([bmim] [Cl]) dan laruta amine yang digunakan ialah N-methyldiethanolamine (MDEA) pada variasi suhu 30ºC hingga 60ºC. 4M dari MDEA dan 2M dari ILs digunakan dalam 100 ml air. Gas karbon dioksida kemudiannya dimasukkan ke dalam larutan selama 5 minit sebelum memulakan eksperimen. Gas nitogen disalurkan melalui batu penyebar ke dalam larutan sebagai gas yang membuatkan larutan itu berbuih. Ketinggian buih dan masa untuk buih hilang direkodkan sebagai hasil eksperimen. Berdasarkan keputusan eksperimen, apabila suhu meningkat, semakin rendah pembentukan buih. Suhu 60ºC adalah suhu dimana kurang buih terhasil berbanding suhu 30ºC. Hal ini kerana, ketegangan permukaan larutan semakin berkurang pada kepekatan yang sama digunakan untuk MDEA. Manakala bagi [bmim][BF_4], ia disebabkan oleh ketidakstabilan buih dan juga pengurangan kelikatan larutan. Selain itu, [bmim][BF_4] menunjukkan kurang buih yang terhasil berbanding [bmim] [Cl]. Kesimpulannya, [bmim][BF_4] ialah larutan ionik terbaik dalam konteks pengurangan buih yang terhasil dan keupayaan dalam menangkap CO_2 yang nyata telah dibuktikan oleh penyelidik yang lain.

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LIST OF ABBREVIATIONS

T	Temperature
Ea	activation energy
R	gas constant
A	frequency factor

Greek

∑	foaming coefficient

LIST OF ABBREVIATIONS

AMP	2-amino-2-methyl-1-propanol
CH_4O	Methanol
CO_2	Carbon dioxide
DEA	Diethanolamine
FeS	Iron sulphide
H_2S	Hydrogen sulphide
HCN	Hydrogen cyanide
H_2O	Water
ILs	Ionic liquids
MEA	Monoethanolamine
MDEA	N-methyldiethanolamine
N_2	Nitrogen gas
[bmim][BF_4]	1-n-butyl-3-methylimidazolium tetrafluoroborate
[bmim] [Cl]	l-n-butyl-3-methylimidazolium chloride

1 INTRODUCTION

1.1 Motivation and statement of problem

Greenhouse gas mitigation technology, particularly with respect to CO_2 is assuming increasing importance in the light of climate change fears. Over the past 30 years, there has been growing concern due to increasing global temperatures. Much of the increase in global temperatures has been attributed to the increasing CO_2 concentration in the atmosphere due to human activity (B.Metz, et al., 2005). The rapid development and progress of technology have gradually altered the environment. Increases of pollutant gases such as carbon dioxide, methane, nitrous oxide, per fluorocarbons, hydro fluorocarbons, sulphur hexafluoride, sulphur dioxide, carbon monoxide, nitrogen oxides and all kind of volatile organic hydrocarbons (VOCS) causes the global warming since the beginning of industrialization by humanity. The biggest contribution to the pollution loads are industrial, transport and the energy production sectors. In order to reduce cause of greenhouse gases, industrial sector should apply the principle of sustainability and green engineering (Baltus et al., 2005).

1.2 Natural gas

Natural gas is a fossil fuel that it is actually the remains of plants and animals and microorganisms that lived millions of years ago. There are many theories to the origin of fossil fuels and the most widely accepted theory says that fossil fuels is formed when organic matter such as the remains of a plant or animal is compressed at high pressure under the earth for a very long time. This is called as thermogenic methane. Thermogenic methane is formed from organic particles covered in mud and other sediment. Over the time more mud and sediment is piled on top of the organic matter. The sediment puts a very high pressure and temperature to the organic matter which in time breaks down the carbon bonds in the organic matter. However, at low temperatures more oil is produced relative to natural gas but at higher temperatures more natural gas is produced relative to oil.

In the beginning, natural gas is only used to light streetlamps and occasionally houses. However, with the improvement of gas transmission and distribution system and advanced technology, it can be used in many sectors. Figure 1.1 shows the distribution of natural gas usage according to sector. From the Figure 1.1, it shown that industrial sector contributes more in usage of natural gas. Then, the usage of natural gas contribute with others sector such as electric regeneration, residential, commercial and others with percentage 24%, 22%, 14% and 8% respectively.

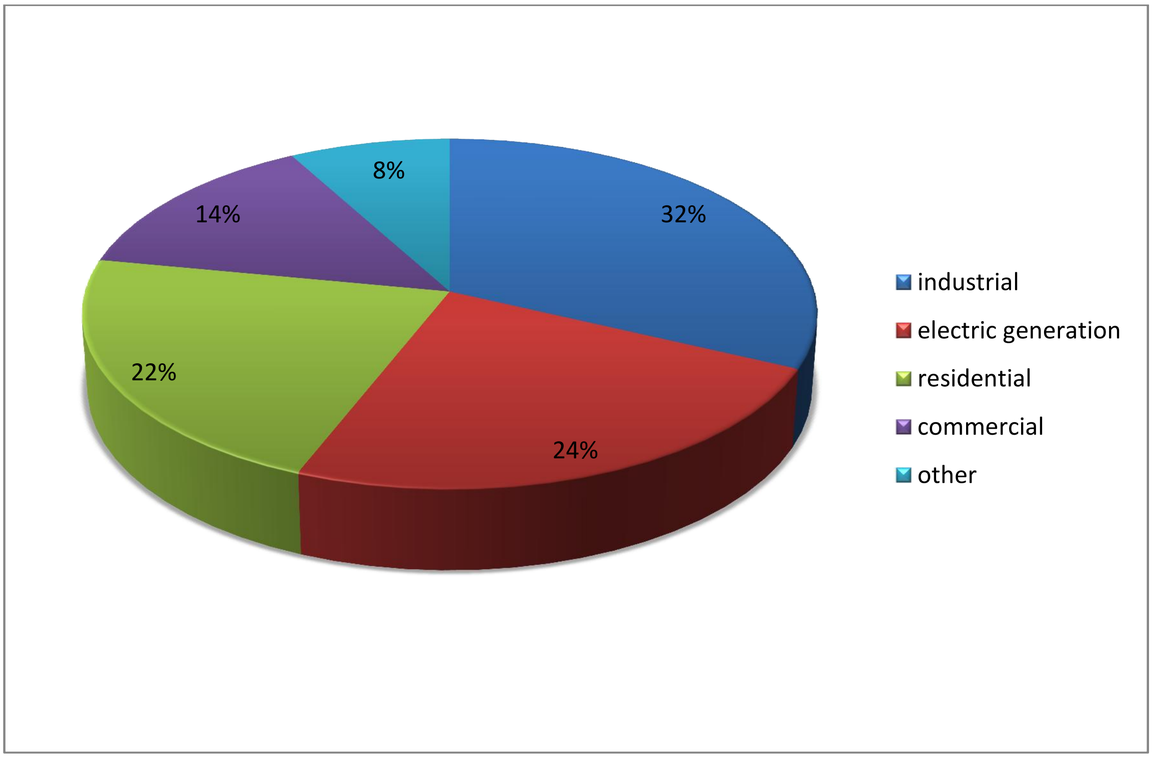


Figure 1.1: Natural gas use by sector. *(Source: EIA-Annual Energy Outlook, 2002)*

Natural gas is the sources from well that contain of the natural gas liquid and the liquefied natural gas. Natural gas is one of the important components of the world's energy supply. Natural gas is a hydrocarbon gas mixture consisting primarily methane and includes lesser percentage of carbon dioxide, nitrogen and hydrogen sulfide. The gases component in the natural gas usually contain of undesired contaminants such ammonia (NH_3) hydrogen sulfide (H_2S), hydrogen cyanide (HCN), carbon dioxide (CO_2), carbonyl sulfide (COS), carbon disulfide (CS_2), mercaptans (RSH), nitrogen (N_2), water (H_2O), sulfur dioxide (SO_2), elemental sulfur, mercury, arsenic and oxygen. Natural gas is one the safest, cleanest and most useful energy sources.

Natural gas is colorless, shapeless and odorless in its pure form. It is combustible and when burned it gives off energy and few emissions. Besides, natural gas is one of the important components of the world's energy supply. Unlike the other fossil fuels, natural gas emits lower levels of hazardous byproduct into the environment. Figure 1.2 below is a schematic block flow diagram of a typical natural gas processing plant. It shows the various unit processes used to convert raw natural gas into sales gas pipelined to the end user markets. The block flow diagram also shows how processing of the raw natural gas yields byproduct sulfur, byproduct ethane and natural gas liquids (NGL) propane, butanes and natural gasoline.

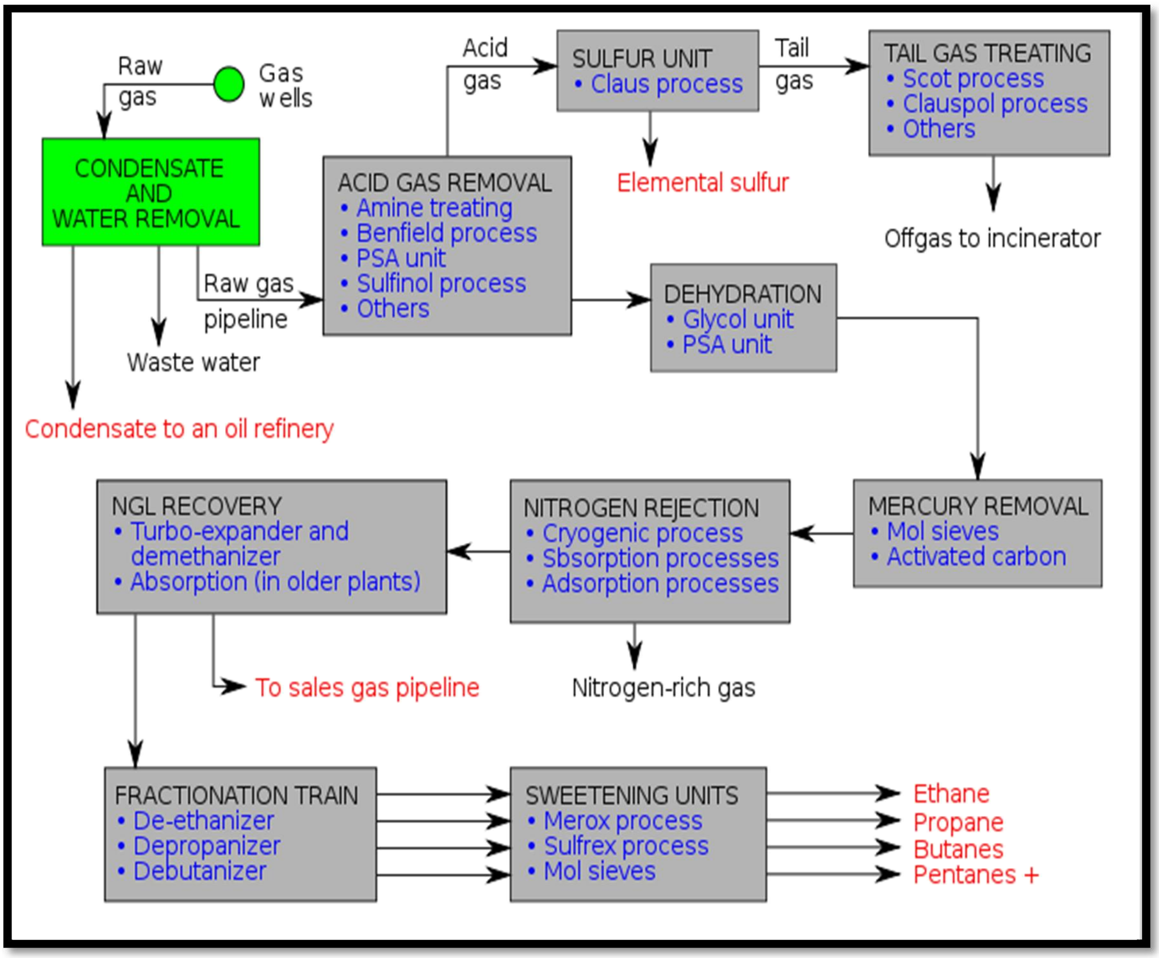


Figure 1.2: Schematic flow diagram of a typical natural gas processing plant.
(Source: EIA- Natural gas processing)

The usage of natural gas has few drawbacks especially the emission of carbon dioxide. Even though the usage of natural gas is cleaner compared to coal and oil, it still contributed to a large amount of carbon dioxide emission. The Table 1.1 shows the level of fossil fuel emission. Based on the table, we can see natural gas emits the lowest value of CO_2 which is 117000 pounds per billion btu of energy input compared to the value of the oil and coal usage which is 164000 pounds per billion btu energy input and 208000 pounds per billion btu of energy input. From this value, we also can conclude that the usage of natural gas is more acceptable compared to the usage of coal because the level of CO_2 in the natural gas is lower than coal.

Table 1.1: Fossil fuel emission level-Pounds per Billion Btu of energy input.
(Source: EIA-Natural Gas Issues and Trends 1998)

Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0.000	0.007	0.016

1.3 Carbon dioxide

Carbon dioxide is the primary greenhouse gas emitted through human activities. Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle. Human activities are altering the carbon cycle by adding more CO_2 to the atmosphere and by influencing the ability of natural sinks to remove CO_2 from the atmosphere. CO_2 produced industrially by using sources of CO_2 obtained through processes in the petrochemical industry or by burning natural gas in cogeneration processes. Air products supplies CO_2 to customers worldwide as a liquefied gas. It is delivered under pressure in steel cylinders and refrigerated in thermally insulated containers. CO_2 can also affect the environment concern. Sales gas need to be sweetened because it can cause corrosiveness because of the toxicity of CO_2 and can cause the heating value of CO_2 decrease. Figure 1.3 above shows the composition of the acid gas in natural gas. The removal of the CO_2 is important since it contribute to approximately 55% of the global warming (IPCC, 1990). Therefore, the removal of the CO_2 from the natural gas must be done before further utilization process of natural gas.

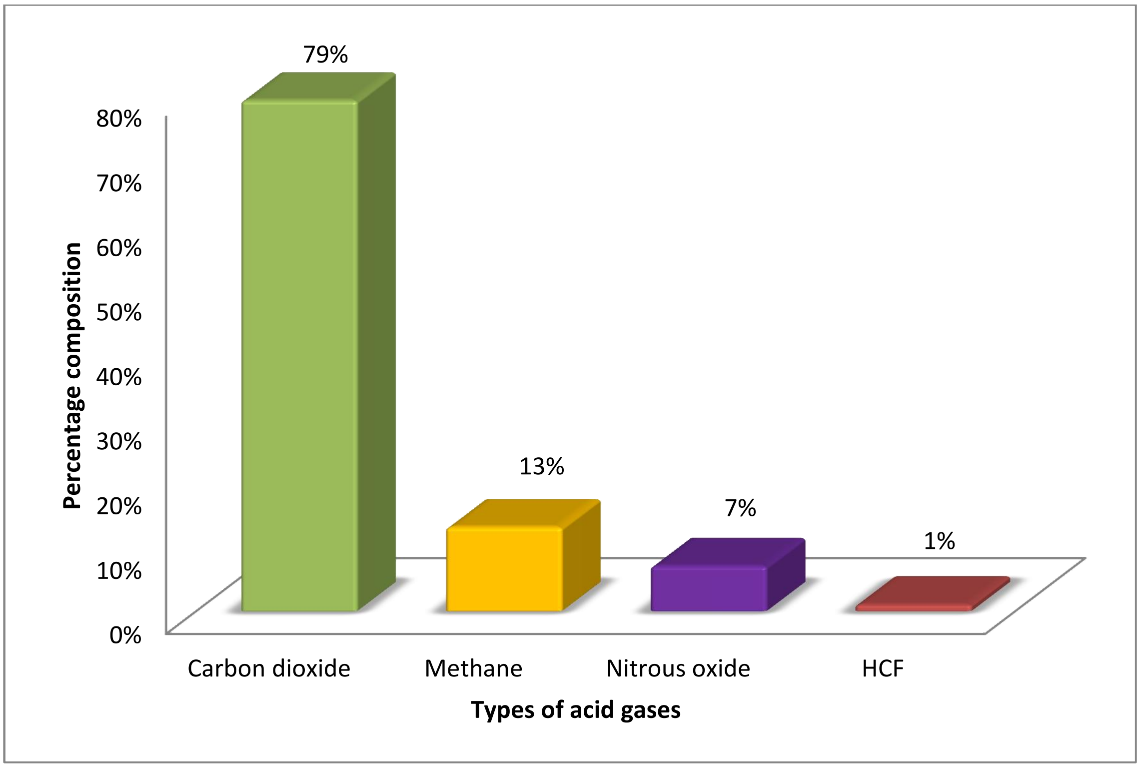


Figure 1.3: The composition of acid gas in natural gas. *(Sources:www.statcan.gc.ca)*

The influence of the CO_2 emission from the fossil fuel by the long term and short term factors including economic and population growth, new technology, changing behavior, changing of energy prices and seasonal temperature. The most effective way to reduce CO_2 emissions is to reduce fossil fuel consumption. Many strategies for reducing CO_2 emissions from energy are cross-cutting and apply to homes, businesses, industry and transportation. Table 1.2 shows examples of reduction opportunities for carbon dioxide.

Table 1.2: Examples of reduced opportunities for carbon dioxide.
(Source: www.epa.gov)

Strategy	Examples of how emissions can be reduced
Energy Efficiency	• Improving the insulation of buildings. • Traveling in more fuel-efficient vehicles. • Using more efficient electrical appliances are ways to reduce energy consumption.
Energy Conversation	• Reducing personal energy use by turning off lights and electronics when not in use reduces electricity demand. • Reducing distance traveled in vehicles reduces petroleum consumption.
Fuel Switching	• Reduce your carbon footprint.
Carbon Capture and Sequestration	• Producing more energy from renewable sources and using fuels with lower carbon contents are ways to reduce carbon emissions.

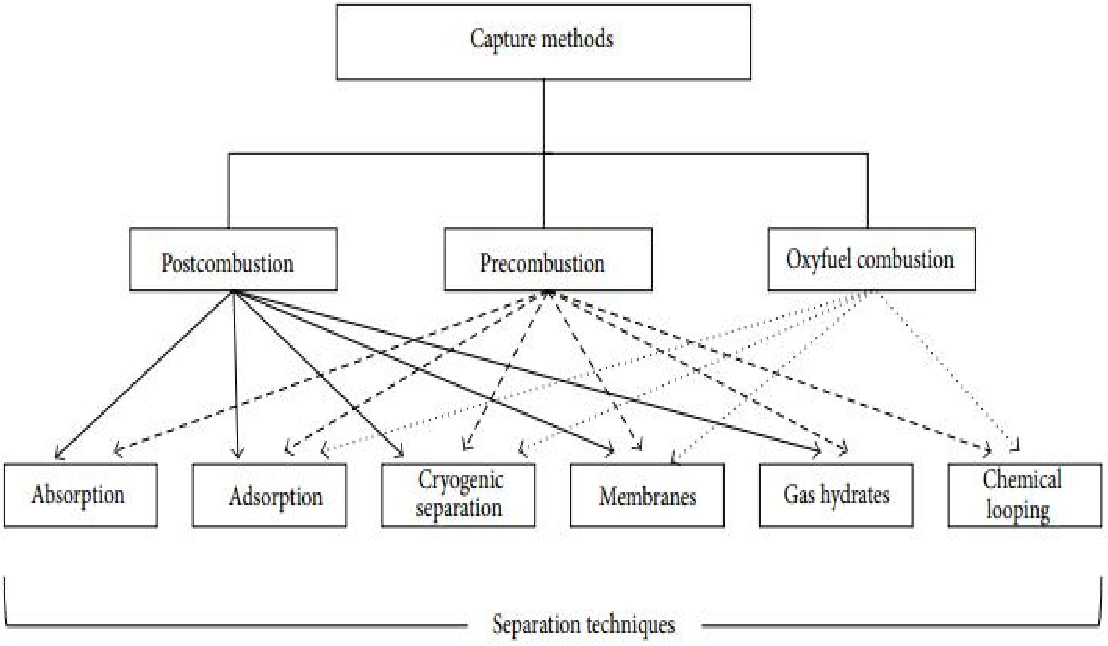


Figure 1.4: Possible technique that can be used in conjunction with the processes.
(Source: Elena et al., 2013).

The capture of CO_2 is achieved through the use of specific materials that interact with the gas in one form or another. The materials that are used depend on the processes in which the flue gas is conditioned. Figure 1.4 above show the three processes, each which conditions the CO_2 for capture in different ways.

i. Postcombustion. The separation of CO_2 from the flue gas after the combustion of fuel. Air is typically used as the oxidant in this process. Therefore, the flue gas becomes largely diluted with nitrogen. A number of methods exist for the post-combustion capture of CO_2 from flue gasses. These include chemical absorption, physical absorptions, membrane separation, adsorption and cryogenic separation.
ii. Precombustion. The hydrocarbon fuel is converted into carbon monoxide (CO) and hydrogen (H_2). This forms a synthesis gas. By using water shift conversion, CO is converted into CO_2 and finally the CO_2 is then separated from the H_2.
iii. Oxyfuel CO_2 Combustion. It uses pure oxygen as the oxidant instead of air, creating a flue gas mainly consisting of high-concentrated CO_2 and steam.

A summary of advantages and disadvantages of each of the above mentioned three CO_2 capture pathways are presented in Table 1.3. Post-combustion capture applies primarily to coal fueled power generators that are air fired. Pre-combustion capture applies to gasification plants. Oxy- fuel combustion can be applied to new plants or retrofitted to existing plants.

Table 1.3: Advantages and Disadvantages of Different CO_2 capture pathways.

Types	Advantages	Disadvantages
Post-combustion	• Applicable to the majority of existing coal fired power plants • Retrofit technology option	Flue gas is: • Dilute in CO_2 • At ambient pressure Resulting in: • Low CO_2 partial pressure • Significantly higher performance or circulation volume required for high capture levels • CO_2 produced at low pressure compared to sequestration requirements
Pre-combustion	Synthesis gas is: • Concentrated in CO_2 • High pressure Resulting in: • High CO_2 partial pressure that increase driving force for separation, more technologies available for separation • Potential for reduction in compression costs/loads	• Applicable mainly to new plants, as few gasification plants are currently in operation • Barriers to commercial application of gasification are common to pre-combustion - Availability - Cost of equipment - Extensive supporting systems requirements
Oxy-fuel combustion	• Very high CO_2 concentration in flue gas • Retrofit and repowering technology option	• Large cryogenic O_2 production requirement may be cost prohibitive • Cooled CO_2 recycle required to maintain temperatures within limits of combustor materials

Within these techniques to capture CO_2, currently the postcombustion process is the most widely researched area for reducing CO_2 emissions from power stations. This is because it can be retrofitted to existing combustion systems without doing modification, unlike the other two processes. The flue gas emitted from the postcombustion of fossil fuels in power stations, has a total pressure of 1-2 bars with CO_2 concentration of approximately 15%. This process also creates low CO_2 concentration and partial pressure, strong solvents have to be used to capture the CO_2, resulting in a large energy input to regenerate the solvent for further use (Elena et al., 2013).

Chemical absorption systems at present are the preferred option for post-combustion capture of CO_2. Chemical absorption systems have been in use since the 1930s for the capture of CO_2 from ammonia plants for use in food applications. Absorption occurs within the bulk of the material via a chemical or physical interaction. Chemical absorbents react with the CO_2, forming covalent bonds between the molecules. The solvent can be regenerated through heating and captured CO_2 is released. Typical compounds used in this process are amines or ammonia-based solutions. Regeneration of the solvent is by increasing the temperatures and lowering the pressure of the system (X.Gui et al.,2010). Selexol and Rectisol are examples of physical absorbents that have been used in natural gas sweetening and synthesis gas treatment.

Cryogenic separation is a technique based on cooling and condensation. This has the advantage of enabling the direct production of liquid CO_2, benefiting transportation options. However, a major disadvantage of cryogenic technology is high amounts of energy required to provide cooling for the process especially prominent in low concentration gas streams (Burt et al., 2010). This technique is more suitable to high concentration and high pressure gases, such as in oxyfuel combustion and precombustion (Elena et al., 2013).

Adsorption takes place at the surface of the material. This interaction can also occur chemically (covalent bonding) or physically (Van der Waals). Typical adsorbers are solid materials with large surface area. These can be used to capture CO_2 by separation, so that flue gas is put in contact with a bed of these adsorbers to allow the CO_2 capture from the other gases which pass through. When the bed fully saturated with CO_2, so the flue gas is directed to a clean bed and the saturated bed is regenerated (Chafee et al., 2007). Three technique can be employed to the adsorption mechanism which are pressure swing adsorption (PSA) introduces the flue gas at high pressure until the concentration of CO_2 reaches equilibrium, then the pressure is lowered to regenerate the adsorbent, temperature swing adsorbent (TSA) increases the temperature to regenerate the adsorbent and electric swing adsorption (ESA) is where a low-voltage electric current is passed through the sorbent to regenerate. However, it may be successful in combination with another capture technology (Elena et al., 2013).

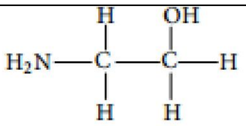
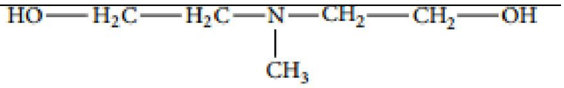
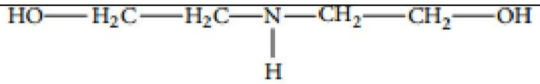
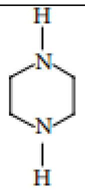
Carbon dioxide in the natural gas is known as acidic gas. Removal of acid gases are required due to some reason such as safety, corrosion control, operational problem, prevent of poisoning of catalyst in downstream facilities and increase the heating value of the gas. Removal of acid gas from gas mixtures is very important part in natural gas processing, hydrogen purification, refinery off gases treatment and synthesis gas for ammonia and methanol baking (Bhide et al., 1988). In the industry, the most common process used to remove CO_2 is the chemical absorption using amine solution (Rao and Rubin,2002). Corrosion is a problem experienced by many alkanolamine gas sweetening plants. When the process is loaded with CO_2 aqueous amine solution can become corrosive to carbon steel. The corrosion rate also increase by the high amine concentration, high acid gas loading, high temperatures, degradation product and foaming.

1.4 Common solvent in CO_2 removal

1.4.1 Alkanolamine

Amine solutions are basic and non-corrosive and some of the amine solution in fact can be used as corrosion inhibitors. Amine solution was frequently used because its high reactivity with CO_2, low solvent cost and it also can be easily generated (Mandat et al., 2003). Monoethanolamine is more reactive compare to other amine aqueous solution but its more corrosive. The effectiveness of amine in capturing CO_2 cannot be denied and its relatively high. The conventional technologies used in this postcombustion process are solvent-based chemical absorbers. The common chemical solvents used for separation are aqueous amines, which are ammonia derivatives, where one or more of the hydrogen atoms have been replaced by alkyl groups. Some common amines used in this process are monoethanolamine (MEA), methyldiethanolamine (MDEA) and diethanolamine (DEA). Table 1.4 shows the chemical structures of commonly used amines. Nowadays, the aqueous amine absorption technology is still used in natural gas sweetening for removal acid gases such as hydrogen sulpide and carbon dioxide and has also been applied to some small-scale fossil fuel power plants (Elena et al., 2013).

Table 1.4: Chemical structures of commonly used amines. *(Source: Elena et al., 2013)*

Amine	Acronym	Structure
Monoethanolamine	MEA	 $H_2N-\overset{H}{\underset{H}{C}}-\overset{OH}{\underset{H}{C}}-H$
Methyldiethanolamine	MDEA	 $HO-H_2C-H_2C-\underset{CH_3}{N}-CH_2-CH_2-OH$
Diethanolamine	DEA	 $HO-H_2C-H_2C-\underset{H}{N}-CH_2-CH_2-OH$
Piperazine	PIPA	

Amines so effective for CO_2 capture because of their properties such as high reactivity with CO_2, high absorbing capacity (in terms of mass of CO_2), relatively high thermal stability and CO_2 selectivity. However, use amine as a solvent to capture CO_2 give some disadvantages which need to be stress in order to make efficient process for CO_2 capture. These disadvantages include forming of high vapour pressure, corrosive nature, and high-energy input for generation (Elena Torralba-Calleje et al., 2013) as well as foaming. Amines are also corrosive especially MEA. They take part in reactions in which waste forms and can eventually corrode the equipment.

The general operating problem in the amine system that been used in industries:

- Amine loss from the system
- Corrosion problem
- Concentration of residual gas in amine solution
- Amine foaming problem

In industry the major problem during the gas sweetening process is foaming. Foaming is a common problem that results in decrease of treating capacity of the plant and amine losses. It is usually detected by a sharp rise in the pressure drop across amine absorber. Amine foaming can occur from the reaction of the amine solution with organic acids or because of the presence of hydrocarbon contaminants, ferric sulphide or impurities. Foaming is caused by hydrocarbon contamination that can eliminate by maintain the temperature of the absorber above the hydrocarbon condensation temperature.

1.4.2 Ionic Liquids (ILs)

Ionic liquids are organic salts composed of cations and anions that form stable liquid below 100^{o}C or even at room temperature. Besides, the cations may be organic or inorganic, while the anions are inorganic. Ionic liquids have recently emerged as 'green' and environment friendly solvents for their use in the industrial manufacture of chemicals. In the past decade, ionic liquids have been increasingly used for diverse applications such as organic synthesis, catalysis, electrochemical devices and solvent extraction of a variety of compounds. There are several reasons that ionic liquids are considered as 'green solvents'. The interest in ionic liquids was initiated because of their advantageous physicochemical properties such as negligible vapour pressure, high solvating power high thermal and electrochemical stability. The cation and anion constituting an ionic liquid has a profound effect on the physical properties such as viscosity, density, conductivity and polarity. The properties of a modern ionic liquid are summarized in Table 1.5. Particularly significant are the low pressures in most instances which contrast the environmental problems of volatile organic solvents and moderate specific conductivities in the same range as those of aqueous electrolytes (Keith E. J, 2007). For the removal of acid gases, room temperature ionic liquids have negligible volatility and have thermal stability that avoid loss of absorbents compared with alkanolamines (Feng et al.,2010).

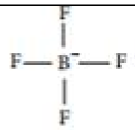
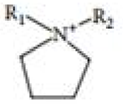
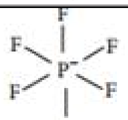
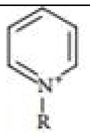
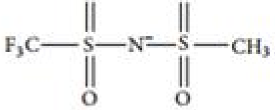
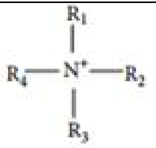
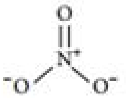
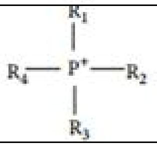
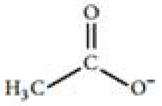
Table 1.5: Physical properties of modern ionic liquids. *(Source: Keith E.J, 2007)*

A salt	**Cation and or anion quite large**
Freezing point	Preferably below 100^{o}C
Liquidus range	Often > 200^{o}C
Thermal stability	Usually high
Viscosity	Normally < 100 cp, workable
Dielectric constant	Implied < 30
Polarity	Moderate
Specific conductivity	Usually < 10 mScm^{-1}, "Good"
Molar conductivity	< 10 Scm^{2} mol^{-1}
Electrochemical window	> 2V, even 4.5 V, except for Bronsted acidic systems
Solvent and/or catalyst	Excellent for many organic reactions
Vapor pressure	Usually negligible

The emission of carbon dioxide from utilization of fossil fuels has received worldwide attention due largely to the rapid growth in worldwide. Therefore, there is a growing interest in developing technologies for efficient capture and sequestration of large quantities of CO_2. The traditional technology for CO_2 capture in industry is chemical adsorption by an aqueous solution of amine that has some advantages such as its maturity, stable operation, good reactivity and high capacity (Oyeneken and Rochelle, 2006). Therefore, developing the economical and energy efficient CO_2 capture technologies is urgently needed.

The use of ionic liquids for CO_2 capture and the removal of acid gases from natural gas and other industrial processes has been one of the foremost research applications. Simple ionic liquids have the ability to independently vary their cation and anions. The formation of mixtures of ionic liquids increases this synthetic flexibility. Ionic liquids have the potential to increase the chemical reactivity and lead to more efficient process but non-flammable and are less toxic than conventional solvents due to their low vapour pressure. Table 1.6 shows structures of common ionic liquids with different cation and anions.

Table 1.6: Structures of common ILs cations and anions. *(Source: Elena et al., 2013)*

Cation	Structure	Anion	Structure
Imidazolium		Tetrafluoroborate	
Pyrrolidinum		Hexafluoroborate	
Pyridinum		Bis(trifluorophosphate) imide	
Quaternary Ammonium		Nitrate	
Tetra Alkyl Phosphonium		Acetate	

1.5 Foaming

Faoms are comprised of thousands of tiny bubbles of mechanical or chemical origin and are generated within a liquid. If bubbles are being formed faster than the existing ones are breaking, they will accumulate as foam. Foam is the dispersion of a gas in a liquid and is characteristics of each system, depending on the chemical structure of the components that compose the system under study (Jacinto and Blanca, 2007). Foam is a colloidal system with agglomeration of closed gas bubbles being dispersed in a liquid. Each bubble is separated by a thin liquid film that called lamella. To form foam, gas is purged into liquid through a diffuser or an orifice. Figure 1.5 shows those three important elements to foam formation which are buoyancy, surface and hydrostatic forces. Once foams are formed in the system, they can undergo the thinning process caused by drainage, foam coalescence and foam rupture (Thitakamol and Vaewab, 2008).

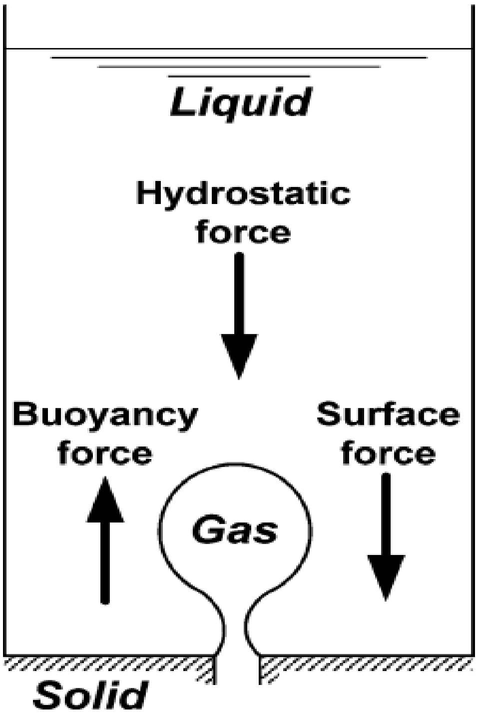


Figure 1.5: Three principal forces influencing bubble formation.
(Source: Thitakamol and Veawab, 2008).