

Maritime CO₂ Capture and Conversion to Sodium Bicarbonate

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Foreword

This professional bachelor's thesis is one of the requirements for obtaining the Professional Bachelor's degree in Marine Engineering at the Antwerp Maritime Academy (AMA).

During my second-to-last year at the AMA in April 2024, I was informed about the possibility of a scholarship to conduct part of my thesis abroad, in the tropical climate of Cuba, during the final months of the Belgian winter. This opportunity motivated me to contact Mr. Olivier Schalm from the AMA International Department and choose one of the thesis topics he suggested and recommended.

I would like to sincerely thank my Belgian co-supervisor, Mr. Olivier Schalm, the Antwerp Maritime Academy, and the Flemish Government for offering and funding this wonderful international experience.

Furthermore, I want to extend my gratitude to Mr. Olivier Schalm and my Belgian supervisor, Prof. Yoei Horvath, for their valuable advice and guidance throughout the thesis journey in Belgium.

I also wish to express my heartfelt thanks to my parents for their unconditional support during my studies.

In Cuba, I am grateful to my Cuban co-supervisor, Prof. Daniellys Alejo Sanchez, and my supervisor, Prof. Alain Martinez, for their support and assistance with the thesis. I also thank Prof. Martinez and his family for their warm hospitality and help in getting acquainted with Cuban life.

Special thanks to Victor Ygualada for his invaluable help in building and preparing the experiments in Cuba, as well as to Juan Pedro (Head of Chemical Engineering at UCLV) and Prof. Nestor Ley Chong for their continuous advice throughout the thesis process in Cuba.

Most importantly, I am deeply grateful to Prof. Liset Roche Delgado for her guidance, theoretical and experimental support, and the significant time and dedication she invested in this project, as well as for the hospitality shown by her and her family.

Abstract

This thesis presents the design, construction, and testing of a prototype system intended to capture and convert carbon dioxide (CO_2) emissions from ships into sodium carbonate (Na_2CO_3), using a sodium hydroxide (NaOH) solution as the reactive medium. The goal is to demonstrate a feasible and simplified system inspired by principles of the Solvay process, offering a potential method to reduce maritime CO_2 emissions while generating a commercially valuable product.

The research was conducted in two phases: initial experiments and prototype testing at the Antwerp Maritime Academy (Belgium), followed by further development and refinement at the Universidad Central “Marta Abreu” de Las Villas (Cuba). The Belgian phase focused on proof-of-concept experiments in which CO_2 was bubbled through NaOH solutions, with pH measurements confirming a chemical reaction. In Cuba, a more advanced prototype was developed using real exhaust gases from a generator as the CO_2 source. Experimental variables such as reagent concentration, gas temperature, and flow rate were tested to optimize reaction conditions.

Key challenges included the slow reaction kinetics and limitations in measurement due to sensor range. A comparative test using calcium hydroxide ($\text{Ca}(\text{OH})_2$) showed similar CO_2 reduction but highlighted issues with by-product handling and lower commercial value. NaOH remains the preferred reagent for long-term use due to the higher value of both Na_2CO_3 and NaHCO_3 , and their compatibility with continuous processes.

Final experiments revealed a clear inverse relationship between NaOH concentration and CO_2 levels in the exhaust after treatment. Although full system optimization, including automation and industrial scaling, lies beyond the scope of this bachelor’s thesis, the results provide a solid foundation for future research into onboard CO_2 capture systems for ships and related industries.

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List of Abbreviations

UCLV	Universidad Central “Marta Abreu” de Las Villas, Cuba
AMA	Antwerp Maritime Academy, Belgium
CaCO₃	Calcium Carbonate
Ca(OH)₂	Calcium Hydroxide
CCS	Carbon Capture and Storage
CO	Carbon Monoxide
CO₂	Carbon Dioxide
CO₂e	Carbon Dioxide Equivalent
CSRD	Corporate Sustainability Reporting Directive
DAC	Direct Air Capture
ESP	Electrostatic Precipitator
ETS	Emissions Trading System
FWG	Fresh Water Generator
GHG	Greenhouse Gas
H₂O	Water
HCl	Hydrochloric Acid
HDPE	High-Density Polyethylene
KOH	Potassium Hydroxide
L/G	Liquid-to-Gas Ratio
Na₂CO₃	Sodium Carbonate
NaCl	Sodium Chloride
NaHCO₃	Sodium Bicarbonate
NaOH	Sodium Hydroxide
NH₃	Ammonia
NO	Nitric Oxide
NO₂	Nitrogen Dioxide
NO_x	Nitrogen Oxides
OH⁻	Hydroxide Ion
PFR	Plug Flow Reactor
pH	Potential of Hydrogen (Acidity/Basicity)

PP	Polypropylene
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO₂	Sulfur Dioxide
SO₃	Sulfur Trioxide
SO_x	Sulfur Oxides

1. Introduction

1.1. Context and Problem Definition

The Global shipping is a cornerstone of international trade, responsible for transporting approximately 90% of world goods. However, this vital sector is also a significant contributor to greenhouse gas emissions, with heavy-duty marine engines emitting vast quantities of carbon dioxide (CO₂) and other pollutants. It is estimated that the shipping industry accounts for nearly 3% of global CO₂ emissions [1], equivalent to the annual emissions of major industrialized countries. These emissions play a considerable role in exacerbating climate change, contributing to rising global temperatures, ocean acidification, and more frequent extreme weather events.

These engines are designed for maximum power and efficiency over long operational periods, consuming substantial amounts of heavy fuel oil and other fossil fuels. As a result, the shipping industry faces increasing scrutiny due to its environmental impact, particularly regarding climate change. Without significant intervention, the industry's share of global emissions is expected to increase, posing a major challenge to international climate goals.

Marine engines require dense, high-energy fuels to sustain long voyages and heavy cargo loads. While electrification and alternative fuels such as hydrogen and ammonia have gained traction in smaller and short-range vessels, scaling these solutions to large ocean-going ships is fraught with technical and economic challenges. The energy density of most e-fuels is insufficient to meet the demands of large-scale shipping without significant changes in fuel storage, engine design, and supply chain infrastructure. Additionally, many alternative fuels are still in early stages of development, with high production costs and limited availability. As a result, the industry remains heavily dependent on conventional fossil fuels, necessitating innovative solutions to mitigate CO₂ emissions.

To address these emissions, regulatory frameworks such as the European Union Emissions Trading System (ETS) have been expanded to include maritime transport. Under the ETS, ship operators are required to purchase emissions allowances to cover their CO₂ output, creating a financial incentive to reduce emissions. Furthermore, the EU's Corporate Sustainability Reporting Directive (CSRD) mandates that large companies, including those in the maritime sector, report on their

environmental performance. This directive is part of the European Green Deal, which aims to make the EU climate-neutral by 2050 by encouraging sustainability across industries.

Interestingly, while CO₂ is often treated as an unwanted by-product of combustion processes, this mindset reflects a classic example of the tragedy of the commons: individual industries benefit from emitting CO₂ freely, while the environmental costs, such as climate change and ocean acidification, are shared by all. The atmosphere's limited capacity to absorb greenhouse gases is a collective resource that is being depleted without coordinated responsibility.

To mitigate this issue, carbon capture and storage (CCS) has emerged as a viable transitional strategy, particularly in sectors like maritime transport where alternative fuels are not yet widely feasible. CCS allows ships to continue using conventional fossil fuels while capturing the CO₂ emitted in the exhaust stream. By converting the captured CO₂ into stable compounds such as sodium carbonate (Na₂CO₃), emissions can be reduced significantly without requiring fundamental changes to ship propulsion systems or fuel supply chains. This approach decouples fuel combustion from carbon emissions and enables progress toward climate-neutral operations.

Examples of CCS technologies include chemical absorption (e.g., amines), membrane separation, and mineral carbonation. Several commercial applications, such as those developed by Carbon Clean and Mitsubishi Heavy Industries, have shown success in industrial-scale [1], although primarily in land-based installations with relatively pure CO₂ streams.

In contrast to treating CO₂ solely as waste, some industries have long utilized it as a valuable raw material. A prominent example is the Solvay process, which consumes high-purity CO₂ to produce sodium carbonate [2]. on a commercial scale, an essential compound in glass, chemical, and water treatment industries, with global production of sodium carbonate (Na₂CO₃) exceeding 50 million metric tons annually [2], driven by its widespread use in glassmaking, chemical manufacturing, detergents, and water treatment applications. This illustrates how CO₂ can function as a feedstock within circular economy models.

While CO₂ derived from ship exhaust is less pure and more difficult to process than industrial CO₂ sources, due to the presence of impurities such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulates that may require gas pre-treatment, the concept of capturing and converting this CO₂ into sodium carbonate reflects a strategic rethinking: from pollutant to resource. Bridging this conceptual and technological gap is crucial for transforming maritime CO₂ emissions from an

unmanaged externality into a controllable input stream, aligning with both environmental responsibility and potential economic benefit. industries.

1.2. Goal

This thesis aims to investigate whether CO₂ from exhaust gases can be captured and converted into sodium carbonate (Na₂CO₃) using a sodium hydroxide (NaOH) solution in a small-scale prototype setup. While the chemistry behind this conversion is known, it is not clear whether a simple, fast-prototyped, lab-scale system can realistically demonstrate this process in a measurable and meaningful way. In other words, the core question becomes: Can such a prototype truly capture CO₂ and convert it into Na₂CO₃ under practical, non-ideal conditions? If so, is the process promising enough to justify further research into optimization, automation, and economic feasibility?

Through hands-on experimentation and limited instrumentation, this project attempts to produce initial, measurable indications that the capture process is occurring, primarily through changes in pH, turbidity, and the possible presence of solid by-products. The goal is not to optimize performance, but rather to demonstrate technical feasibility. Future research, discussed later in the conclusion, may explore how to increase reaction efficiency, separate the products more effectively, purify the CO₂ beforehand, or design a continuous automated reactor setup that could eventually become economically viable for industrial use.

Ultimately, this dissertation seeks to provide a first practical step toward evaluating whether sodium-based carbon capture systems have enough merit to be considered as part of future marine emissions-reduction strategies..

2. Background

This chapter provides a comprehensive overview of prior scientific and technical research relevant to CO₂ capture and conversion. It synthesizes background knowledge, existing literature, and experimental results from other researchers concerning both the broader environmental problem of rising CO₂ emissions and the specific technological approaches developed to address it. The aim is to equip the reader with a detailed understanding of what has already been accomplished in the field, including chemical reaction pathways, process engineering concepts, and performance data for various CO₂ capture strategies. This contextual foundation is essential for appreciating the direction and rationale behind current innovations in carbon capture, including those not limited to but including NaOH-based systems, calcium hydroxide methods, the Solvay process, direct air capture, and integrated simulations. By highlighting the range of previously explored techniques and their respective outcomes, this background chapter offers a knowledge base that informs the relevance and novelty of future work and the practical research of this thesis itself.

2.1. Carbon Dioxide Capture Technologies

In the scientific literature, CO₂ capture techniques are generally divided into three primary categories: pre-combustion, oxy-combustion, and post-combustion. These classifications help distinguish the stage of the energy conversion process at which the CO₂ is removed, and each has distinct technical requirements, advantages, and limitations.

- **Pre-combustion capture** refers to removing CO₂ from a fuel gas before combustion. This is typically done in gasification systems where fossil fuels or biomass are converted to syngas (a mix of CO and H₂). The CO is then reacted with water in a shift reactor to form CO₂ and more H₂, after which the CO₂ is separated.
- **Oxy-combustion capture** involves burning a fuel in pure oxygen instead of air. This results in a flue gas that is primarily CO₂ and water vapor, making it easier to separate the CO₂ after condensing the steam. However, generating pure oxygen is energy-intensive.
- **Post-combustion capture**, the most widely applicable and commonly used method, involves removing CO₂ from the flue gas after combustion has occurred. This category is particularly compatible with existing power plants and industrial facilities.

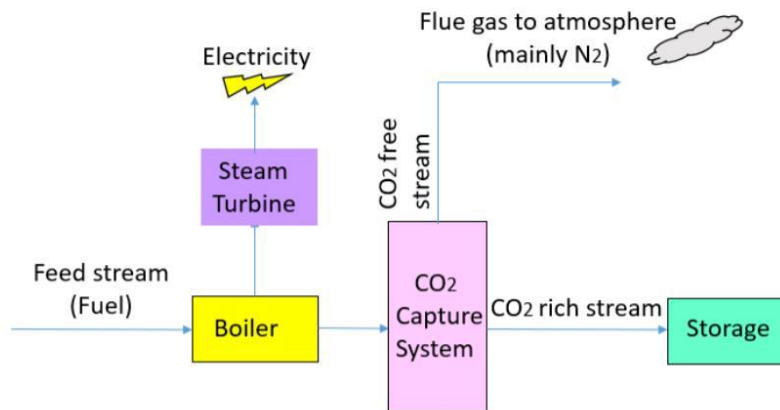


Figure 1: Block flow diagram of a post-combustion CO₂ capture system ([3] , Figure 4, Page 16)

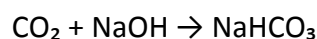
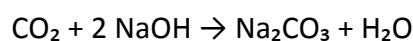
2.2. Post-combustion examples

In the context of this thesis and its simplified prototype system, the focus is entirely on post-combustion capture methods. The technologies discussed in the remainder of this chapter, including NaOH absorption, the Solvay process, soda ash carbonation and calcium hydroxide methods, fall directly under the post-combustion category. Out of the following examples, only Direct air capture(DAC) falls outside the traditional combustion classification.

2.2.1. CO₂ Capture with Sodium Hydroxide

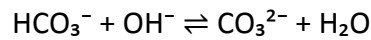
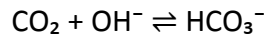
This particular method will be the main focus of this thesis.

The reaction of carbon dioxide (CO₂) with sodium hydroxide (NaOH) in aqueous solution is a well-known acid-base reaction. The resulting products, either sodium carbonate (Na₂CO₃) or sodium bicarbonate (NaHCO₃), are determined by both the molar ratios and the prevailing chemical environment, including temperature and pH. The basic reactions are given here below:



Both reactions listed above are not one-way reactions, but rather equilibrium reactions, meaning they can proceed in both the forward and reverse directions depending on conditions such as pH,

temperature, and CO₂ partial pressure. The reactions occur in sequential steps, starting with bicarbonate (NaHCO₃) formation and followed by further conversion to carbonate (Na₂CO₃) if excess hydroxide ions are present:



At high pH and high NaOH concentration, the system favors carbonate formation. At lower pH or lower alkalinity, bicarbonate becomes more stable. These are all equilibrium reactions governed by Le Chatelier's Principle [3, 4]

This dynamic behavior is relevant for controlling the final product (NaHCO₃ vs. Na₂CO₃), as well as for understanding why titration and pH monitoring are critical for evaluating capture efficiency and speciation.

Na₂CO₃ formation typically occurs at higher NaOH concentrations and when the CO₂ supply is continuous and in stoichiometric excess. NaHCO₃ formation is preferred in dilute alkaline media or when CO₂ is present in low partial pressures, conditions common in ambient air capture and early stage absorption. [4, 12]

The reagents CO₂ and the water in which NaOH is dissolved is not homogenous. Instead the CO₂ gas is located in small gas bubbles surrounded by the alkaline NaOH solution.

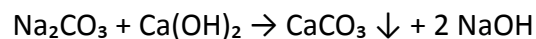
Gas-liquid contact processes, especially those involving alkaline solutions, are often limited by how quickly the gas (such as CO₂) can move from the gas phase into the liquid. This phenomenon is called "mass-transfer limitation," and it means that the chemical reaction itself is fast, but the overall process is slowed down because the CO₂ needs time to physically dissolve into the solution before it can react.

According to the two-film theory, resistance to this transfer exists both in the gas phase (where CO₂ diffuses through air) and in the liquid phase (where CO₂ must pass through a thin layer at the surface before reaching the bulk liquid). In strongly alkaline solutions, the reaction between CO₂ and hydroxide ions (OH⁻) is so fast that CO₂ is consumed almost immediately after entering the liquid. As a result, the bottleneck becomes the gas-to-liquid transfer step, especially in applications like direct air capture (DAC), where CO₂ is present in very low concentrations (around 400 ppm) [3].

Experimental presented in a 2024 master's thesis [3] using a controlled spray tower setup demonstrated that key operational parameters influence both the rate at which CO₂ is absorbed and the total amount that is eventually converted. The following factors were found to significantly impact gas-liquid contact and absorption efficiency:

- **NaOH Concentration:** Higher concentrations increase both the reaction rate and the final CO₂ conversion. For example, 7.5 wt% NaOH solutions performed significantly better than 2 wt% solutions in terms of CO₂ removal.
- **Liquid-to-Gas Ratio (L/G):** A higher L/G ratio, meaning more absorbent liquid relative to the amount of gas, improves gas-liquid contact and increases the residence time of CO₂ in the system. This enhances the probability of CO₂ being absorbed before it exits the reactor. However, it does not necessarily mean that lower gas flow is always better; rather, the effectiveness depends on optimizing both liquid and gas flow rates together to maximize absorption efficiency.
- **Temperature:** Lower temperatures improve CO₂ solubility but slow down the reaction kinetics. An optimal range between 20–35 °C was identified for balancing both factors.
- **Gas Flow Rate:** Lower gas velocities increase contact time and improve absorption efficiency. At higher flow rates, CO₂ has less time to dissolve and react, reducing conversion and possibly leading to gas bypass effects [3].

Regeneration of spent NaOH solutions is vital for long-term system operation. One commonly explored method involves precipitating carbonate ions as calcium carbonate using calcium hydroxide:



While this approach requires a second reagent (Ca(OH)₂), the benefit lies in the potential to recycle NaOH, reducing overall chemical consumption. Calcium hydroxide is often more affordable and may be easier to handle or source in large quantities. Furthermore, in an integrated industrial or marine setting, Ca(OH)₂ could be regenerated from CaCO₃ via calcination, creating a partially closed-loop system. FTIR analysis in Lawal's experiments showed that regeneration is rarely 100% efficient, with

residual carbonate remaining in solution. This highlights the need for further optimization in pH control, Ca:Na molar ratios, and solid-liquid separation techniques [3].

2.2.2. The Solvay Process

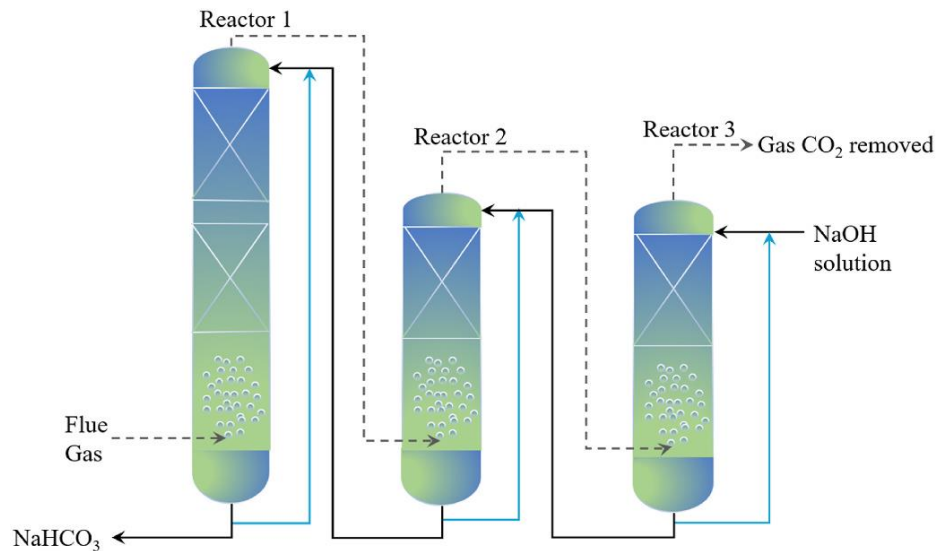
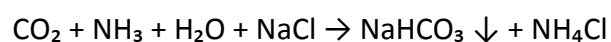
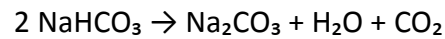


Figure 2: Process flow diagram of the conventional Solvay carbonation process (Source: [4], Figure 6)

The Solvay process remains the most widely implemented industrial procedure for producing sodium carbonate. Importantly, this process also served as the core inspiration for the conceptual development of the present thesis. While the original Solvay process integrates brine (NaCl), ammonia (NH₃), and CO₂ in a closed-loop chemical system, the practical research in this thesis investigates a significantly simplified version that omits both salt and ammonia, using sodium hydroxide (NaOH) as the sole absorbent for CO₂. A key advantage of using ammonia in the Solvay process is that it increases the alkalinity of the brine, enabling the selective precipitation of sodium bicarbonate (NaHCO₃) while leaving other salts in solution. Moreover, ammonia reacts reversibly with CO₂ and water to form ammonium bicarbonate, which enhances CO₂ absorption efficiency under relatively mild conditions. Because ammonia is regenerated within the cycle, the process remains continuous and resource-efficient. The chemical sequence is as follows:

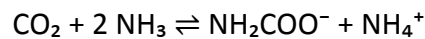


The bicarbonate is filtered and thermally decomposed:

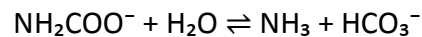


This results in soda ash as the main product and recycled CO_2 , which is routed back into the system to minimize waste [4].

The Solvay cycle progresses through the intermediary formation of ammonium carbamate and bicarbonate. The primary reaction is:



This fast and reversible reaction forms ammonium carbamate in aqueous solution. As the system evolves and pH decreases, the carbamate is hydrolyzed:



The overall process is strongly influenced by pH and temperature. Ammonia maintains an alkaline environment that favors bicarbonate formation and precipitation in the presence of Na^+ ions. Optimal precipitation occurs around 20–25 °C, while above 35 °C, the solubility of NaHCO_3 increases, reducing product yield [4, 5].

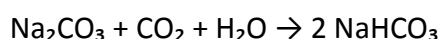
Though CO_2 is consumed in the reaction, the calcination of limestone to generate process CO_2 introduces large CO_2 emissions:



The process is thus not inherently carbon neutral. Newer designs attempt to offset emissions by integrating CO₂ capture systems or by using industrial waste CO₂ streams. However, the net carbon footprint remains an active challenge in the sustainability of the Solvay process [4].

2.2.3. Soda Ash Carbonation and Trona-Based Pathways

Na₂CO₃ (soda ash), derived either from mined trona ore or from industrial processes, can be re-carbonated in aqueous solution to form NaHCO₃. This transformation is crucial in food-grade bicarbonate production:



Typical operating parameters include temperatures between 45–70 °C, a CO₂ concentration of 10–15%, and a controlled L/G ratio between 2–5. Packed-bed and bubble column reactors are commonly used in industry to achieve this. CO₂ capture efficiencies reach up to 90% depending on operating conditions and reactor design [4].

Trona, a natural ore of Na₂CO₃·NaHCO₃·2H₂O, can be calcined and re-carbonated. Structural characteristics of trona, initially nonporous, transform during thermal exposure, improving reaction surface area. CO₂ absorption rates increase significantly when particle cracking enhances internal accessibility. The ideal temperature range for this conversion lies between 42–70 °C, where recrystallization and carbonation are optimized [4].

This following table compares several sodium bicarbonate precipitation technologies based on different sodium sources and reactor configurations, highlighting typical parameters and reported CO₂ capture efficiencies.

Table 1: Summary of industrial CO₂ capture technologies using soda ash and trona-based pathways ([4] , Table 2)

Technology	Reactor Type	Na Source	Temperature (°C)	CO ₂ Concentration (%)	L/G Ratio	CO ₂ Capture Efficiency (%)
Soda Ash Carbonation	Packed Bed	Na ₂ CO ₃	45–70	10–15	2–5	Up to 90
Trona Re-carbonation	Bubble Column	Trona (Na ₂ CO ₃ ·NaHCO ₃ ·2H ₂ O)	42–70	10–15	2–5	High (optimized)
Slurry Carbonation	Stirred Tank	Na ₂ CO ₃ or Trona	50–60	10	3	Moderate
Spray Tower Carbonation	Spray Column	Na ₂ CO ₃	60–70	10–15	2–4	80–90

2.2.4. Calcium Hydroxide (Ca(OH)₂) Absorption

The exothermic reaction given here below (-109 kJ/mol) proceeds rapidly under ambient conditions. Ca(OH)₂ is a viable absorbent due to its strong basicity, low cost, and wide availability. Thermodynamically, it provides a reliable sink for CO₂ mineralization in either slurry or saturated solution forms [6].

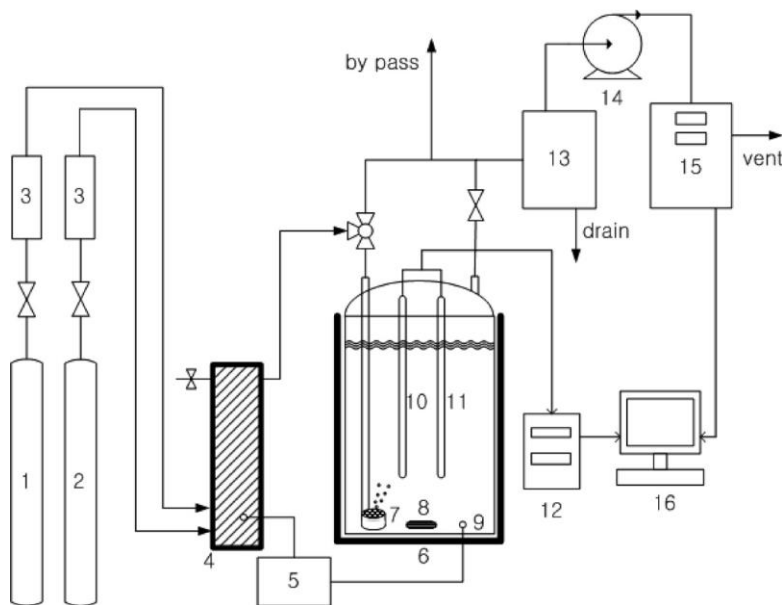
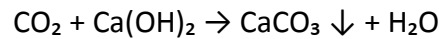


Figure 3: Schematic setup for CO₂ absorption using calcium hydroxide slurry ([6] , Figure 1)

Experiments by Han et al. revealed that CO₂ absorption is significantly higher in saturated solutions than in low-concentration slurries. However, once CaCO₃ begins to form, its precipitation reduces the reactive surface area due to agglomeration.[6]

This limits further absorption unless agitation, dispersion, or vacuum techniques are introduced [6].



- The CaCO₃ product often has poor crystallinity, requiring post-treatment.
- Regeneration of Ca(OH)₂ from CaCO₃ is energy-intensive (requires >850 °C).
- Sludge separation and water recycling are complex and require multistage handling [6]

2.2.5. Simulation and Kinetics Based on Levenspiel's Reactor Theory

In Chemical Reaction Engineering by Octave Levenspiel, several foundational principles are laid out that have shaped the understanding of chemical reactor behavior. Levenspiel's treatment of reactor types, particularly plug flow reactors (PFRs), continuous stirred-tank reactors (CSTRs), and batch reactors, has informed kinetic modeling in gas–liquid CO₂ absorption systems. His use of performance equations, reaction rate expressions, and residence time distributions is particularly relevant when analyzing or designing absorption columns and spray towers for CO₂ capture applications [7].

In addition to analytical reactor models, process simulation software such as Aspen Plus is widely used to model gas–liquid CO₂ absorption systems under more complex or industrially relevant conditions. Aspen Plus is a steady-state process simulator commonly used in chemical engineering to predict system behavior based on mass and energy balances, phase equilibrium, and chemical kinetics. It allows the user to simulate entire process flows, including heat exchangers, reactors, absorbers, and separation units.

In CO₂ absorption modeling, Aspen Plus has been used to investigate how varying operational parameters—including the liquid-to-gas ratio (L/G), NaOH concentration (2–10 wt%), reactor

temperature (20–60 °C), and CO₂ partial pressure (ambient to 10%)—affect system performance. These simulations are often validated against experimental data such as pH trends and absorption isotherms. While Aspen Plus does not directly apply Levenspiel’s analytical equations, the two approaches are complementary: Levenspiel provides the theoretical framework for understanding reactor behavior, while Aspen Plus enables detailed, system-level simulation for process optimization [7].

2.2.6. Potassium Hydroxide (KOH)

Potassium hydroxide (KOH) is conceptually and chemically analogous to sodium hydroxide in terms of CO₂ absorption capabilities. Both KOH and NaOH are strong bases and readily absorb CO₂ to form carbonate or bicarbonate species. While the article primarily studies the combined removal of SO₂ and NO using KMnO₄/NaOH solutions, it references similar studies involving other oxidizers and alkaline agents such as NaClO and indirectly supports the logic of using strong alkalis like KOH in post-combustion scrubbing scenarios [8].

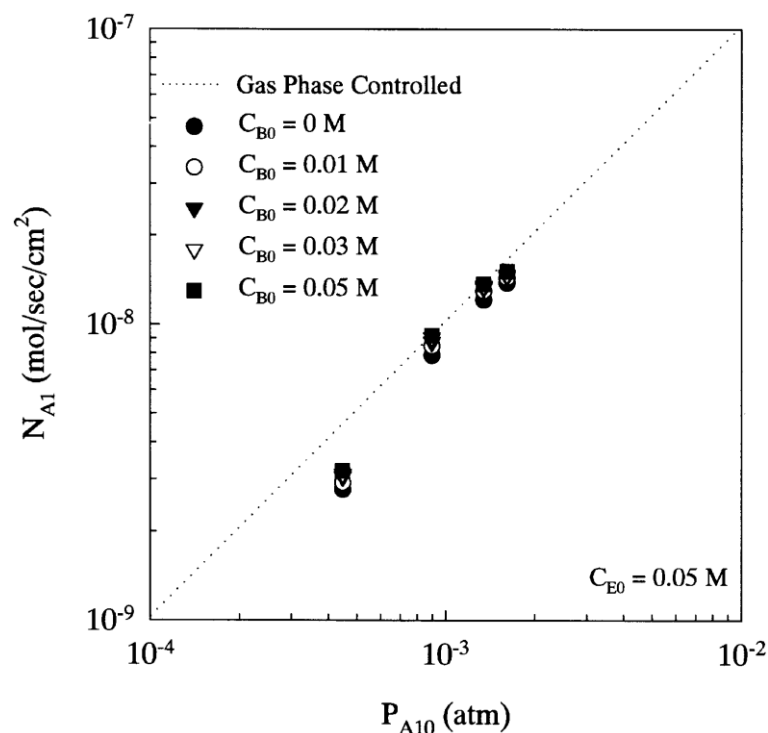
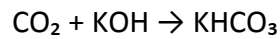
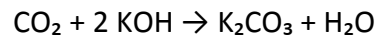


Figure 4: Effect of KMnO₄ concentration with 0.05 M NaOH on SO₂ absorption rate (Source: [4], Figure 5)

The general CO₂ absorption reactions using KOH are:



This mirrors the behavior observed with NaOH and enables the use of KOH as a viable alternative in capture systems. The key benefit of KOH is its potential for higher solubility and less precipitation tendency in some conditions compared to NaOH, though KOH is generally more expensive.

These reactions are both post-combustion, occurring after fuel combustion and flue gas generation, making them compatible with current CO₂ scrubbing infrastructure, including those used in marine and industrial contexts.

2.2.7. Direct Air Capture (DAC) and Industrial Feasibility

Direct air capture using alkaline solutions such as NaOH targets CO₂ at ambient levels (~400 ppm). The low partial pressure presents a challenge for absorption kinetics. Therefore, physical design (e.g., use of structured packing, fog nozzles, or fluidized beds) plays a pivotal role in enhancing performance. The mass transfer zone is widened to compensate for the low CO₂ flux [4].

Post-capture, CO₂ is either mineralized or used to produce synthetic fuels or carbonates. In Vincent's research, partial regeneration using Ca(OH)₂ was explored, revealing the persistence of carbonate residues post-precipitation. Strategies to improve regeneration include counter-current mixing, ion-selective membranes, and electrochemical regeneration cells [3].

While DAC offers decentralized carbon removal, its high energy demand, especially for sorbent regeneration, limits scalability. Integration with renewable energy or industrial waste heat is recommended to reduce the carbon footprint. Lifecycle analyses suggest that CO₂-neutral operation is possible but not guaranteed without careful systems integration [4].

2.2.8. Reaction Plane and Film Theory in Gas–Liquid Absorption

In gas–liquid CO₂ absorption systems, the interface between the gas and liquid phases is governed by mass transfer principles that are critical to understanding reaction performance. According to Levenspiel's two-film theory, mass transfer occurs through a thin gas film and a thin liquid film on

either side of the interface. CO_2 diffuses across the gas film, dissolves at the interface, and then diffuses further into the liquid before reacting with hydroxide ions [7].

Figure 23.3 in the book of 'Chemical Reaction Engineering' by Octave Levenspiel [7], illustrates several interface behaviors, including two key cases relevant to this thesis: Case B and Case D. These are shown in Figure 5 below.

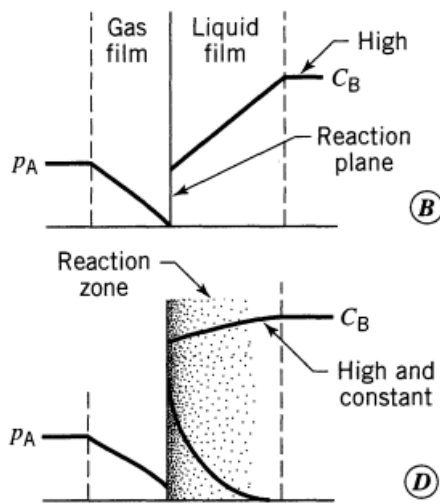


Figure 5: Concentration profiles across the gas-liquid interface for fast and instantaneous reactions. (Source: [7], Figure 23.3, p. 528)

In the figure, the vertical axis represents the concentration of CO_2 in the gas phase (left side) and the concentration of hydroxide ions or carbonate species in the liquid phase (right side).

- Case B (upper diagram) shows a scenario where the chemical reaction occurs at a distinct reaction plane just inside the liquid film. This corresponds to an instantaneous reaction, where CO_2 reacts immediately upon entering the liquid due to a very high concentration of hydroxide ions near the interface.
- Case D (lower diagram) illustrates a fast but finite-rate reaction, where CO_2 continues to diffuse through the liquid film and is gradually consumed over a defined reaction zone. This results in a smoother concentration gradient within the liquid.

In the context of the experiments described in this thesis—particularly the UCLV experiments using NaOH and $\text{Ca}(\text{OH})_2$ at 10% and 20% weight concentrations—the conditions are best represented by Case D. This is because although the chemical reaction between CO_2 and OH^- is rapid, it is not strictly instantaneous under the moderate concentrations and bubbling contact method used. CO_2 diffusion continues into the liquid film and reacts over a finite distance rather than at a sharply defined reaction plane. Therefore, a distributed reaction zone exists in these experiments, characteristic of Case D ([7], pages 512–514).

This behavior is consistent with the mass transfer limitations observed during the practical tests, where the rate-limiting step was the physical transport of CO_2 molecules into the solution, rather than the speed of the chemical reaction itself. As such, optimizing surface area and residence time becomes more critical than enhancing reaction kinetics in this regime.

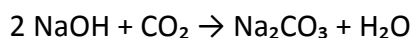
Moreover, understanding whether the system operates under Case B or Case D is essential when considering process design improvements. For instance, spray towers or membrane contactors would increase interfacial area and thereby shrink the thickness of the liquid film, promoting faster absorption in a Case D scenario. This supports the broader conceptual direction of the thesis, which investigates ways to improve absorption efficiency through both chemical and mechanical optimization.

2.3. Initial Conceptual Approach

At the start of the project, the core idea was to explore whether it would be possible to build a compact, on-board system capable of capturing CO_2 emissions from ship exhaust and converting the captured CO_2 into a solid product such as sodium carbonate (Na_2CO_3). This concept was inspired by the well-established industrial Solvay process, which reacts carbon dioxide with ammonia and salt in aqueous solution to form sodium bicarbonate, a precursor to soda ash [2]. To simplify the system and make it more suitable for shipboard integration, the concept was adapted to focus exclusively on sodium hydroxide (NaOH) as the CO_2 absorbent.

2.3.1. Chemical and Mechanical Design Considerations

The reaction initially considered was:



The plan was to use a highly concentrated NaOH solution, specifically 50% by molar ratio. At this concentration, NaOH provides a strong chemical driving force for CO₂ capture, and based on stoichiometry, considering that the NaOH solution is diluted and partially saturated, an estimated four moles of 50% NaOH solution were anticipated to be required per mole of CO₂ to drive the reaction to completion, accounting for real-world inefficiencies such as incomplete mixing and non-instantaneous reaction kinetics. According to the available literature, this reaction proceeds readily at room temperature and does not require a catalyst [2, 6]. These thermodynamic and kinetic conditions supported the viability of the concept in decentralized or field-based applications.

The central feature of the conceptual design was a vertical column, envisioned to operate as a counter-current absorption reactor. NaOH solution would be sprayed from the top, while CO₂-rich gas would be introduced from the bottom. This configuration was selected to maximize contact time and surface area between the gas and liquid phases. Such vertical arrangements have also been observed in other spray tower research aimed at maximizing mass transfer efficiency [3].

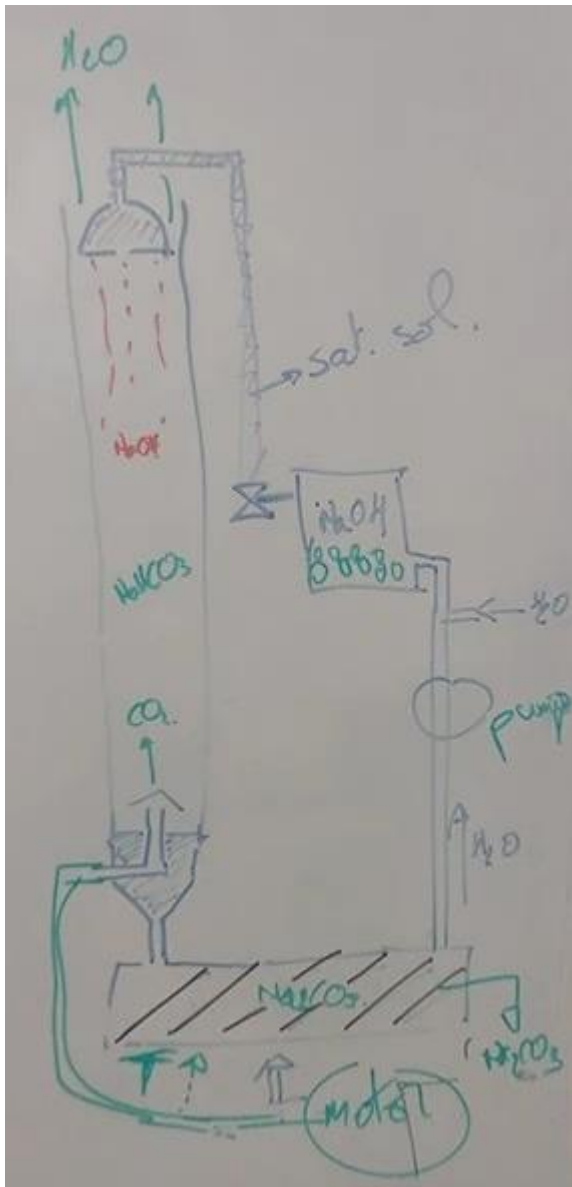


Figure 6: Initial Idea (Source: Co-Supervisor Olivier Schalm's Conceptual Drawing)

Initially, a showerhead was considered for dispersing the NaOH, but this approach was strongly rejected due to its tendency to produce large droplets, resulting in low contact surface area and inefficient reaction. Instead, a pressurized nozzle was favored, allowing for fine droplet atomization, similar to the fuel injection systems used in internal combustion engines. Smaller droplets offer significantly increased surface area, enhancing CO₂ absorption.

The assumed dimensions for the column were a diameter of 10–15 cm and a height of 1–2 meters. These measurements were based on practicality for prototyping and handling. While such specific sizes are not universally standardized, they are consistent with column-based gas-liquid absorption setups that rely on similar principles of surface area and residence time.

2.3.2. Process Design Constraints and Optimization

One early practical consideration was selecting appropriate materials for the column and nozzle. Brass nozzles were readily available and compatible with most water-based fluids, but their long-term durability in contact with concentrated NaOH posed concerns due to potential corrosion and weakening. Research indicated that while PVC is commonly used in laboratory setups, it is not recommended for long-term exposure to concentrated NaOH due to stress cracking and chemical degradation. Polypropylene (PP) and high-density polyethylene (HDPE) were identified as more chemically resistant alternatives. Despite this, PVC was ultimately recommended by academic supervisors for initial prototyping, due to its ease of availability and machining.

Another major design consideration was the optimal NaOH concentration for efficient capture and processing. While a higher NaOH concentration reduces the amount of water in the final product, making separation easier, it also increases the solution's viscosity. A more viscous liquid leads to greater pressure drop through the atomizer, potentially producing larger droplets and decreasing surface area for gas contact. On the other hand, a more diluted NaOH solution results in better atomization and droplet distribution, but introduces more water into the final carbonate mixture, complicating post-reaction separation and drying. Therefore, the system required a carefully balanced NaOH concentration that would offer a compromise between reactivity, sprayability, and downstream processing.

The decision of whether to operate the absorption column as an open or closed system was also debated. An open system would operate at atmospheric pressure, reducing risk in the event of a leak or failure, since pressure buildup is minimal and spray distances limited. In contrast, a closed system, while potentially more controlled, poses a higher risk in case of leaks due to pressurization. For safety and simplicity, especially in early prototyping, it was concluded that an open system was more appropriate, particularly given the chemical handling risks involved.

2.3.3. Evolving Scope and Field Recommendations

As the project progressed, several challenges emerged. These included limitations in equipment availability (e.g., lack of high-pressure CO₂ cylinders or specialized nozzles in resistant material), safety considerations, and the complexity of reliably atomizing NaOH of high concentrations due to a potentially high viscosity. These constraints eventually led to a decision to first conduct smaller-scale

proof-of-concept experiments using simpler setups, such as bubbling CO₂ into a beaker of NaOH solution and monitoring pH changes to observe reaction progression.

During field research in Cuba, further input from professors and lab personnel revealed that the original column concept, while theoretically valid, closely resembled existing designs already discussed in literature and implemented in other CO₂ capture research [4]. This realization prompted a partial shift in focus: rather than developing a column system from scratch, the experimental work would concentrate on characterizing and comparing CO₂ capture efficiencies using NaOH and Ca(OH)₂ (calcium hydroxide), both independently and in combination. Research has shown that Ca(OH)₂, while effective, suffers from challenges such as agglomeration of CaCO₃ and handling solid precipitate, making NaOH a more desirable candidate for continuous systems [6].

In addition to this, concerns about the purity of CO₂ in flue gases led to a strong recommendation from senior figures within the chemical engineering department to investigate pre-treatment steps for CO₂ purification. This included studying how contaminants like nitrogen, water vapor, and particulates in exhaust gases could interfere with carbonate formation and overall system performance. These concerns align with industrial research showing that flue gas impurities reduce amine solvent lifespan and reaction efficiency, underscoring the importance of gas conditioning before capture [1]. Due to limitations in available equipment and materials during the research stay in Cuba, this aspect of the project remained theoretical in nature. While valuable discussions and literature review on purification strategies took place, no practical experiments in this direction could be carried out under the given circumstances.

In addition to the column-based bubbling and spray system, two other CO₂ delivery methods were briefly considered during early discussions at UCLV but were ultimately discarded. One involved passing CO₂ through a U-shaped tube filled with the alkaline solution, in an attempt to increase contact time and bubble retention. However, this design was deemed unsuitable for conducting further experiments. Another idea was to replicate the carbonation method used in soda and sparkling water production, where CO₂ is dissolved into liquid under pressure to create fine bubbles and maximize surface area. While conceptually appealing, this technique was rejected due to the extremely low CO₂ flow rates and the difficulty of potentially implementing such a system in a continuous, scalable manner.

Overall, while the final prototype and experiments diverged from the initial full-column concept, the iterative development process offered valuable insight into the practical challenges and trade-offs of implementing CO₂ capture technology in real-world, resource-limited settings such as ship environments. The decision to continue focusing on NaOH, supported by its higher commercial value in forming Na₂CO₃ and easier handling in liquid form, was consistent with insights from comparative studies in industrial CO₂ capture systems [2, 3].

2.4. Pre-Treatment Steps for CO₂ Purification

At the start of the project, the core idea was to explore whether it would be possible to build a compact, on-board system capable of capturing CO₂ emissions from ship exhaust and converting the captured CO₂ into a solid product such as sodium carbonate (Na₂CO₃). This concept was inspired by the well-established industrial Solvay process, which reacts carbon dioxide with ammonia and salt in aqueous solution to form sodium bicarbonate, a precursor to soda ash [2]. To simplify the system and make it more suitable for shipboard integration, the concept was adapted to focus exclusively on sodium hydroxide (NaOH) as the CO₂ absorbent.

During the research stay at the UCLV, senior figures within the chemical engineering department recommended conducting theoretical research into pre-treatment steps for CO₂ purification. This was considered necessary to address potential gas contaminants before introducing CO₂ into the absorption system. However, due to limitations in available laboratory equipment, machinery, and technical resources at UCLV, these purification concepts could not be tested or applied experimentally. Nonetheless, the importance of CO₂ pre-treatment justified the inclusion of a dedicated background section on this topic elsewhere in the thesis.

Particulates, including soot and ash, are often present in flue gases and can physically damage equipment, clog absorption systems, and reduce reaction surface areas. Mechanical filters, cyclones, or electrostatic precipitators (ESP) are commonly employed to remove particulate matter prior to CO₂ capture stages. This step is especially critical in marine exhaust systems where space is limited, and fouling could critically impact system reliability and maintenance intervals [1].

- **Desulfurization (SO_x Removal):**

Sulfur dioxide (SO₂) and sulfur trioxide (SO₃) can interfere with both chemical solvents and alkaline absorbents. In amine-based post-combustion capture, SO_x reacts irreversibly with amine groups, leading to solvent degradation and formation of non-regenerable salts. In NaOH or Ca(OH)₂ systems, SO₂ reacts to form sulfites or sulfates, consuming reactant and competing with CO₂ for absorption. Therefore, flue gas desulfurization (FGD) is a vital step before introducing the gas to the absorption column. FGD units typically use limestone or magnesium hydroxide slurries to capture SO₂ [1]. Additionally, research has demonstrated that the inclusion of potassium permanganate (KMnO₄) in NaOH solutions can significantly improve SO₂ absorption rates. In particular, absorption becomes gas-film controlled at NaOH concentrations above 0.1 M or KMnO₄ concentrations above 0.05 M, with increased gas flow enhancing the rate further [8].

- **De-NO_x (Nitrogen Oxides Removal) :**

Similar to SO_x, nitrogen oxides (NO and NO₂) also degrade amine solvents and pose problems in basic systems. NO_x can form nitric or nitrous acid when dissolved in water, altering pH balance and forming unwanted nitrates. Selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR) are typically used upstream of CO₂ capture units to reduce NO_x concentrations to below 10 ppm [1]. However, the use of KMnO₄/NaOH solutions has also been shown to remove NO in flue gas applications. Chu et al. found that NO removal efficiency improves with increasing KMnO₄ concentration and that NaOH enhances the kinetics, making it a viable additive system for simultaneous SO₂ and NO removal [8].

- **Cooling and Dehumidification:**

The presence of water vapor can dilute CO₂ concentration and impact the performance of sensors and mass flow controllers. More importantly, temperature and humidity affect the equilibrium and reaction kinetics of CO₂ absorption in alkaline solutions. For example, it has been shown that the CO₂ mass transfer coefficient in NaOH-based absorption systems decreases with increasing temperature and water saturation, emphasizing the need to regulate gas stream conditions before entry into the reactor [2]. Dehumidifiers, water traps, or refrigeration units are often employed to achieve this.

- **Compression or Flow Conditioning:**

Many experimental and industrial CO₂ capture systems, especially those based on aqueous absorbers, are sensitive to gas velocity and pressure. If the flue gas pressure is too low, it may be insufficient to overcome the hydrostatic resistance in the reactor (as was experienced in field tests in Cuba). To counter this, research suggests using compressors or fans to ensure gas flows adequately through spray columns or bubble contactors [2]. In smaller systems or research settings, this step is crucial to maintaining proper flow rates and ensuring measurable absorption performance.

- **Pre-scrubbing and Multi-stage Conditioning:**

In advanced applications or highly contaminated streams, a pre-scrubbing step may be introduced to remove acid gases and fine particulates simultaneously. This is typically done using a water-based scrubber with additives such as NaOH or amines. According to a 2007 report, a two-stage setup is sometimes used, where an initial scrubber removes SO_x and NO_x, and a secondary unit ensures gas drying and final conditioning before entering the CO₂-specific capture system [1]. Research also suggests that combining KMnO₄ with NaOH provides a highly effective scrubbing solution, capable of removing both SO₂ and NO from flue gas in a single stage, especially under elevated temperature conditions (50°C) typical of exhaust streams [8]

- **Relevance to Marine Systems:**

In the context of maritime applications, such as the one investigated in this thesis, these pre-treatment steps become particularly relevant due to the high variability and impurity levels of ship exhaust gases. Marine diesel engines typically emit exhaust with around 13–15% CO₂, but also a large quantity of N₂, H₂O vapor, and trace contaminants. Colleagues at UCLV highlighted that such impurities must be addressed before any meaningful CO₂ capture can occur. Their insights underscore the necessity of pre-treatment as a foundational design component for future shipboard carbon capture installations.

- **Summary of CO₂ Purification Relevance to This Thesis:**

Pre-treatment of CO₂-containing gases is important to ensure the efficiency, longevity, and safety of downstream capture processes. Whether in stationary power plants or mobile maritime platforms, these steps help mitigate chemical interference, mechanical fouling, and energy inefficiency. The specific combination of treatments should be tailored to the exhaust composition, system constraints, and chosen capture technology. In the context of this research, however, such pre-treatment procedures could not be implemented during the practical experiments in Cuba due to significant limitations in available equipment, materials, and time. As a result, this component of the system remains a theoretical consideration in the current phase of work, pending further development and resourcing.

2.5. Initial Conceptual Separation Techniques

Following the chemical absorption of CO₂ in an aqueous sodium hydroxide (NaOH) solution, the primary products are sodium carbonate (Na₂CO₃), water (H₂O), and potentially some sodium bicarbonate (NaHCO₃), depending on the reaction conditions. To obtain a purified and valuable end product, it is necessary to separate the carbonate salts from the liquid water phase.

Since both Na₂CO₃ and NaHCO₃ are solid under ambient conditions, an early conceptual idea involved using a mechanical separation technique based on the Archimedes screw principle.

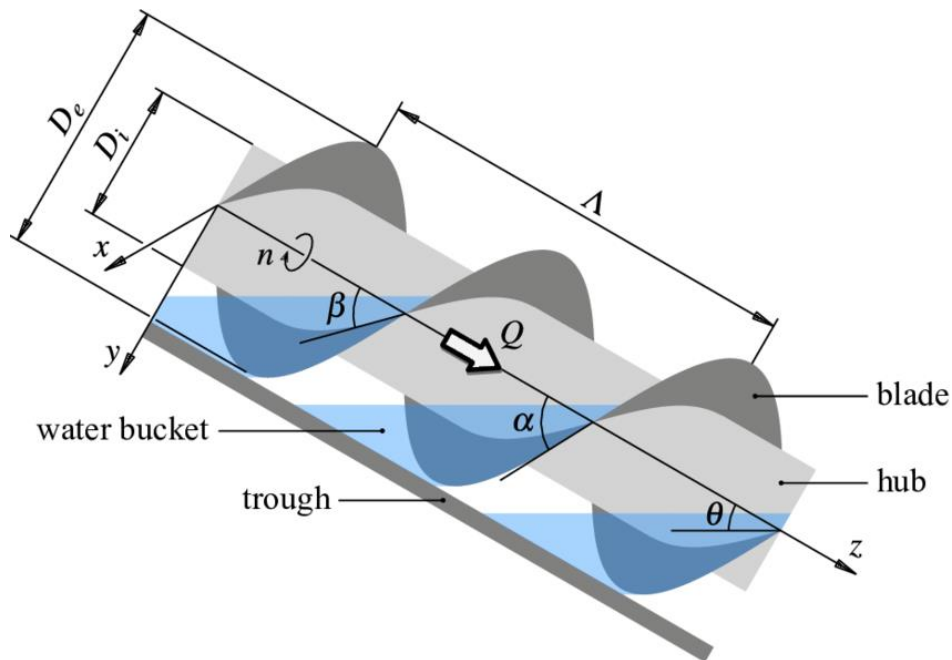


Figure 7: Archimedes screw (Source: [9])

This approach assumed that the carbonate product would settle as a solid, which could then be physically extracted from the bottom of the reactor. However, this method faces major limitations due to the high solubility of both Na_2CO_3 (21.5 g/100 mL at 20 °C) and NaHCO_3 (9.6 g/100 mL at 20 °C) in water [4] . Under the dilute and relatively cool conditions typical of CO_2 absorption systems, these salts generally remain dissolved, and little to no solid is expected to precipitate. As a result, mechanical extraction methods such as sedimentation or screw-based removal would likely be ineffective unless the solution is first brought to saturation or supersaturation.

To overcome this challenge, an alternative approach based on vacuum-assisted thermal separation was proposed. This concept draws inspiration from the freshwater generators (FWGs) commonly used on board maritime vessels. In these systems, seawater is heated to around 80 °C and placed under vacuum (approximately 0.05 bar), allowing water to evaporate at reduced temperature and pressure. The vapor is directed through a demister to prevent carryover of salt or droplets, and then condensed into fresh water.

2.6. Initial Conceptual CO₂ Source

In laboratory environments where access to pressurized gas cylinders of 100% CO₂ gas is nonexistent, as was the case at the UCLV in Cuba, alternative methods for CO₂ generation had to be considered. One conceptual alternative that was briefly evaluated was the use of a Kipp apparatus, a classic laboratory device designed to generate gases on demand through the reaction of a solid and a liquid reagent. In the case of CO₂ production, the Kipp apparatus typically utilizes marble chips (CaCO₃) or powdered calcium carbonate and dilute hydrochloric acid (HCl). The following reaction occurs:



The apparatus is composed of three vertically aligned chambers. The upper chamber holds the liquid acid, the middle chamber contains the solid reactant, and the lower chamber serves as the gas collection and outlet section.

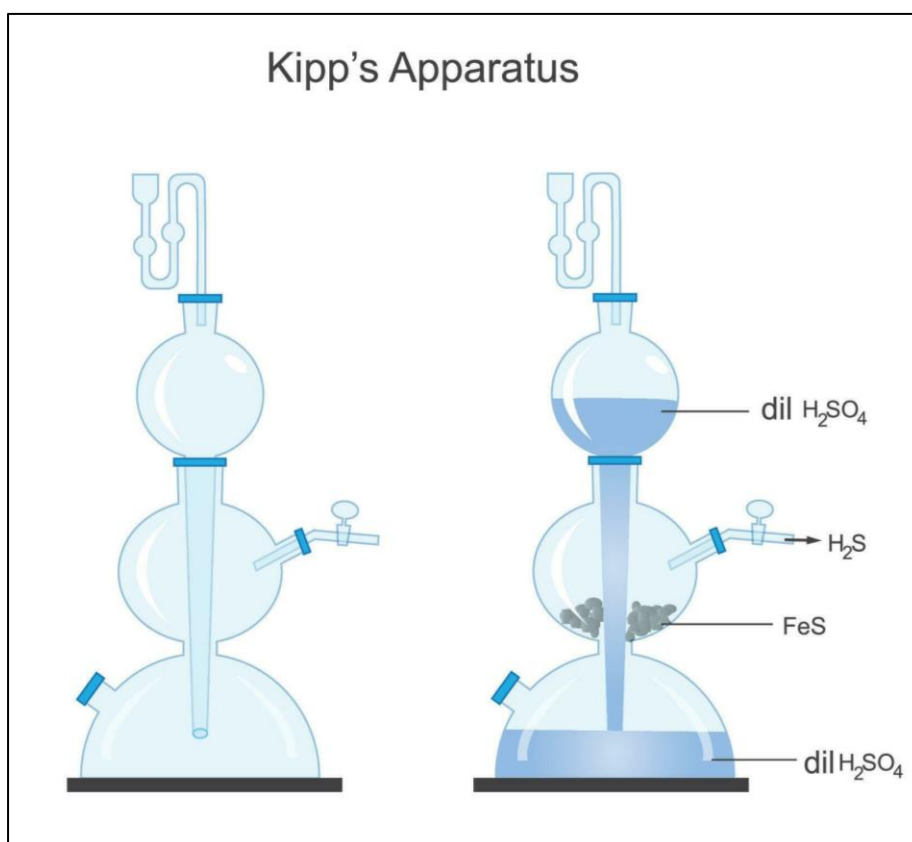


Figure 9: Illustration of a Kipp's apparatus for gas generation (Source:[11])

When the valve is opened, the acid comes into contact with the carbonate, releasing CO_2 gas which can then be directed into external tubing or equipment. The system is self-regulating to a degree, once the internal pressure builds to a certain level, it suppresses further acid contact with the carbonate, halting gas production.

Although the Kipp apparatus is a clever and compact solution for small-scale gas generation, it was ultimately deemed unsuitable for this research project. Its output pressure is limited to near-atmospheric conditions, which is insufficient to overcome the hydrostatic pressure in the CO_2 absorption reactor used in these experiments. Furthermore, the system is not capable of delivering the sustained gas flow required for continuous bubbling, making it impractical for high-volume gas supply. While it may be theoretically possible to increase outlet pressure using a compressor, the additional atmospheric air drawn into the Kipp apparatus during operation, air that does not participate in the chemical reaction, would dilute the gas stream, resulting in a CO_2 -to-flue-gas ratio that is likely too low for effective absorption.

As a result, alternative sources of CO_2 , such as exhaust gas from a gasoline-powered generator, were explored and selected instead at the UCLV.

3. Materials & Methods

The practical part of this thesis aimed to explore the feasibility of capturing carbon dioxide (CO_2) and converting it into sodium carbonate (Na_2CO_3) using a simplified setup inspired by the principles of the Solvay process. While the traditional Solvay process makes use of ammonia and salt brine, this project focused solely on sodium hydroxide (NaOH) as the reactive absorbent, prioritizing simplicity and rapid prototyping over chemical complexity. Experiments using calcium hydroxide ($\text{Ca}(\text{OH})_2$) were also performed at UCLV in order to compare results and gain insight into differences in absorption behavior between the two alkaline substances.

This chapter provides an overview of the experimental conditions established, the materials selected, and the methods employed to carry out the proof-of-concept experiments. Given the experimental nature of this work, both basic setups (such as bubbling CO_2 a beaker, involving electronic pH measurements) and more structured apparatus (bubbling flue gas through a reactor, involving CO_2

measurements) were used. Several trials were conducted to monitor pH changes over time as an indirect indicator of CO₂ absorption and chemical transformation.

The following sections form the technical backbone of the conducted experiments. The focus is on recording the conditions under which CO₂ capture and transformation were observed, the limitations encountered (e.g., CO₂ source purity, equipment availability), and how these challenges were addressed both in the AMA in Belgium and during the phase at the UCLV in Cuba.

3.1. AMA Experiment 1 Setup

The first and only experiment conducted in Belgium involved bubbling pure CO₂ into a tall plastic beaker containing an aqueous sodium hydroxide (NaOH) solution. The CO₂ source was a pressurized cylinder (2 kg) containing 100% pure CO₂ at 55 bar.

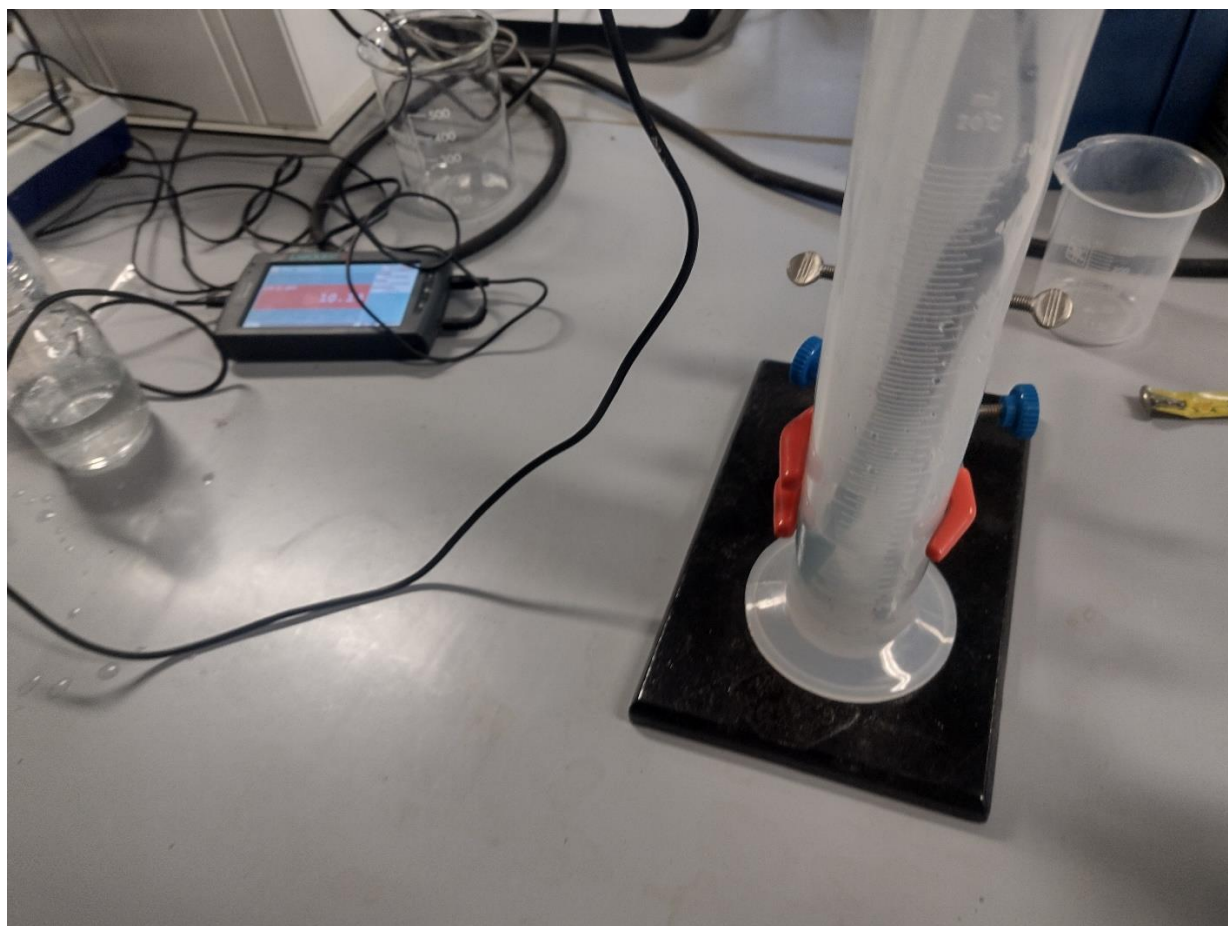


Figure 10: AMA experimental setup (Source: Own work)

Three separate tests were conducted using different NaOH-to-water ratios:

- Test 1: 4.5 g of solid NaOH dissolved in 250 mL of water (H₂O)
→ NaOH concentration: 0.45 mol/L (~1.77 wt%)
- Test 2: 5.3 g of solid NaOH dissolved in 100 mL of water (H₂O)
→ NaOH concentration: 1.32 mol/L (~5.03 wt%)
- Test 3: 4.5 g of solid NaOH dissolved in 120 mL of water (H₂O)
→ NaOH concentration: 0.94 mol/L (~3.61 wt%)

In the first two tests, pH measurements were taken every 5 minutes using paper pH indicator strips with a maximum readable value of pH 10. These strips were not capable of detecting higher alkaline values.

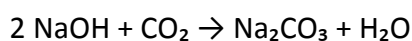
In the third test, a digital pH meter (Vernier LabQuest 2 Data Logger) with a higher measurement range was used. This device was able to detect the initial pH of 13.55 prior to the start of CO₂ bubbling. The duration of the third test was limited to 50 minutes due to time constraints.

Table 2: Inventory of equipment used in AMA experiment 1 (Source: Own Work)

No.	Name	Supplier	Price per unit (Euros)	Quantity	Total price (Euros)
1	Accessory kit for single-tap beer dispenser – with Type A keg coupler, 10 mm beer hose, CO ₂ cylinder 2.0 kg <i>(Accessoirepakket voor biertap 1-kraans - met Fustkoppeling type A, bierslang 10 mm, CO2 fles 2,0 kg)</i>	HAJUS AG (bol.com)	€ 157,00	1	€ 157,00
2	500 mL Measuring Cylinder	N.A., Readily Available at AMA	N.A., Readily Available at AMA	1	N.A., Readily Available at AMA
3	pH meter: Vernier LabQuest 2 Data Logger			1	

4	laboratory retort stand with clamp			1	
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Although it wasn't possible to measure the flow of the CO₂ gas, there was a way to estimate the amount of CO₂ captured. Stoichiometric calculations were applied based on the following chemical reaction:



The initial amount of NaOH (in mol) was determined using the known mass of NaOH and its molar mass (40.0 g/mol):

$$n(\text{NaOH}) = \text{mass of NaOH (g)} / 40.0$$

The final amount of NaOH remaining in the solution was estimated from the final pH value by converting pH into hydroxide ion concentration using:

$$[\text{OH}^-] = 10^{-(14 - \text{pH})}$$

Then, using the volume of the solution (in liters):

$$n(\text{NaOH remaining}) = [\text{OH}^-] \times \text{volume of solution (L)}$$

The amount of NaOH that reacted during the experiment was calculated as:

$$n(\text{NaOH reacted}) = n(\text{NaOH initial}) - n(\text{NaOH remaining})$$

Based on the reaction stoichiometry (2 mol NaOH per 1 mol CO₂), the amount of CO₂ captured was determined by:

$$n(\text{CO}_2 \text{ captured}) = n(\text{NaOH reacted}) / 2$$

These calculations allowed for a quantitative estimate of the total amount of CO₂ absorbed and the extent of NaOH conversion under batch-mode bubbling conditions.

3.2. UCLV Experiments

At the UCLV, experiments were conducted to evaluate the absorption of CO₂ using sodium hydroxide (NaOH) solutions. To enable a comparative assessment, calcium hydroxide (Ca(OH)₂) was also tested under similar conditions. Both chemicals were used at concentrations of 10 wt% and 20 wt%, resulting in four experimental configurations. A dedicated setup was constructed on-site, incorporating a jacketed glass reactor filled with a solution, into which the exhaust gas from a gasoline-powered generator was bubbled.

3.2.1. Construction of Experimental Setup UCLV

To conduct the experiments at UCLV, a custom gas-liquid absorption system was constructed. The core of the setup was a Pobel 2000 mL jacketed glass reactor, with an internal liquid height of 15 cm when full and an internal diameter of 13 cm. For temperature control, a SDC-6 water cooler was used, capable of supplying cooling water near 0 °C. The cooler required 1200 W of power. Flexible tubing with a 3/4-inch inner diameter was used to connect the reactor jacket to the cooler.



Figure 11: Pobel 2000 mL jacketed glass reactor and SDC-6 water cooler (Source: Own Work)

To enhance gas-liquid contact time and improve absorption efficiency, a custom funnel-shaped gas inlet was fabricated. A plastic foam insert was placed inside the funnel to disperse the gas stream into finer bubbles. During fabrication, cooling water was applied to the grinding tool to prevent overheating, as shown below in Figure 12.



Figure 12: Funnel Fabrication (Source: Own Work)

The source of CO₂ was a K-Power K-3000 gasoline-powered generator, producing 7 horsepower (up to 3000 W AC) while running on Octane 95 fuel. To ensure sufficient gas pressure to overcome the hydrostatic pressure in the reactor, an ILM VAC Type 40171 membrane compressor was installed between the generator and the reactor. The flexible tubing used for both the gas inlet to the compressor and the gas outlet to the reactor had an inner diameter of ½ inch.



Figure 13: K-Power K-3000 gasoline-powered generator (Source: Own Work)



Figure 14: ILM VAC Type 40171 membrane compressor (Source: Own Work)

To interface the generator exhaust with the flexible tubing and allow gas flow control and measurement, a custom cylindrical manifold was fabricated at the UCLV workshop. The manifold was 3 inches in diameter and 12 inches in height. The inlet port, directly connected to the generator's exhaust outlet, had a 1-inch inner diameter. On the opposite side, the manifold had two outlet ports, each with a ½-inch inner diameter.



Figure 15: Manifold Outlets View (Source: Own Work)



Figure 16: Manifold Inlet View (Source: Own Work)



Figure 17: Manifold Side View (Source: Own Work)

One of the manifold outlets was connected to the compressor inlet via a ball valve (purchased in Belgium) to regulate the exhaust gas flow to the reactor. The second outlet served as a bypass for excess exhaust gas, vented outside using ½-inch tubing. An additional hole in the center of the circular wall of the manifold allowed the insertion of a flue gas sensor.



Figure 18: Manifold with Ball Valve ((Source: Own Work)

To secure the manifold to the generator, two metal mounting bars were welded onto the cylinder. These were initially misaligned and had to be repositioned by grinding and rewelding them at the correct angle.



Figure 19: Misaligned bars welded on Manifold (Source: Own Work)



Figure 20: Corrected Alignment of bars on Manifold, Flue gas meter in the manifold (Source: Own Work)

Gas composition at the generator outlet was measured using a Gasboard 3800P flue gas analyzer, capable of measuring SO_2 , NO , CO (in ppm), and O_2 and CO_2 (in %). In these experiments, only the CO_2 data was recorded.



Figure 21: Gasboard 3800P flue gas analyzer (Source: Own Work)

A second sensor, the SCD30 CO₂ meter, was placed in the outlet tube leading from the top of the reactor to outside the laboratory. This meter was capable of measuring CO₂ concentrations up to 40,000 ppm (4%), which limited its use but was the only sensor available. The sensor had a 20-second response time and was configured to log measurements every 30 seconds. The outlet tubing had an internal diameter of 1.5 inches.

The Vernier LabQuest 2 Data Logger, brought from the AMA to UCLV, was initially intended to be used as a pH meter during the experiments at UCLV as well. However, due to a malfunctioning sensor, it could not be used.

Figure 22 shows the complete experimental setup used at UCLV, with the exception of the final outlet tube, which is not visible in the image.



Figure 22: Entire setup at UCLV except final Outlet tube (Source: Own Work)

Figure 23 shows a schematic drawing of the setup, which provides a more structured and comprehensive overview of the experimental configuration.

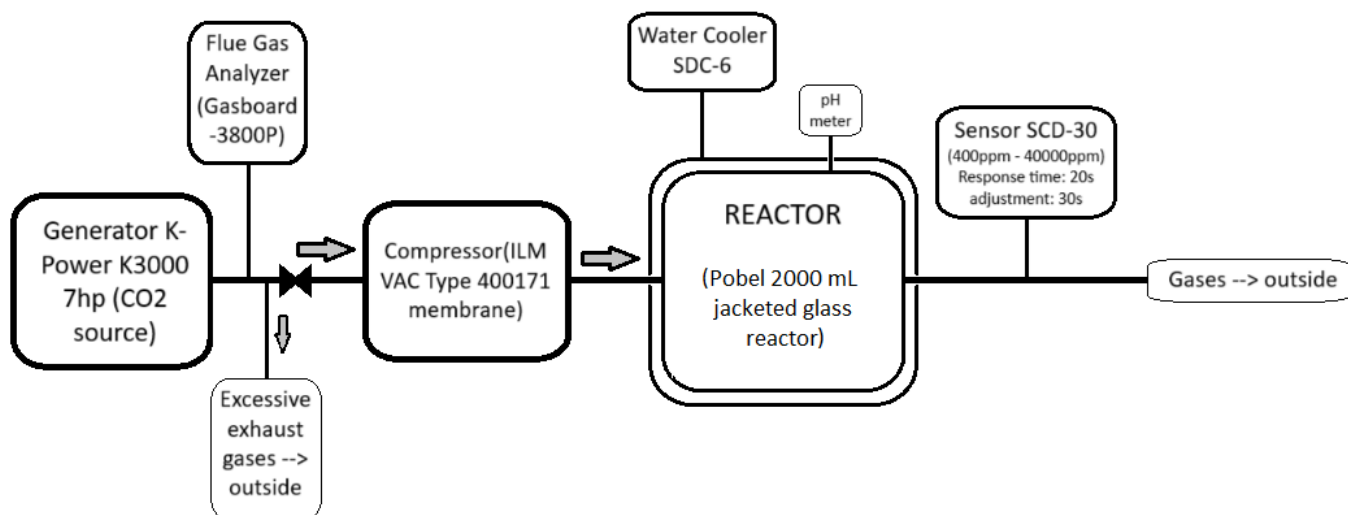


Figure 23: Simplified Drawing of the Entire Setup at UCLV (Source: Own Work)

Table 3: Inventory of Equipment and Key Specifications Used in the Experimental Setup (Source: Own Work)

No.	Component	Model / Description	Specifications / Notes	Supplier	Price per unit (€)	Quantity	Total price (€)
1	Flow Regulation	Ball valve	Installed between manifold and compressor inlet, ½ inch Ø stainless steel,	BV De Kinder	€38,82	1	€38,82
2	Reactor	Pobel Jacketed Glass Reactor (2000 mL)	Inner Ø 13 cm, liquid height 15 cm	N.A. Readily Available at UCLV	N.A. Readily Available at UCLV	1	N.A. Readily Available at UCLV
3	Cooling Unit	SDC-6 Water Cooler	Output near 0 °C, 1200 W power requirement			1	
4	Tubing (Cooler–Reactor)	Flexible PVC tubing	¾ “ inner diameter			2	
5	CO ₂ Source	K-Power K-3000 Generator	Gasoline-powered, 7 hp, 3000 W max AC			1	

6	Compressor	ILM VAC Type 40171 Membrane Compressor	Used to overcome hydrostatic pressure			1	
7	Tubing (Gas Lines)	Flexible PVC tubing	½ " inner diameter (inlet/outlet)			2	
9	Mounting System	Welded metal bars	Re-welded to correct alignment			2	
10	Flue Gas Analyzer	Gasboard 3800P	CO ₂ , O ₂ (%); SO ₂ , NO, CO (ppm); only CO ₂ used			1	
11	CO ₂ Sensor (Post-Reactor)	SCD30	Range: 0–40,000 ppm CO ₂ ; 20 s response time; 30 s logging interval			1	
12	Reactor Outlet Tubing	Flexible tubing	1.5 inch inner diameter			1	
13	pH meter	Vernier LabQuest 2 Data Logger		AMA		1	

3.2.2. Chemicals, Methods, and Measurements

To evaluate CO₂ capture efficiency using alkaline absorption, 5 experiments were performed using sodium hydroxide (NaOH) and calcium hydroxide (Ca(OH)₂) solutions at varying concentrations. All solutions were prepared by dissolving pure NaOH solid or Ca(OH)₂ powder in demineralized water. For each test, 2000 mL of solution was added to the jacketed glass reactor. After each run, the solution was removed from the reactor by siphoning, then the reactor was rinsed with clean water and siphoned again before the next solution was introduced.

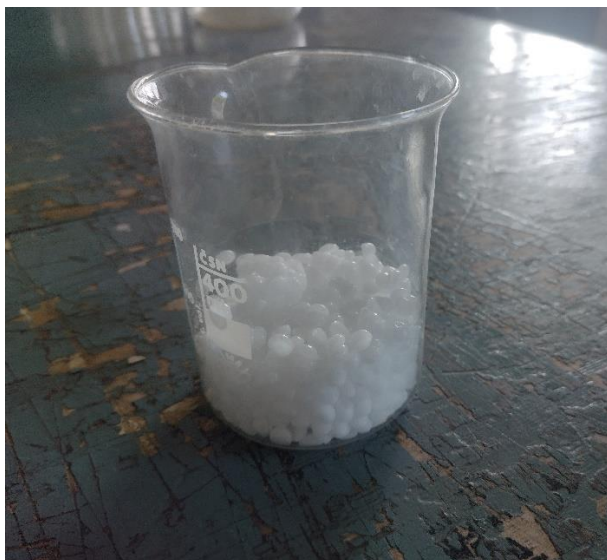


Figure 24: Beaker with pure NaOH Pellets (Source: Own Work)



Figure 25: Beaker & Container with pure NaOH Pellets (Source: Own Work)

The following experimental configurations were used:

- **UCLV Experiment 0(discarded) → 5% NaOH:** Performed early on with only a pH meter (which malfunctioned) measuring the solution inside the reactor. The CO₂ sensor (SCD30) at the reactor outlet was not yet present. This configuration was discarded because no usable data was obtained from this trial.
- **UCLV Experiment 1 → 10% NaOH:** Full measurement setup used: both CO₂ sensors installed and post-reaction titration conducted.
- **UCLV Experiment 2 → 20% NaOH:** Same procedure as above with increased NaOH concentration.
- **UCLV Experiment 3 → 10% Ca(OH)₂:** Full test performed under identical conditions with calcium hydroxide.
- **UCLV Experiment 4 → 20% Ca(OH)₂:** Final test using increased Ca(OH)₂ concentration.

The manifold after the generator, split the exhaust flow into two paths: one toward the reactor, and the other vented outside. This was necessary because the sensor placed after the reactor (SCD30) had a maximum detection limit of 40,000 ppm (4%). If the CO₂ concentration exceeded that limit, the sensor could no longer provide valid readings — hence, the exhaust stream was partially bypassed to reduce CO₂ levels entering the reactor.

Gas concentrations were measured at two locations:

- Before the reactor, using a Gasboard 3800P flue gas analyzer, capable of measuring SO₂, NO, and CO in ppm, and CO₂ and O₂ in percentage.
- After the reactor, using a SCD30 CO₂ sensor, limited to 40,000 ppm, with a 20-second response time and 30-second measurement interval.

These devices measured only the concentration of CO₂ at their respective points, but not the gas flow rate. As a result, although the difference between pre- and post-reactor CO₂ readings indicated whether capture occurred, it was not possible this way to quantify the exact fraction of total CO₂ that was captured. In addition to the lack of flow measurement, gas leaks occurred at the connection between the generator exhaust and the manifold, due to high temperatures and lack of available sealing materials rated for high exhaust temperatures.

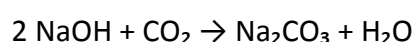
Due to a faulty pH-sensor, real-time pH measurements during the experiment could not be obtained. Instead, CO₂ uptake was quantified indirectly after each test through acid-base titration using methyl orange. This allowed determination of the amount of unreacted base (NaOH or Ca(OH)₂) remaining in the solution. A standardized hydrochloric acid solution of 1 mol/L was used to neutralize the remaining unreacted base. For NaOH, the product formed is Na₂CO₃; for Ca(OH)₂, it is CaCO₃. This method provided the most reliable estimate of total CO₂ captured during each experiment.

A known and fixed volume of the base solution was used in each titration. The volume of HCl added was used to calculate the final concentration of unreacted base as follows:

- For NaOH (1:1 stoichiometry with HCl):
Final concentration (mol/L) = Volume of HCl added (mL) ÷ V_{sample} (mL)
- For Ca(OH)₂ (1:2 stoichiometry with HCl):
Final concentration (mol/L) = Volume of HCl added (mL) ÷ (2 × V_{sample} (mL))

where V_{sample} refers to the volume of the base solution used for titration.

Based on the chemical reaction:



the number of moles of CO₂ captured was calculated from the change in alkali concentration using:

$$\Delta n(\text{NaOH}) = n(\text{initial}) - n(\text{final})$$

$$n(\text{CO}_2) = \Delta n(\text{NaOH}) \div 2$$

Titration data are presented in the accompanying Table 8, showing for each test: the volume of HCl added, the final concentration of the solution, and the estimated CO₂ uptake.

Standard laboratory safety precautions were followed when handling corrosive chemicals such as NaOH and Ca(OH)₂. Exhaust gases were handled outdoors, and appropriate protective equipment was used during experimental operations.

3.3. Purchased Materials Not Used in the Final Experiments

In preparation for the experiments at AMA and at UCLV in Cuba, a variety of materials and equipment were purchased in Belgium to ensure operational flexibility. Regarding the UCLV, this precaution was taken due to communication delays and uncertainty regarding the availability of technical resources at the UCLV and in Cuba in general. At the time, it was not yet clear which specific experimental setups would be feasible, and reliable information on the local availability of laboratory materials was limited. Furthermore, the transport between countries for certain items, such as gas cylinders, was not possible due to air travel and customs restrictions.

To mitigate these uncertainties and avoid potential delays, additional components were acquired based on the anticipated needs and logistical risks. Once on-site in Cuba however, the equipment already available at the UCLV, as well as supplementary items found locally, proved mostly sufficient for the execution of the planned experiments.

Certain items in this list were originally intended for experiments planned at the Antwerp Maritime Academy (AMA), but these experiments were ultimately not conducted due to time constraints and the absence of a sufficiently safe laboratory environment relative to the potential risks of the experiments considered at the certain time.

As a result, the vast majority of these materials originally purchased in Belgium were ultimately not used, and kept in the laboratories at the UCLV and the AMA, available for potential future researches.

These items are listed in the following inventory table.

Table 4: Inventory of materials purchased but not used in the experiments (Source: Own Work)

Name	Supplier	Price per unit (€)	Quantity	Total price (€)
Nitril gloves XL (<i>Partially used during multiple experiments</i>)	HUBO	€ 11,99	1	€ 11,99
PVC pipe Ø 125mm Max. 16 Bar	BV De Kinder	€ 59,04	1	€ 59,04
Sodastream CO ₂ Quick-Connect cylinders	Bol.com	€ 26.51	2	€ 53,02
Adapter for Sodastream Quick-Connect	CO ₂ Supermarket	€ 49,00	1	€ 49,00
Advanced Adapter for Sodastream Quick-Connect	CO ₂ Supermarket	€ 85,78	1	€ 85,78
Teflon Yellow Approved Gastec Tape	BV De Kinder	€ 3,32	4	€ 13,26
Gardena Classic Garden Sprayer	BV De Kinder	€ 9,79	1	€ 9,79
Pvc Ball Valve Mega Safe 20mm 10bar	BV De Kinder	€ 9,20	2	€ 18,39
Stainless Steel Hose Nozzle 1/2" X 15mm	BV De Kinder	€ 4,14	1	€ 4,14
Repair Connector For 13mm And 15mm Gardena	BV De Kinder	€ 5,29	1	€ 5,29
Clamp Ring Stainless Steel 12–22mm (<i>Mostly used in UCLV</i>)	BV De Kinder	€ 0,81	8	€ 6,49
Angle Funnel 460mm 1.2l With Strainer Pressol	BV De Kinder	€ 12,50	1	€ 12,50
Funnel Pe 150mm 0.7l	BV De Kinder	€ 3,48	1	€ 3,48
Pressure Sprayer Tukan 5l Gloria	BV De Kinder	€ 19,88	1	€ 19,88

Pressure Sprayer 1.25l Gardena	BV De Kinder	€ 26,60	1	€ 26,60
Tap Connector – 2 Outlets 1" Gardena	BV De Kinder	€ 15,79	1	€ 15,79
Adjustable Sprayer – Brass Hollow Cone Nozzle	BV De Kinder	€ 21,39	2	€ 42,79
Premium Hose Connector 19mm (3/4") Gardena	BV De Kinder	€ 12,69	2	€ 25,39
Hand Shower Belem 1 Jet Chrome Ridder	BV De Kinder	€ 6,78	1	€ 6,78
Control Valve Gardena	BV De Kinder	€ 15,65	1	€ 15,65
Superflex Hose 12x12 1/2"–20m Gardena	BV De Kinder	€ 65,49	1	€ 65,49
Flexible Spout Of Metal 300mm Pressol	BV De Kinder	€ 8,11	1	€ 8,11
Wolfcraft Drill-operated pump Ø 13 mm, max. 1300l/h	BV Geboorte bedankjes	€ 39,95	1	€ 39,95
Wolfcraft Drill-operated pump Ø 19 mm, max. 3000l/h	Amazon	€ 34,82	1	€ 34,82
SWAWIS Submersible Water Pump, DC 12V Brushless Motor 800L/H Ceramic Core <i>(Used by other student for research)</i>	Amazon	€ 23,87	1	€ 23,87
100 pieces of 11mm glue sticks for hot glue gun	Bol	€ 33,90	1	€ 33,90
Transparent reinforced hose 40x49 mm	BV De Kinder	€ 29,57	1	€ 29,57
DEMAK UP Expert Cotton makeup removal pads 5x70 pieces	BWN Belgium	€ 19,98	5	€ 99,90

All of the purchased materials in this study, including the purchased materials that were used, which can be found in other tables than the one above, were financially covered using research funds made available by co-supervisor Olivier Schalm.

The following chapter presents the experimental results obtained through the procedures and setups described above.

4. Results

4.1. AMA Experiment 1 (Test 3) 3,61 wt%

During the third test of the Belgian experiment, the pH of the sodium hydroxide solution was measured over time while CO₂ was bubbled into the beaker. The initial NaOH concentration was approximately 0.94 mol/L (3,61 wt%). A digital pH meter (Vernier Labquest 2 Data Logger) was used to record the pH at specified intervals.

The following table summarizes the recorded values:

Table 5: Results of Test 3, AMA experiment (Source: Own work)

Time (in minutes)	pH level
0	13,5
1	13,45
2,5	13,42
5	13,23
10	12,71
15	11,55
20	10,5
25	10,3
35	10
50	9,72

A graphical representation of the data is shown in the following figure.

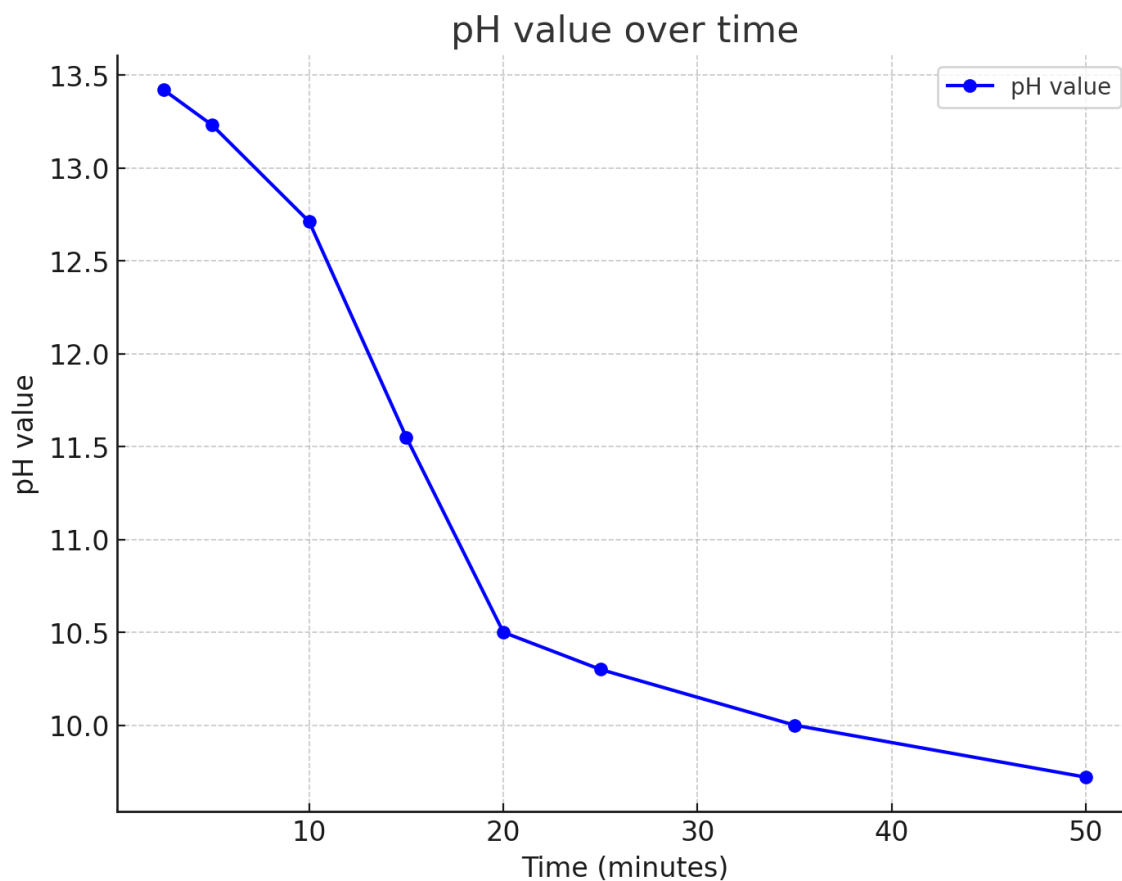


Figure 26: Results of Test 3, AMA experiment (Source: Own work)

Based on the final pH measurement after 50 minutes (pH = 9.72), stoichiometric calculations are used to estimate how much NaOH had reacted, how much CO₂ was captured, and how much sodium carbonate (Na₂CO₃) was formed during the experiment.

The initial amount of NaOH is calculated from the mass used:

$$n(\text{NaOH initial}) = 4.5 \text{ g} \div 40.0 \text{ g/mol} = 0.1125 \text{ mol}$$

Using the final pH value, the hydroxide ion concentration was determined:

$$[\text{OH}^-] = 10^{-(14 - 9.72)} = 1.905 \times 10^{-5} \text{ mol/L}$$

With a solution volume of 120 mL (0.120 L), the remaining amount of NaOH was:

$$n(\text{NaOH remaining}) = 1.905 \times 10^{-5} \text{ mol/L} \times 0.120 \text{ L} = 2.29 \times 10^{-6} \text{ mol}$$

Thus, the amount of NaOH that reacted over the 50-minute period was:

$$n(\text{NaOH reacted}) = 0.1125 \text{ mol} - 2.29 \times 10^{-6} \text{ mol} \approx 0.1125 \text{ mol}$$

From the balanced chemical equation ($2 \text{ NaOH} + \text{CO}_2 \rightarrow \text{Na}_2\text{CO}_3 + \text{H}_2\text{O}$), the amount of CO_2 captured is half the amount of NaOH reacted:

$$n(\text{CO}_2 \text{ captured}) = 0.1125 \text{ mol} \div 2 = 0.05625 \text{ mol}$$

As the CO_2 reacts with NaOH in a 1:1 molar ratio to produce sodium carbonate, the amount of Na_2CO_3 formed is also:

$$n(\text{Na}_2\text{CO}_3 \text{ formed}) = 0.05625 \text{ mol}$$

In summary, the results of Test 3, with a 120mL solution of 3,61 wt% NaOH, after 50 minutes:

Table 6: Derived results of AMA Experiment 1

Description	Amount (mol)	Amount (g)
NaOH consumed	0.1125	4.5
CO_2 captured	0.05625	2.476
Na_2CO_3 formed	0.05625	5.962

4.2. UCLV Experiments

This section presents the results obtained during the experiments conducted at UCLV in Cuba. The CO_2 concentration was measured over time at the reactor outlet for each of the four alkaline solution configurations: 10% and 20% NaOH, and 10% and 20% $\text{Ca}(\text{OH})_2$. The measurements were taken using the SCD30 sensor and are shown in the graph in Figure 27.

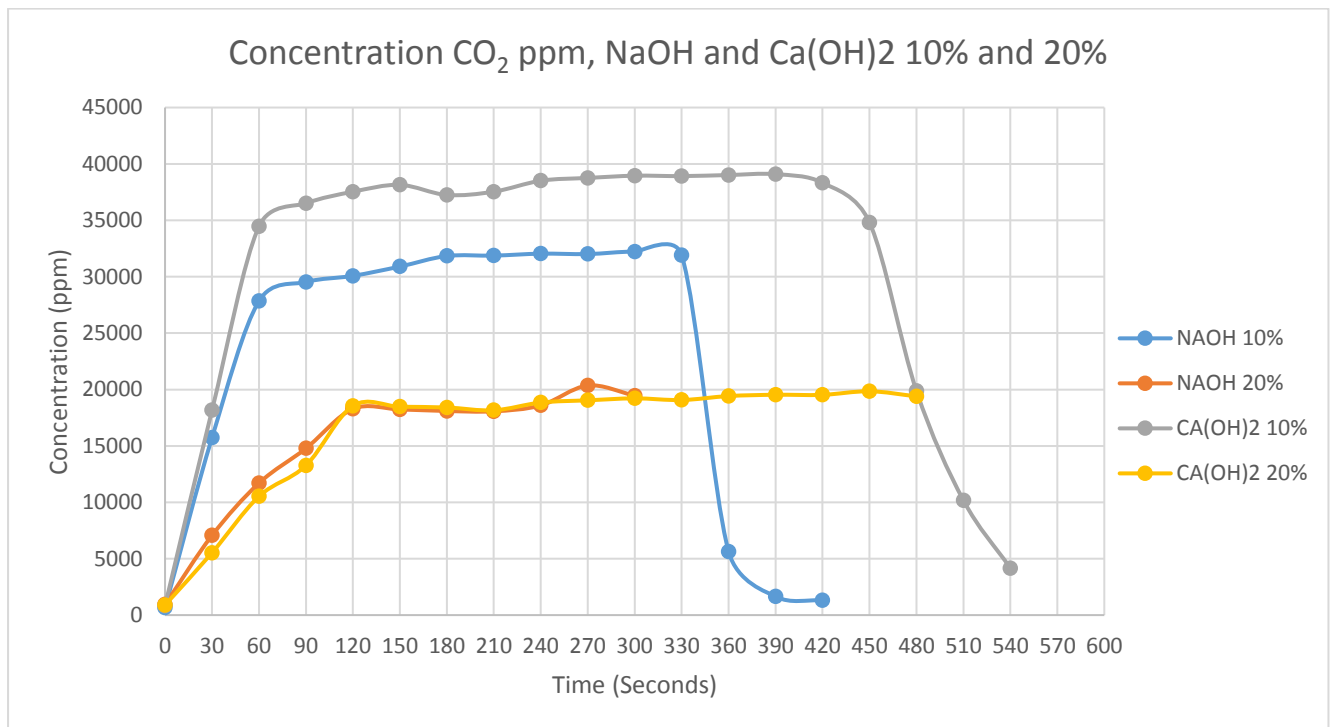


Figure 27: CO_2 concentration (ppm) over time for NaOH and $\text{Ca}(\text{OH})_2$ solutions at 10% and 20% wt. concentration. Measured at the reactor outlet using the SCD30 sensor. (Source: Own Work, assistance by Prof. Liset Roche Delgado)

The data presented in the graph above are derived from the table shown below.

Table 7: CO₂ concentration (ppm) over time for NaOH and Ca(OH)₂ solutions at 10% and 20% wt. concentration. Measured at the reactor outlet using the SCD30 sensor. (Source: Own Work, assistance by Prof. Liset Roche Delgado)

Time(Seconds)	Concentration (ppm)			
	NaOH 10%	NaOH 20%	Ca(OH) ₂ 10%	Ca(OH) ₂ 20%
0	647	937	827	897
30	15724	7061	18158	5523
60	27849	11700	34466	10528
90	29531	14778	36506	13267
120	30075	18279	37536	18550
150	30902	18233	38143	18472
180	31838	18096	37249	18405
210	31873	18068	37540	18158
240	32043	18589	38512	18845
270	32011	20351	38759	19042
300	32222	19460	38957	19215
330	31918		38922	19068
360	5626		39016	19420
390	1652		39090	19535
420	1296		38326	19527
450			34815	19845
480			19877	19396
510			10172	
540			4162	

The CO₂ concentration measured before the reactor using the Gasboard 3800P remained consistently within the range of 8.3% to 9.3% (equivalent to 83,000 – 93,000 ppm) while the generator was operating. Exact measurements at 30-second intervals were not recorded, as such detail was not relevant for assessing CO₂ capture performance. The variation within this range was considered negligible and, even if logged with the same frequency as the SCD30 sensor, would not have provided meaningful additional insight into the amount of CO₂ captured versus unreacted CO₂ passing through the system.

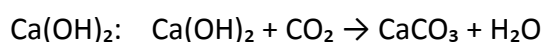
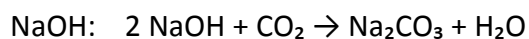
In addition to concentration measurements of the flows of the gases before and after the reactor, titration was performed on each solution after the experiment to estimate how much of the base had reacted. The resulting final concentrations are presented in Table 8.

Table 8: Final concentrations of NaOH and Ca(OH)₂ after CO₂ absorption, based on titration with methyl orange (Source: Own Work, assistance by Prof. Liset Roche Delgado)

Solution Type	Trial	Volume HCl (mL)	Final Concentration (mol/L)
10% NaOH	1	0.90	0.018
	2	0.85	0.017
	3	0.90	0.018
10% NaOH	Average	—	0.01767
20% NaOH	1	1.50	0.030
	2	1.60	0.032
	3	1.60	0.032
20% NaOH	Average	—	0.03133
10% Ca(OH) ₂	1	1.50	0.030
	2	1.35	0.027
	3	1.25	0.025
10% Ca(OH) ₂	Average	—	0.02733
20% Ca(OH) ₂	1	5.30	0.106
	2	5.30	0.106
	3	5.20	0.104
20% Ca(OH) ₂	Average	—	0.10533

Based on the titration results in Table 5, the amount of CO₂ captured in each experiment was calculated by comparing the known initial quantity of base with the remaining concentration measured after the test. All alkaline solutions were prepared by weight percentage: 10 wt% and 20 wt% NaOH or Ca(OH)₂ dissolved in 2.0 L of solution. From this, the moles of base initially present, the moles consumed, and the resulting CO₂ capture were determined.

The following chemical reactions were used:



Step-by-Step Example: 10% NaOH:

- Initial mass of NaOH: 200 g
- Molar mass of NaOH: 39.997 g/mol (~0.04 kg/mol)
- Moles of NaOH initially present: $200 \div 0.04 = 5.000 \text{ mol}$
- Final concentration of NaOH after experiment: 0.01767 mol/L
- Final moles remaining in 2.0 L: $0.01767 \times 2.0 = 0.03534 \text{ mol}$
- Moles of NaOH consumed: $5.000 - 0.03534 = 4.96466 \text{ mol}$
- Grams of NaOH consumed: $4.96466 \times 39.997 = 198.59 \text{ g}$
- Moles of CO₂ captured (NaOH ÷ CO₂ = 2 ÷ 1): $4.96466 \div 2 = 2.48233 \text{ mol}$
- Grams of CO₂ captured: $2.48233 \times 44.01 = 109.26 \text{ g}$
- Grams of Na₂CO₃ formed: $2.48233 \times 105.99 = 263.12 \text{ g}$

As a result of these calculations, the following values were obtained for each experimental configuration.

Table 9: CO₂ Capture Results Based on Titration Data (Source: Own Work)

Experiment	Base Consumed (g)	CO ₂ Captured (g)	Carbonate Formed (g)
10% NaOH	198.59	109.26	263.12
20% NaOH	397.49	218.69	526.67
10% Ca(OH) ₂	195.95	116.39	264.70
20% Ca(OH) ₂	384.39	228.32	519.26

The following chapter discusses the significance of these results, comparing the performances of the tested absorbents and addressing key experimental observations and limitations.

5. Discussions

5.1. AMA experiment 1 (Test 3) 3,61 wt%

The pH curve shown in Figure 26 provides clear evidence that a chemical reaction took place between the sodium hydroxide solution and the bubbled CO₂ gas. The overall downward trend in pH demonstrates the progressive neutralization of hydroxide ions, indicating the formation of carbonate (Na₂CO₃) and potentially bicarbonate (NaHCO₃) species.

While the reaction was visibly progressing, the rate of pH decrease suggests that it occurred at a relatively slow pace under the given conditions. The most rapid pH decline occurred between 10 and 20 minutes into the experiment, during which the pH dropped by approximately 2.25 units. This implies a temporary acceleration of the reaction rate, likely due to the increasing CO₂ saturation in the solution reaching a threshold that enabled more effective conversion.

Quantitative calculations based on the final pH value (9.72) after 50 minutes indicate that approximately 0.1125 mol of NaOH was consumed. From the stoichiometric relationship (2 NaOH : 1 CO₂), this corresponds to an estimated 0.05625 mol of CO₂ captured and 0.05625 mol of Na₂CO₃ formed. These values confirm that nearly all of the initial NaOH (4.5 g) reacted during the experiment, demonstrating high conversion under batch conditions despite relatively slow kinetics.

It is important to note that this experiment was performed in a batch configuration with a fixed quantity of NaOH and CO₂, rather than in a continuous-flow system. As such, the reaction was limited both by the availability of reactive surface area and by the gas-liquid interaction time.

Regarding the gas-liquid interaction itself, only the outer molecular layer of each CO₂ bubble is in direct contact with the solution at any moment. The vast majority of CO₂ molecules within each bubble remain unreacted as they rise through the liquid. This limited contact area greatly reduces absorption efficiency. Moreover, as previously mentioned, a portion of the CO₂ may dissolve into the liquid phase without immediately reacting. These dissolved molecules can later react gradually with hydroxide ions, leading to a continued pH decrease over time as the system approaches chemical equilibrium.

This behavior is consistent with literature findings on gas-liquid CO₂ absorption processes, where the efficiency of mass transfer is influenced by droplet size, gas residence time, and interfacial area [2, 6].

In the absence of atomization or surface renewal (e.g., through agitation or fine dispersion), such systems tend to exhibit slow and incomplete reactions, especially at moderate pH values.

5.2. UCLV Experiments

The experiments conducted at UCLV provided important insights into the CO₂ absorption performance of NaOH and Ca(OH)₂ solutions at different concentrations, as well as the limitations and practical considerations of the experimental setup.

During UCLV Experiment 0 (5% NaOH), the pH appeared to remain at approximately 13,5 even after 30 minutes, suggesting that no reaction was taking place. This was initially attributed to the significantly lower CO₂ concentration in the generator exhaust (approximately 8.5–9%) compared to the 100% pure CO₂ used in the AMA experiments. It was hypothesized that the reaction rate was directly proportional to the CO₂ concentration and would therefore be approximately 11 times slower. However, it was later discovered that the pH sensor used in Experiment 0 was malfunctioning. Titration results obtained after subsequent experiments confirmed that CO₂ had in fact been captured, thereby invalidating the initial hypothesis.

For UCLV Experiments 1 through 4, CO₂ concentration was monitored before and after the reactor using the Gasboard 3800P and SCD30 sensors, respectively. Although the exact gas flow rate through the reactor was not measured, the CO₂ concentration before the reactor was consistently between 83,000 and 93,000 ppm. By comparing this to the SCD30 readings at steady state, approximate CO₂ capture efficiencies solely of the flue gas which passes through the reactor, can be estimated.

For example, in the 10% NaOH experiment, the steady-state CO₂ concentration after the reactor was around 32,000 ppm as seen in figure 27. Given an input concentration of approximately 87,000 ppm, this suggests that roughly 63% of the CO₂ was captured. Similarly, the 20% NaOH experiment stabilized at around 18,500 ppm, corresponding to a capture estimate of approximately 79%. The 10% Ca(OH)₂ and 20% Ca(OH)₂ experiments showed approximate capture efficiencies of 55% and 78%, respectively. While NaOH appeared to perform slightly better than Ca(OH)₂ overall, the difference was more pronounced at 10% concentration. At 20%, the performance difference became negligible.

It should be noted, however, that these estimations are based solely on the concentration of gas entering and leaving the reactor and do not account for the portion of flue gas that bypassed the system via the secondary outlet of the manifold. Additionally, minor gas leaks were present at the

connection between the generator and the manifold, as well as at the insertion point of the Gasboard sensor. These factors contributed to uncertainty in the actual gas flow through the reactor.

Despite these limitations, the slope coefficients of the SCD30 curves were nearly identical for both NaOH and $\text{Ca}(\text{OH})_2$ at equivalent concentrations. A consistent trend was observed: solutions at 20% concentration exhibited slower rises in CO_2 ppm values and took approximately twice as long to stabilize. This is likely due to their greater CO_2 absorption capacity. The higher concentration solutions were able to capture more CO_2 during the initial increase in flue gas, resulting in a slower rise and less steep slope in the measured ppm curves.

Additionally, while both absorbents were effective, NaOH may be more suitable for continuous operation. Na_2CO_3 is highly soluble and unlikely to cause clogging, whereas CaCO_3 is poorly soluble and prone to precipitating in tubing, which increases the risk of blockages. This aligns with general findings in the literature, which show that calcium carbonate buildup can pose maintenance challenges in flow systems [2].

To prevent the SCD30 sensor from exceeding its maximum measurement threshold of 40,000 ppm, the CO_2 flow into the reactor was partially restricted using a ball valve. This measure helped maintain a suitable gas-to-liquid (G/L) ratio, which, if too high, would have led to reduced CO_2 capture efficiency and sensor saturation.

Unfortunately, due to the lack of gas flow measurement equipment, it was not possible to compare CO_2 absorption efficiency relative to the total CO_2 emitted by the generator. Attempts to estimate generator fuel consumption before and after each run were deemed too unreliable for meaningful interpretation, due to inconsistencies in residual fuel volumes and fuel recovery limitations.

Some ppm drops observed in the SCD30 graph—particularly in the 10% NaOH and 10% $\text{Ca}(\text{OH})_2$ experiments—occurred when the generator was shut off while the sensor remained on. During the 20% concentration experiments, the sensor was turned off before shutting down the generator, avoiding this artifact seen in figure 27.

Despite these limitations, the titration results provided reliable post-experimental data on base consumption and CO_2 capture. As detailed in the Results chapter, 20% NaOH and 20% $\text{Ca}(\text{OH})_2$ captured nearly identical amounts of CO_2 (109.26 g and 116.39 g, respectively), with NaOH performing slightly better in terms of measured ppm concentration. However, as stated before, due to the lack of gas flow measurements, this data does not tell us anything about CO_2 % capture

efficiency. Interestingly, the 10% $\text{Ca}(\text{OH})_2$ experiment resulted in slightly higher total CO_2 capture than the 10% NaOH trial (116.39 g vs. 109.26 g), despite the latter showing lower outlet ppm during operation. This discrepancy is most likely due to a higher gas flow rate during the $\text{Ca}(\text{OH})_2$ test, highlighting once again the importance of accurate flow control in future experiments.

While pH measurement could not be used in these trials due to sensor malfunction, it would not have enabled accurate quantification of CO_2 captured without known flow rates. Attempts to estimate CO_2 generation based on fuel usage were also deemed unfeasible due to the imprecision of gasoline measurements under these conditions.

Nevertheless, the main objective of this phase of the thesis was achieved: to demonstrate that CO_2 can indeed be captured using a basic, fast-prototyped system under realistic field conditions. Despite the challenges and limitations, the experiments conducted at UCLV successfully validated the concept and yielded measurable results.

5.3. Recommendations for Future Buildup Research

Building on the results and insights obtained from this study, several avenues for future research are recommended to optimize the system, validate its robustness, and assess its real-world applicability.

- Additional experiments should be conducted using the current setup with a broader range of concentrations. Testing higher NaOH concentrations such as 40% or 50% could provide valuable insight into how increased reagent strength affects CO_2 absorption dynamics, reaction rate, and overall system behavior.
- Future trials should include improved gas flow control and measurement equipment. The use of mass flow meters or rotameters would allow for more accurate determination of CO_2 capture efficiency as a percentage of the total emitted gas.
- High-range CO_2 sensors (with a detection limit above 40,000 ppm) should be implemented to avoid sensor saturation and ensure more accurate post-reaction measurements.
- Improved pH monitoring is recommended, either by using a high-temperature- and corrosion-resistant pH probe or by introducing an automated titration system for post-experiment analysis.

- The current bubbling-based reactor configuration allows for only limited gas-liquid contact, as only the outer molecular layers of CO₂ bubbles are in direct interaction with the solution. This constrains mass transfer and reduces capture efficiency. Future research should either explore ways to minimize the size of the bubbles and/or explore alternative reactor designs that offer a greater interfacial area between the gas and liquid phases. Options such as spray columns, packed towers, or fine dispersion systems (e.g., membrane contactors) could enhance CO₂ absorption by increasing the effective surface area and improving overall mass transfer rates [2,7].
- The system should be adapted to continuous or semi-continuous operation instead of a batch-process. This includes integrating automated fluid handling, gas delivery, and product separation components.
- The separation of the carbonate product (Na₂CO₃ or CaCO₃) from the liquid phase must be studied in detail, particularly in preparation for continuous flow applications. Reliable solid-liquid separation methods such as sedimentation, filtration, or crystallization should be explored.
- The long-term behavior of the system under continuous flow conditions should be evaluated. Ca(OH)₂ poses a known risk of clogging due to CaCO₃ precipitation, while Na₂CO₃ is far more soluble and less likely to obstruct fluid pathways. The impact of this difference on maintenance and system stability should be investigated further.
- Regeneration techniques for NaOH from Na₂CO₃, such as electrochemical or thermal regeneration, should be examined to improve sustainability and reduce ongoing reagent costs.
- Future experiments should include realistic flue gas conditions, such as those from marine diesel engines or industrial exhaust streams. This will allow assessment of material durability, CO₂ capture rates, and the influence of flue gas contaminants on system performance.
- The economic viability of the process must be carefully evaluated. Key factors include the cost of NaOH, energy consumption, the market value of the resulting carbonate product, and the potential for reagent regeneration. If the value of the final product can exceed or justify the operational costs, the system could become attractive for industrial implementation on a voluntary basis, without requiring regulatory enforcement.

- Future work should investigate which final carbonate product—sodium carbonate (Na_2CO_3) or sodium bicarbonate (NaHCO_3)—is preferentially formed under different reaction conditions. From a stoichiometric standpoint, only one mole of NaOH is required to produce one mole of NaHCO_3 , while two moles are consumed to produce one mole of Na_2CO_3 . Additionally, NaHCO_3 tends to have a higher market value per kilogram than Na_2CO_3 [4], making it potentially more attractive from an economic perspective. However, NaHCO_3 poses greater challenges in storage and stability. Literature confirms that sodium bicarbonate is thermodynamically less stable at elevated temperatures and can undergo decomposition, releasing CO_2 and forming Na_2CO_3 and water. This decomposition generally accelerates above $\sim 50\text{--}80\text{ }^\circ\text{C}$ [4]. Onboard systems—particularly on ships operating in tropical climates—may require active temperature control to avoid premature product degradation. The energy and infrastructure required for proper storage could therefore possibly offset the higher product value of NaHCO_3 . These trade-offs between chemical yield, energy input, market value, and storage cost must be evaluated through a techno-economic assessment. If a CO_2 capture system can be optimized to primarily produce NaHCO_3 under stable conditions, and the energy cost of storage is acceptably low, the entire system could become economically viable. Such a system would not only offer environmental benefits but also present commercial incentives, potentially making regulatory enforcement unnecessary for adoption.

6. Conclusion

This thesis investigated the feasibility of capturing and converting CO₂ emissions into sodium carbonate (Na₂CO₃) using aqueous sodium hydroxide (NaOH) solutions in a simplified, fast-prototyped reactor setup. The central objective was to determine whether a small-scale system, built with readily available materials and equipment, could successfully demonstrate the fundamental chemical absorption reaction under realistic conditions.

Initial proof-of-concept testing at the AMA confirmed the occurrence of the reaction between NaOH and CO₂, as evidenced by the progressive decline in pH and supported by stoichiometric calculations based on final pH values. These calculations showed that nearly all of the NaOH in the solution was consumed over the course of the experiment, leading to the formation of Na₂CO₃. However, the observed reaction rates were notably slower than originally anticipated.

Subsequent experiments conducted at the UCLV in Cuba provided further insight using a more advanced setup involving real exhaust gases. Both NaOH and calcium hydroxide (Ca(OH)₂) were tested at 10% and 20% weight concentrations. Although limitations in gas flow measurement and sensor ranges precluded exact efficiency calculations, CO₂ concentration trends and post-reaction titrations clearly demonstrated that significant capture occurred in all tests. The highest levels of CO₂ captured, as calculated from titration results, exceeded 200 grams in the 20% solution experiments.

These experiments confirmed that NaOH was slightly more effective than Ca(OH)₂ in terms of capture efficiency. In addition, NaOH offers greater compatibility with continuous flow systems due to the higher economical value and higher solubility of its carbonate product, Na₂CO₃, which minimizes the risk of clogging, which is an issue observed with CaCO₃ precipitating from Ca(OH)₂.

Although full-scale optimization, automation, and economic analysis fall outside the scope of this project, this thesis has successfully demonstrated that CO₂ capture and transformation to carbonate salts is possible using basic tools, under field conditions, and with flue gas from a combustion engine. The experiments provide a strong proof of principle for further research into onboard CO₂ capture systems, especially for maritime applications where emission reduction targets continue to tighten.

Ultimately, this work not only reaffirms the chemical validity of NaOH-based carbon capture but also showcases its practical viability, serving as a small but meaningful step toward turning CO₂ from an environmental burden into a potentially valuable industrial resource.

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