

Revised to amine-based solvent systems : an integrated review with a focus on Cesar-1

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Abstract

Carbon dioxide (CO₂) emissions are widely recognized as meaningful contributors to climate change and global warming. Technologies of various kinds have been proposed to address this issue, and among them, amine-based solvents are widely utilized. However, monoethanolamine (MEA), the prototypical amine-based solvent, exhibits critical limitations due to its relatively higher energy consumption compared to recent developments, as well as corrosion, degradation, and carcinogenic byproducts. CESAR-1, a mixture of AMP (2-amino-2-methyl-1-propanol) and PZ (piperazine), is consequently proposed as an alternative solution. This paper presents a comparative analysis of MEA, MDEA, and CESAR-1 while highlighting their structural properties, reaction pathways, CO₂ absorption capacity, regeneration energy requirements, and by-product formation. Previous research had compiled CO₂ reaction pathways and outcomes for each solvent under varying conditions, encompassing reaction of both absorption and regeneration, and by-product formation. MEA has been commercially used and can operate continuously for over 4,000 hours, as demonstrated in numerous studies. Continuous operation enabled these studies to yield highly reliable results. However, MEA has high energy consumption, which significantly increases operating costs. In other words, it greatly reduces efficiency. Based on a comprehensive review of the materials provided, CESAR-1 is particularly noteworthy because of its synergistic strengths of AMP and PZ, which somewhat negate the disadvantage of MEA. Nevertheless, drawbacks remain in CESAR-1; hence, we proposed an alternative by introducing Selective Catalytic Reduction (SCR). SCR may be a suitable strategy for reducing the formation of nitrosamines during the process. However, as NO and NO₂ pose greater environmental and health risks than CO₂, further studies are required to determine which by-products emitted from the entire process are not hazardous to the environment.

Keywords

CO₂ capture; amine-based solvents; CESAR-1; Selective Catalytic Reduction; CCS; solvent degradation

Introduction

While the world continues to search for solutions to the worsening issues of climate change and global temperature increases, it is not debatable that carbon dioxide (CO₂) emissions remain the largest contributor to global warming. To counter this, the international community has suggested a host of solutions and made ongoing efforts to reduce CO₂ levels. Amines are used for capturing hydrogen sulfide and CO₂ in both laboratory-scale and industrial settings. For desirable CO₂ capture, the reaction rate is a considerable subject in minimizing the release of greenhouse gases to the atmosphere, regenerating CO₂, and reusing solvents. However, highly stable products originating from rapid reactions can impede CO₂ release during the regeneration process. On the other hand, the slow rate may increase the possibility of emitting greenhouse gases into the atmosphere due to insufficient absorption of flue gas. Hence, amine-based solvents are expected to ensure moderate reversibility and efficient

CO₂ absorption. The diverse structures of amines, developed until recent study, are categorized into primary (1°), secondary (2°), and tertiary (3°) structures, focusing on the implication of electron lone pairs and disparity of reactivity due to differences in geometrical arrangement, which influence the kinetics of CO₂ reactivity and the stability of the products.

Most scientists largely govern this subtle interplay, then. They did so to provide relatively fast reaction rates, along with lower regeneration energy, to react with social demands and address global warming, utilizing carbon capture technology. The concept of Carbon Capture and Storage (CCS) began in 1972. This large-scale project revealed weaknesses in Monoethanolamine (MEA), including high energy consumption and chemical degradation, setting the stage for CESAR-1 development in the 2010s through the European FP7 project. CESAR-1 is a second-generation solvent designed to address the limitations of MEA. However, carbon capture technology began back in the 1850s, when Anselme Payen and Jean-François Persoz, two French chemists, first synthesized MEA, a compound that would later be applied commercially in the 1940s. MEA has seen commercial use since the mid-1900s. MEA is known for well-proven solvent. Studies that were on MEA yielded very reliable results for two reasons: continuous operation was enabled, and many MEA issues were identified and partially resolved over time. Nevertheless, the MEA still faces several significant challenges. These problems necessitate replacing MEA with a more efficient and environmentally friendly solvent, such as CESAR-1. Pilot tests and industrial applications indicate that CESAR-1 reacts slightly faster and absorbs CO₂ with a higher capacity than MEA. According to these tests, CESAR-1 also requires less regeneration energy and corrodes to a lesser degree. It also evolved, with people using it comparatively recently, but its applications are still limited. In fact, Norway first meaningfully deployed CESAR-1 industrially back in 2019. Enough long-term industrial operation results are still lacking thus far. Humans represent the primary source of increasing carbon dioxide emissions, with the actions in daily life, ones we don't think are important, being able to cause severe environmental consequences. That is the reason why we chose this research topic to raise awareness among people, even if only slightly, and to help impact the world through a sustainable system. Thus, we desired to learn more about CESAR-1, an amine-based solvent. This paper compares three amine-based solvents, such as Monoethanolamine (MEA), CESAR-1 (a blend of PZ and AMP), and Methyldiethanolamine (MDEA), or a three-phase system including PZ, AMP, and also NMF in this paper, in order to suggest the best method. As carbon capture technologies and research on amine-based solvents began to gain traction and become an industrial trend, diverse amine-based solvents were developed; nonetheless, they often formed unexpected and carcinogenic by-products, such as nitrosamines and nitramines, from the reaction pathways. Furthermore, we identified research gaps regarding the environmental effects of such substances. Unlike previous studies that mainly focus on absorption capacity and regeneration energy, our paper's goal is to propose Selective Catalytic Reduction (SCR) as an alternative for mitigation of carcinogenic substances, and then, to discuss reaction pathway of CESAR-1, instability of AMP-carbamate by comparing PZ-carbamate with orbital structure, our assumption of mechanism of carbon-capture by introducing pH, and Gibbs free energy. This large-scale project highlighted the weaknesses of MEA, including high energy consumption and chemical degradation, which ultimately paved the way for the development of CESAR-1 in the 2010s through the European FP7 project CESAR1—a second-generation solvent designed to address the limitations of MEA. We humans are the primary source of increasing carbon dioxide emissions, and the actions we often do in daily life, ones we don't really think are important, can actually cause severe environmental consequences. That is why we chose this research topic: to raise even a small amount of awareness in people and to help leave a good impact on the world through a sustainable system. Through that, we came to want to learn more about CESAR-1, an amine-based solvent. We introduce and compare three amine-based solvents—Monoethanolamine (MEA), CESAR 1 (a blend of PZ and AMP), and Methyldiethanolamine (MDEA), a three-phase system composed of PZ, AMP, and NMF—in order to suggest the most ideal method for carbon capture. Starting with a comprehensive review of previous studies, we mapped out all reported reaction pathways involving by-product formation and utilization. We then examined how these amine-based solvents are applied in

real industrial CO₂ capture processes, and finally proposed several promising directions for future research.

Methods

A search for precedent research was conducted using databases such as Google Scholar and PubMed. Keywords are initially focused on “carbon capture system” to gain insight into the historical and sociological context, and then narrowed down to “amine-based solvent” because there is a wealth of up-to-date research and real-world industrial applications. Beyond analyzing reaction pathways, this paper diversifies the understanding of absorption and regeneration by addressing certain keywords, such as “pH”, “activation energy”, and “Gibbs free energy”. To propose an alternative to existing amine-based systems, “Selective Catalytic Reduction” is considered a staple attachment system.

Results and Discussion

CO₂ Capture Method

Oyenekan et al. (2010) : Post-combustion capture is known as one of the most reliable and widely used CO₂ capture methods. As “post” implies, it captures CO₂ from the flue gas that comes out after the combustion of fossil fuels. This method is well-known for using amine-based solvents and is renowned among scientists for its effectiveness in capturing CO₂ at moderate temperatures between 40°C and 120°C. Among post-combustion capture methods, the most researched and most commonly applied solvents in large-scale industries are MEA, MDEA, and CESAR-1. MEA has been applied since the 1940s and is recognized as the first solvent to mark the beginning of carbon capture. CESAR guarantees the best performance among amine-based solvents. One of the advantages of post-combustion capture is that it can be retrofitted to existing power plants without major modifications. This makes the method very cost-effective and simple to install. Additionally, considering the cost, it captures a significant amount of CO₂ — over 90%. However, unlike these seemingly positive characteristics, the disadvantage of the post-combustion capture method is its very large equipment requirements. Even if it doesn’t cost much, the fact that it takes up so much space raises questions about the technique's efficiency. This method can also cause thermal degradation, as well as health and environmental issues.

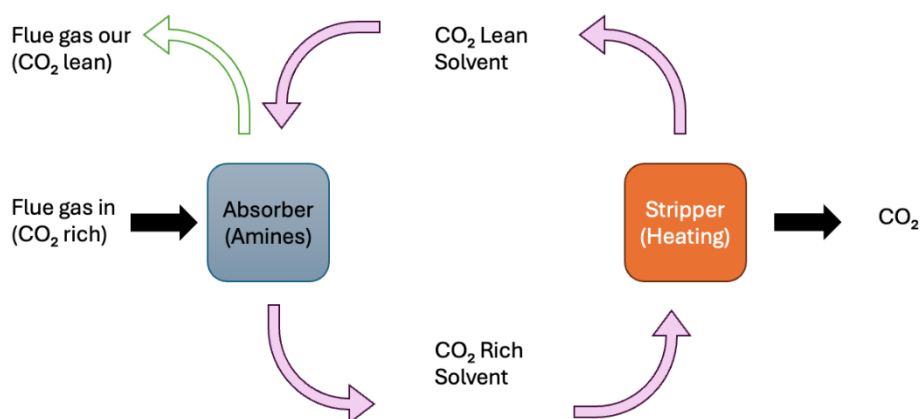


Figure 1: Typical post-combustion capture schematic utilizing amine-based solvents

This absorber will reduce CO₂ from the flue gas using amine-based solvents. Afterwards, the solvent will pass through the stripper via a heating process, and finally, pure CO₂ will be produced.

Romano et al. (2010) : Pre-combustion capture refers to a method of removing CO₂ before fossil fuels are burned, and it operates most effectively under high-pressure conditions. Although the concept of pre-combustion has existed for approximately 90 to 100 years, it was not commercialized

until the late 20th century, meaning it has been used practically for only a few decades. Thus, compared to post-combustion capture, which originated in the 1800s, pre-combustion capture has received less research attention and is less well-known. Pre-combustion capture is often used in power plants employing Integrated Gasification Combined Cycle (IGCC) technology. In this process, fossil fuels are gasified to produce a mixture of CO and H₂, helping to minimize their negative impact on the environment. Pre-combustion capture benefits from high pressure and high CO₂ concentration, making CO₂ separation relatively easier. Most importantly, because it passes through an Integrated Gasification System—which first gasifies coal or other hydrocarbon fuels before using the resulting gas as fuel—it achieves high thermodynamic efficiency. However, the reason this capturing technique is less popular and less widely used than post-combustion capture is the difficulty of installation. To apply pre-combustion capture, an entirely new plant must be designed, making retrofitting difficult. In addition, equipment such as gasifiers and shift reactors is highly complex in design and expensive to install.

Yadav and Mondal (2022) : Among the other carbon capture methods, Oxy-fuel combustion is a new approach that burns fuel not in air, but using pure oxygen and capturing the resulting carbon dioxide. Therefore, after condensation, this separates water vapor and CO₂, making the capturing process even easier. At the same time as producing this pure CO₂, it will also be easy to separate and manage. In addition, NO_x emissions, which we consider the most troublesome aspect of our project, will also be reduced since nitrogen itself is excluded from the combustion process. However, there is a separate reason why oxy-fuel is used less often than the other two combustion methods. The reason is the high cost of maintenance and the significant amount of energy required. The device used at this time is called an Air Separation Unit (ASU), and through this, pure oxygen is produced. However, producing pure oxygen is extremely expensive, and maintaining it will require a significant amount of time and energy.

Comparison of amines within Post-combustion capture

Aqueous amines, such as monoethanolamine (MEA), are still widely used for chemically capturing CO₂ in the flue gas emitted from power plants. According to *Global Market Insights, 2025*, the MEA region accounted for 38.6% of the market share in 2024. Due to its being the most studied solvent for post-combustion CO₂ capture, MEA serves as the benchmark amine. MEA's structure can be described as HO-CH₂-CH₂-NH₂.

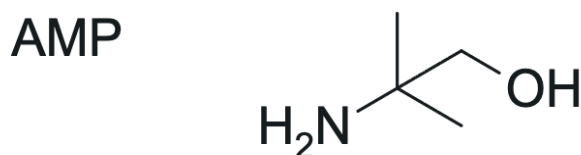
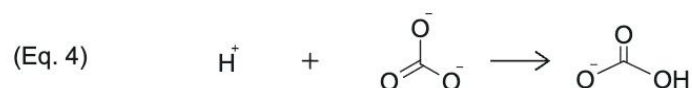
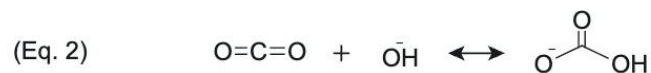
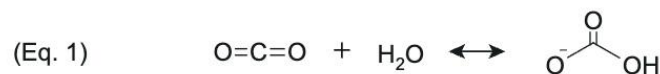


Figure 2: the structure of the AMP

Considering the environment in which MEA is used, there are two functional groups related to CO₂ capture methods. Firstly, the primary amine group(-NH₂) has an electron lone pair, which acts as a nucleophilic center. Meanwhile, the carbon of the CO₂ molecule has a partially positive charge due to the electronegativity disparity between Carbon and Oxygen. Based on the periodic table, the electronegativity of Carbon is 2.5, whereas oxygen is 3.5. It means that the carbon of CO₂ acts as an electrophile and can attack the lone electron pair of nitrogen in an amine group, forming a carbamate in an aqueous solution. Second and lastly, the Hydroxyl group(-OH) increases MEA's solubility in water by contributing to making its hydrogen-bonding with surrounding water molecules. The primary amine of MEA mostly reacts with CO₂ and forms carbamate and bicarbonate.

Li et al. (2024) proposed the following reaction formula below.



Products are mostly present in carbamate($AmCOO^-$), and some exist in the form of bicarbonate(HCO_3^-). Furthermore, in this paper, the relative field between these two products is affected by pH conditions and steric hindrances. The absorption characteristics of the MEA- CO_2 system were studied using a 2.0 M aqueous MEA solution (Table 1). The CO_2 loading capacity was approximately 0.51 mol CO_2 /mol MEA, and equilibrium was reached after 60 or 75 minutes when absorption occurred. During this process, the pH level decreased from 12.2 to approximately 9.0. Within this pattern, a certain range from 11 to 9.4 is shown to decrease rapidly, aligning with the CO_2 loading of MEA. Carbamate ($AmCOO^-$) as well as protonated MEA were found as the dominant carbon-containing species at pH values greater than 9, while bicarbonate concentrations stayed low (less than 0.1 M) even at CO_2 loadings of 0.50, 0.55 mol/mol.

Parameter	Value / Observation
Absorbent	2.0M monoethanolamine (MEA) aqueous solution
Absorption time	~75min (reaching equilibrium after ~60min)
CO_2 loading (capacity)	~0.51 mol CO_2 / mol MEA
Initial pH	12.2

Final pH at equilibrium	~9.0
pH decline pattern	Rapid CO ₂ loading as pH drops from 11 to 9.4
Main carbon species at pH > 9	Carbamate (AmCOO ⁻), protonated MEA dominate
Bicarbonate/carbonate at equilibrium	HCO ₃ ⁻ < 0.1 M at CO ₂ loading 0.50–0.55 mol/mol

Table 1. Overview of MEA(2.0 M)-CO₂ system

Consistent with the thermodynamic model of CO₂-H₂O-MEA model, it can be seen that carbamate is the dominant product over bicarbonate in the equilibrium of loading. *Li et al. (2024)* suggested that only MEA was dealt with, and there were no experimental results for other amines, which regards a research gap. If we assume that the CESAR 1 solvent also affects the yields of bicarbonate, depending on CO₂ loading and pH level, while absorbing CO₂, then we can expect that the reason bicarbonate is a staple product is closely related to the trajectory of the pH level. The more CO₂ loading increases, the less the amount of free amine, which does not participate in the absorbing reaction, and then, it will decrease the amount of flue gas emission to the atmosphere, yet also naturally increase the probability of forming carcinogenic compounds, such as nitrosamine and nitramine, by thermal degradation or oxygen degradation, throughout the whole process in the absorber and stripper. Furthermore, increasing the pH level means that there is an increase in hydrogen ions in the solvent. Considering CO₂ size itself, it is small enough to conduct electrophilic attack on electron lone pairs of amines due to its formal charge, thereby the hydrogen ion makes the amine's CO₂-capturing ability lower. MEA is the most widely used solvent for post-combustion CO₂ capture; however, it has intrinsic limitations, including high energy consumption, corrosion issues, and environmental concerns. According to Luis et al., for the energy consumption, the reported scope of energy requirement is when using 30-35 wt% MEA varies from 2,900 to 5,500 kJ/kg-CO₂. For corrosion, the use of MEA solvent at high temperatures and a specific pH level can facilitate corrosion of equipment, especially in the desorber, where temperatures can reach up to 120°C. Additionally, O₂, SO₂, and NO_x in the flue gas can cause degradation of MEA at high temperatures, leading to a higher MEA degradation rate. Regarding environmental impact, the degradation of MEA solvent during the process can form hazardous by-products, such as nitrosamines and nitramines, which possess carcinogenic properties.

Methyldiethanolamine, also known as MDEA, is used to treat CO₂ and H₂S gases from various sources, such as natural gas and flue gas streams. MDEA is a tertiary amine with the molecular formula CH₃-N-(CH₂-CH₂-OH)₂. One methyl group is attached to the central Nitrogen atom, and two hydroxyethyl groups are also attached to the same Nitrogen atom. It is quite a different situation compared to MEA, as the steric hindrance of the hydroxyethyl group and methyl group is significantly greater than that of MEA. Therefore, there is already considerable research indicating that MDEA alone has a significantly lower CO₂ absorption rate compared to MEA. Specific figures vary from one experimental condition to another, but compared to when MDEA was used alone, the rate of CO₂ absorption increased significantly when used in combination with MEA. Therefore, it is challenging to use MDEA commercially on its own.

CESAR 1 is a solvent that is about to be commercialized the most among the amine-based solvents developed to date after MEA. CESAR 1 uses water as a solvent, and AMP(2-amino-2-methyl-1-propanol) and PZ(Piperazine) are usually concentrated at 3M and 1.5M concentration, respectively.

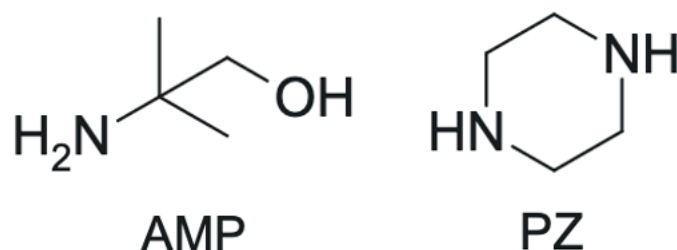
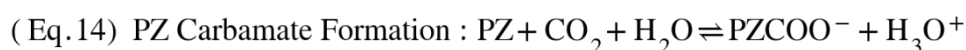
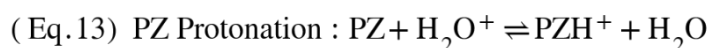
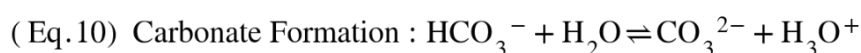
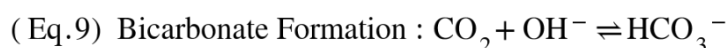
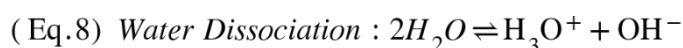


Figure 3: the structure of AMP and PZ

Like MEA, AMP has a primary amine, but two methyl groups are attached to a secondary carbon, which acts as a sterically hindered amine, contributing to the formation of bicarbonate rather than carbamate, and is a major cause of the lower regeneration energy of CESAR 1 solvent than MEA. PZ is a secondary amine, composed of a six-membered ring that has cyclohexane with the 1- and 4-CH₂ groups replaced by NH. Also, there are two nucleophilic centers in a molecule; the absorption of CO₂ rate is faster than that of AMP, and PZ stores CO₂ as a form of carbamate. This characteristic contributes to a faster absorption rate compared to MEA.

Morgan et al (2022) : The process of generating bicarbonate is interpreted as $\text{AMP} + \text{CO}_2 \rightarrow \text{AMPCOO}^-$ (AMP-carbamate) + $\text{CO}_2 + \text{OH}^- \rightarrow \text{HCO}_3^-$. Equations 1 to 3 represent the AMP and water/carbonate basic equilibrium, which always holds in the AMP and PZ system. Equations 4 to 6 represent the main reaction pathway of AMP, which indicates that the carbamate is unstable and is therefore hydrolyzed to HCO₃. Equations 6 to 9 are the reaction pathway of PZ.



In addition, when the amine-based solvent absorbs CO₂, the amount of product is affected, but the effect of steric hindrance also affects the amount of product. Despite the lower activation energy of AMP-carbamate formation than the activation energy of bicarbonate formation, in reality, the form of carbamate is unstable due to the influence of steric hindrance by AMP's two bulky methyl groups, and

CO₂ is absorbed into a certain form of bicarbonate, which means that activation energy doesn't solely determine reactivity.

	Activation Energy (kJ/mol)
Bicarbonate	55.43
AMP-carbamate	34.32
PZ Carbamate	1.33
PZ Bi-Carbamate	33.61

Table 2. Activation Energy of staple products during absorption with CO₂ by using CESAR 1 solvent.

Shadab et al. (2024): We mentioned earlier that activation energy doesn't solely determine reactivity; rather, the reaction pathway is controlled by the Gibbs free energy.

$$(Eq.17) \Delta G = \Delta H - T \Delta S$$

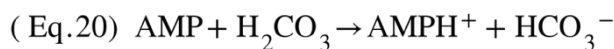
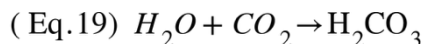
Additionally, the rate of the reaction is represented by the Arrhenius equation.

$$(Eq.18) k = Ae^{\frac{-E_a}{RT}}$$

k is represented as reaction rate constant, A has the name of a frequency factor, and is termed the energy of activation of the reaction. According to Collision theory, the Arrhenius A factor is interpreted as the product of the frequency of collision and the steric factor, and the larger the steric factor, the smaller the A factor. Therefore, in the case that AMP's two methyl groups work as a steric hindrance, A is lower than in the case that is not affected by those hindrances. Therefore, the reaction rate constant, k, maintains a lower amount of size unless there is not as much difference between the energy of activation of the reactions, especially the formation of the carbamate of AMP and bicarbonate. When an experiment is conducted at the same temperature, even if the enthalpy, which represents the activation energy, is lower for AMP-carbamate formation than for bicarbonate formation, we must consider the effect of entropy. The molecular properties are largely dependent on its structure, including the type of amine, functional groups, and carbon backbone chain length. In other words, these factors can play a certain role in directing the reaction orientation and controlling the reaction rate.

Steric and Electronic Effects

In many papers, the method used proposes that bicarbonate is formed by breaking down the structure of carbamate, which acts as an intermediate product during the absorption of CO₂. Although the explanation is based on the dominant reaction pathway, we propose an alternative explanation: bicarbonate is a more dominant product of CESAR1 than AMP-carbamate. Rather than explaining the reaction mechanism in that way, we interpreted the same result through a different pathway. Water also acts as a reservoir of CO₂, as evidenced by Earth's oceans, which contain around 38,000 gigatons of carbon. Therefore, in our alternative interpretation, the suggested reaction pathway proceeds in two ways:



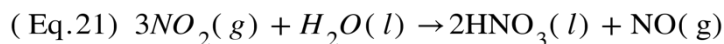
AMPH⁺ means that it is not able to capture CO₂ due to the absence of AMP's electron lone pair. And bicarbonate indirectly represents that CO₂ is included throughout the whole reaction. Both reactions proceed through two steps; however, compared to the reaction offered by Morgans et al., there are no concerns about steric hindrance. It is clear and understandable that bicarbonate is the dominant product over AMP-carbamate.

In many studies, the steric hindrance has been addressed as a contributor that restricts the formation of AMP-carbamate. However, to gain a deeper understanding of the unstable structure of AMP-carbamate, we introduce concepts related to orbitals. It is clearer to examine the stable PZ-carbamate in terms of the orbital model. Concentrating on a substituent attached to a Nitrogen atom, both carbon and nitrogen are in *sp*² hybridization, and a negatively charged ion on the substituent makes a resonance form. Furthermore, an electron lone pair of a nitrogen atom is placed on the rest of the p orbital. Therefore, by sharing the electron over the whole substituent and nitrogen atom, the C-N bonding is stronger and much stable than without the effect of delocalized electrons.

Future research is expected to conduct research about what by-products, such as AMPH⁺, affect the whole cycle of the carbon capture system.

Proposal of a revised carbon capture system

Although the CESAR-1 solvent outperforms MEA, MDEA, and other amine-based solvents in nearly every aspect, one of its most critical drawbacks is that it forms nitrosamines, which are highly toxic substances, when it reacts with NO or NO₂ - gases commonly found in flue gas. Nitrosamines are known to be both carcinogenic and genotoxic, meaning they can cause cancer and permanently damage DNA. For this reason, their release is considered a much more serious issue than the release of CO₂ itself. Another reason why the CESAR-1 solvent should not come into contact with NO or NO₂ is that these compounds can accelerate the degradation of AMP, ultimately reducing the overall efficiency of the solvent. Moreover, when NO₂ reacts with water (H₂O), the following reaction occurs:



This reaction produces nitric acid, which is highly acidic and can promote severe corrosion of equipment, significantly compromising the system's stability and durability.

To address this issue, we propose installing a Selective Catalytic Reduction (SCR) system upstream of the CO₂ absorber. SCR releases NO_x, such as NO and NO₂, substances as toxic as nitrosamines, into the atmosphere. SCR is one of the already proven flue gas treatment technologies, developed by Engelhard Industries in 1957, and is a technique that many companies actively utilize in practice. Starting with its first application in Japan in the late 1970s, and following the emergence of many credible studies and results, it spread to Europe in the mid-1980s and reached the United States by the 1990s. After its first application, the focus of SCR technology shifted from small-scale systems to controlling large amounts of NO_x. In 1989, SCR units were installed on two Korean 30,000 metric ton carriers, powered by MAN B&W 2-stroke 8 MW diesel engines, resulting in a 92% reduction in NO_x emissions. Having confirmed its applicability on a large scale, many researchers began aiming for nearly 100% NO_x reduction in their studies.

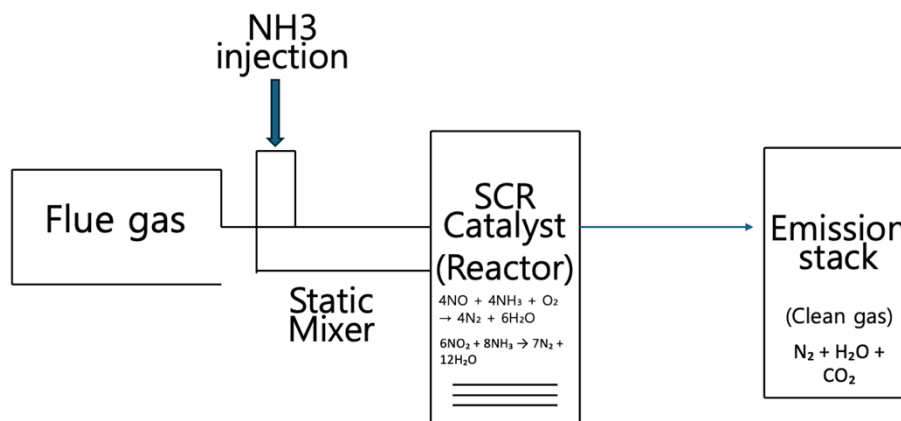
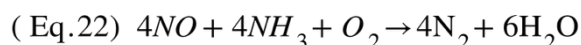


Figure 4: Process of Selective Catalytic Reduction (SCR) system

The Selective Catalytic Reduction (SCR) process works by injecting ammonia (NH₃) into the flue gas stream, which is operated upstream of the CO₂ absorber. The flue gas then passes through a catalyst bed, typically composed of V₂O₅-WO₃ or zeolite-based materials. At this point, NO and NO₂ react with the injected reducing agent NH₃, converting them into harmless nitrogen (N₂) and water (H₂O) molecules. In simple terms, NH₃ is oxidized and donates electrons, while NO and NO₂ are reduced and transformed into harmless N₂. This reaction mainly produces two equations:



Through these reactions, both NO and NO₂, compounds that we want to avoid releasing, are converted into N₂ and H₂O, thereby eliminating potential environmental and human health concerns.

It is true that SCR is one of the most optimal and well-developed techniques for addressing the drawbacks of the CESAR solvent, but it also has clear limitations. To operate SCR effectively, one of the essential sources, ammonia (NH₃), must be continuously supplied. This requires significant control and management, as well as additional costs. Moreover, SCR can produce results that contradict the main focus of our project, which is CO₂ capture through the application of CESAR. While SCR successfully converts NO_x into clean gases such as N₂ and H₂O, it can also generate small amounts of CO₂. This means that the total amount of carbon dioxide to be absorbed increases as a result of SCR. Therefore, the ideal proposal is to enhance the CO₂ absorption capacity of the CESAR solvent so that it can also capture the CO₂ generated from the SCR system.

Conclusion

CESAR solvent is currently one of the most promising and high-quality technologies in CO₂ capturing methods. To make CO₂ capturing methods successful in the future, many companies will develop technology focusing on the CESAR solvent. Nevertheless, further research is needed to address the still-existing problems that actual data and industrial operation do not adequately support, specifically whether CESAR-1 is sufficient to replace the MEA and how to overcome its limitations.

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