Constructing and Developing a Technology to Capture SO_2 from Exhaust Gas

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Abstract - *Sulfur dioxide (SO_2) emissions pose significant environmental and health hazards, necessitating effective mitigation strategies. This thesis explores the design and development of a novel SO_2 capturing system tailored for scenarios where the availability of pure SO_2 is restricted due to regulatory constraints. The absence of pure SO_2 presents a challenge, as conventional absorption methods rely on its direct utilization. However, by leveraging alternative sources and enhancing absorption efficiency, this study proposes a viable solution. The addition of calcium carbonate ($CaCO_3$) to the absorption process is a key component of this study. One easily accessible compound, $CaCO_3$, shows promise as a catalyst for SO_2 absorption reactions, making up for the absence of pure SO_2. The study methodology includes theoretical modeling, experimental validation, and system optimization to elucidate the mechanisms underlying the enhanced absorption kinetics enabled by $CaCO_3$. The thesis clarifies the function of $CaCO_3$ in catalyzing the reaction kinetics by first looking at the basic ideas guiding SO_2 absorption mechanisms. By means of extensive testing, the effects of different parameters. The results of this study advance our knowledge of SO_2 capture technologies, especially in situations where the availability of pure SO_2 is limited. The importance of CaCO3 as a catalyst in SO_2 absorption reactions is highlighted in this work, which offers insightful information for the planning and creation of effective and long lasting SO_2 mitigation techniques. In the end, the suggested system might provide a viable way to address SO_2 emissions and lessen their detrimental effects on the environment and public health.*

Key Words: **Sulphur Dioxide, Emissions, Air pollution, Greenhouse Gases, Industrial Processes, Calcium Carbonate, Ionic Solutions, Environmental Pollution**

1. INTRODUCTION

Sulfur dioxides, like nitrogen oxides, carbon monoxide, and non-methane volatile organic compounds (VOC_s), are classified as indirect greenhouse gases. Through a chemical process or by altering the Earth's ability to balance radiative radiation, an indirect greenhouse gas contributes to atmospheric warming. A growing number of people are interested in developing workable strategies to lower air pollution because of concerns about environmental pollution and its negative effects on ecosystems and public health. Emissions of sulfur dioxide, or SO_2, which are mostly caused by industrial processes and the burning of petroleum and other fossil fuels, are a major cause of air pollution and acid rain. In this regard, lowering these environmental issues now depends on removing and absorbing sulfur dioxide. Human-caused emissions in the United States as of 2020 are primarily from burning fuel, accounting for around 1.8 million short tons of sulfur dioxide annually (compared to slightly over 6 million short tons in 2011). The largest emitters of emissions are power plants, commercial and institutional boilers, internal combustion engines, manufacturing, and industrial processes like metal processing and petroleum refining. Diesel engines found in old buses and trucks, locomotives, ships, and off-road equipment like construction vehicles are next in line for emissions. Over the next years, when many of these sources are cleaned up, sulfur dioxide emissions will decrease. This thesis examines the significance of using calcium carbonate to trap sulfur dioxide, with a focus on the project's background, problem statement, aims, and scope. In this context, this report aims to provide a comprehensive overview of the SO_2 capture process using ionic solutions, highlighting the various aspects of the process from the preparation of the materials to the reactor vessel setup and the efficiency of the system. The report will also discuss the results and recommendations for future research in this area. In a fixed bed reactor, the mechanism of activated carbon-based SO_2 removal was studied. On SO_2 adsorption, the effects of concentrations of SO_2, O_2, and H_2O as well as adsorption temperature were investigated. The findings indicate that the initial adsorption rate of SO_2 rises as SO_2 concentration rises, but falls as adsorption temperature rises. For SO_2, the reaction order is 0.896 when SO_2 is pulled in at 65° C. The initial adsorption rate constant of SO_2 and its reaction order steadily decrease as adsorption proceeds. temperature rising and the SO_2 initial adsorption stage activation energy of -16.344 kJ/mol, suggesting that SO_2 adsorption is unfavorable at higher temperatures on activated carbon, and the rate-limiting step is SO_2 adsorption [1].

Absorption of CO_2 in aqueous suspensions of $Ca(OH)_2$ with the addition of a suitable additive at 27 °C and 1 bar resulted in high surface area and porous $CaCO_2$ particles. The primary particles' size and shape played a major role in determining the $CaCO_2$ surface area. The $CaCO_3$ surface area varied with the initial $Ca(OH)_2$ concentration in the absence of any additive, reaching its maximum value (19.6 m^2/g) at 2.4 weight percent $Ca(OH)_2$. The $CaCO_3$ surface area declined with increasing solution temperature (27–45°C) and was largely unaffected by the CO_2 flow rate (1.0–3.5 L/min). The type, quantity, and timing of the addition all had a significant impact on the $CaCO_3$ surface area. For every addition, the ideal circumstances for increasing the $CaCO_3$ surface area were found. Dispel A40 and N40 were more effective among the six additives tested (ammonium stearate, stearic acid sodium, sodium bis (2-ethylhexyl) sulfosuccinate, Disponer 926). Enhancing the formation of fine $CaCO_3$ primary particles and their loose aggregation was an effective addition in increasing the $CaCO_3$ surface area and pore volume. When an efficient additive was added after CO_2 was bubbling into the $Ca(OH)_2$ suspension, high surface area $CaCO_3$ was produced [2].

The article "Experimental examination of sulfur di oxide dry removal from a mixture of gases by calcium oxide, calcium carbonate and dolomite" shows an experiment of SO_2 absorption to the three different sorbents: calcium-oxide (CaO), calcium-carbonate ($CaCO_3$) and dolomite 7 ($CaMg(CO_3)_2$). The study found that in the reactor under the condition of oxidation atmosphere with the mass of sorbent (sample) of 100 g with fractional composition of 500-700µm, the gas temperature varied from 200°C and 400°C. The examinations indicated that the highest degree of sorbent utilization of 14 % was determined for dolomite ($CaMg(CO_3)_2$) and the binding degree of SO_2, from 65-80% and the lowest for calcium oxide (CaO) of 4% and the binding degree of SO_2 from 34-60% at the reaction temperature of 200°C. When the reaction temperature is 400°C the degree of sorbent utilization is a bit lower [3].

1.1 Problem Statement

The utilization of calcium carbonate ($CaCO_3$) presents a viable strategy for removing sulfur dioxide (SO_2) from gas streams by means of a reaction that can yield calcium sulfite ($CaSO_3$) as the intended byproduct. However, the efficacy and feasibility of this approach may be impeded by the possibility of partial conversion and the creation of less advantageous calcium sulfate ($CaSO_4$). In order to maximize the formation of $CaSO_3$, improve the efficiency of SO_2 removal, reduce operational costs related to byproduct management, and lessen equipment problems brought on by $CaSO_4$ precipitation, this thesis will examine the factors influencing the product distribution in the $CaCO_3$–SO_2 reaction.

1.2 Significance of the Research

Developing a deeper understanding of the factors influencing the product distribution in the $CaCO_3$-SO_2 reaction will enable:

- Improved SO_2 Capture Efficiency: By optimizing reaction conditions and potentially using additives, the system's capacity to remove SO_2 from gas streams can be significantly enhanced.

- Reduced Operational Costs: Strategies to minimize $CaSO_4$ formation can lead to lower water consumption for byproduct removal and less frequent equipment cleaning, resulting in cost savings.

- Mitigated Equipment Issues: Minimizing $CaSO_4$ precipitation can prevent scaling and equipment damage, leading to improved operational efficiency and reduced downtime.

2. EXPERIMENTAL DETAILS

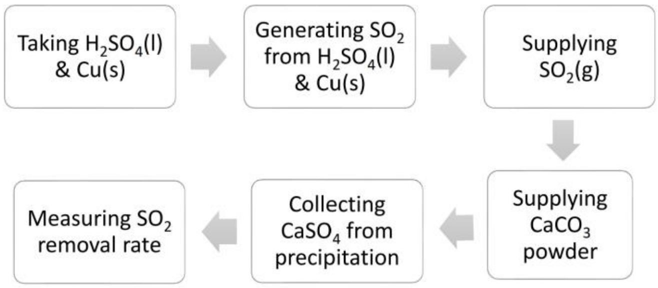

Fig -1: Methodology in Flow Chart

The reaction can be represented as:

$$Cu_{(s)} + 2H_2SO_{4(aq)} \rightarrow CuSO_{4(aq)} + SO_{2(g)} + 2H_2O_{(l)}$$

In the presence of heat, concentrated sulfuric acid can decompose to release sulfur dioxide gas (SO_2). The decomposition reaction of sulfuric acid can be represented as:

$$2H_2SO_{4(aq)} \rightarrow 2SO_{2(g)} + 2H_2O_{(l)} + O_{2(g)}$$

This step occurs simultaneously with the formation of copper sulfate and is favored at high temperatures.

Overall Reaction:

$$Cu_{(s)} + 2H_2SO_{4(aq)} \rightarrow CuSO_{4(aq)} + SO_{2(g)} + 2H_2O_{(l)}$$

2.1 Experimental Setup

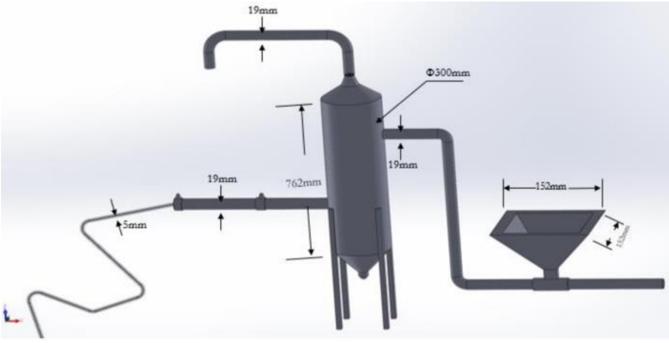

Fig -2: Final Design by SolidWorks

Fig -3: Overall Fabricated Setup

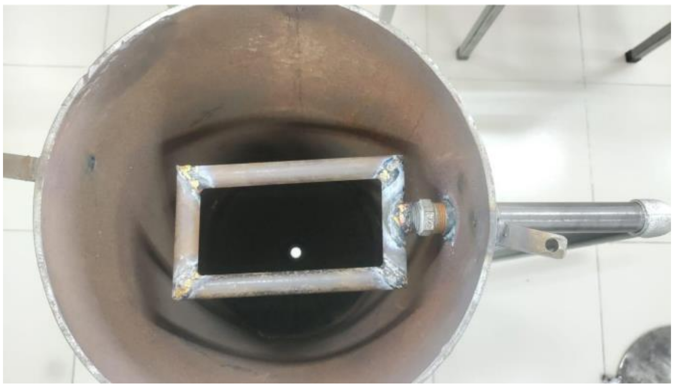

Fig -4: Internal Upper View

Fig -5: Spray Pipe

3. RESULT AND DISCUSSION

Research faced challenges due to the unavailability of pure SO_2, which is a banned item. As a result, the absorption of SO_2 in the developed system was significantly lower than anticipated. Despite these challenges, a series of tests were conducted to evaluate the performance of the system in capturing SO_2 from simulated gas streams. The experiments involved varying the opening of inlet valve for supplying $CaCO_3$, concentration of $CaCO_3$ & amount of Cu. Each test was meticulously conducted to ensure reliability and accuracy of the data obtained. The absorption rates & reaction time were recorded and analyzed to understand the system's efficiency in capturing SO_2.

Table -1: Absorption Results (Data table by varying inlet valve opening)

Inlet Valve (%)	Concentration of $CaCO_3$ (gm)	H_2SO_4 (ml)	Cu (gm)	CO_2 (%)	Absorption Rate (%)	Reaction Time (sec)
25	128	98	5	37	2.34	420
50	128	98	5	41	3.9	300
75	128	98	5	42	4.68	220
100	128	98	5	44	6.25	175

The first reaction, where 128gm (1M) $CaCO_3$ was introduced into the system for the reaction, resulted in a SO_2 capture rate of 2.34%. The amount of precipitation after the reaction was 25, 125gm which indicated that only 3 gm $CaCO_3$ reacted with SO2 and turned into the products (CaSO4 & CO_2) from which the absorption rate was determined.

$$Absorption\ Rate = (3 \div 128) \times 100 = 2.34\%$$

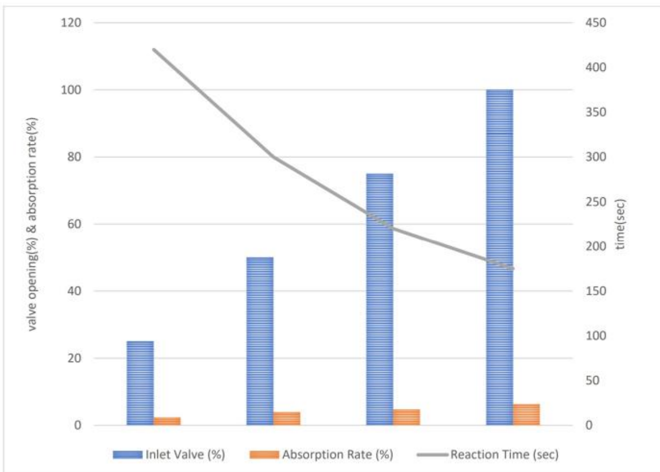

Chart -1: Absorption Rate vs Valve Opening (parameterized by reaction time)

Chart 1 shows the inverse relationship between absorption rate and reaction time which is noteworthy. As the inlet valve opening increases, the reaction time decreases. This indicates that higher inlet valve opening facilitate faster absorption of SO_2, resulting in shorter reaction times. Shorter reaction times are desirable in practical applications as they contribute to higher throughput and system efficiency.

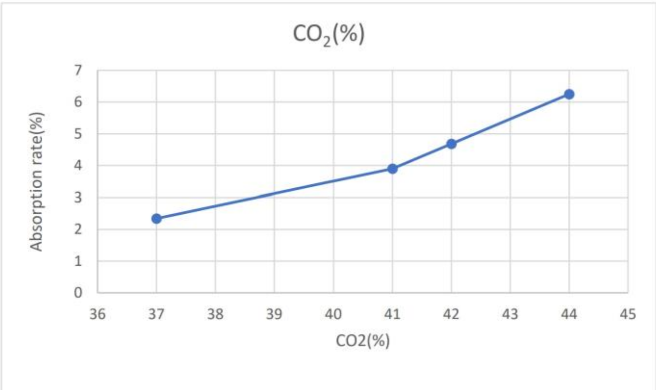

Fig -6: Absorption rate (%) vs CO_2 (%)

Fig 6 illustrates the relationship between both the absorption rate and the concentration of CO_2 in the exhaust gas.

Table -2: Absorption Results (Data table by different concentration of $CaCO_3$)

Inlet Valve (%)	Concentration of $CaCO_3$ (gm)	H_2SO_4 (ml)	Cu (gm)	CO_2 (%)	Absorption Rate (%)	Reaction Time (sec)
100	128	98	5	42	5.46	190
100	150	98	5	41	5.3	220
100	192	100	5	41	5.2	240
100	256	98	5	40	4.68	290

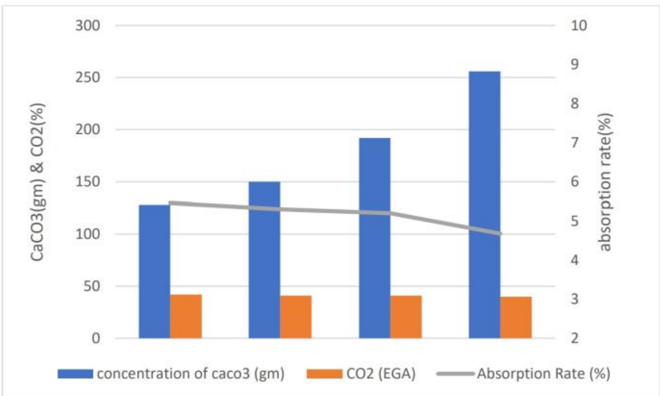

Chart -2: Concentration $CaCO_3$ vs CO_2 (parameterized by Absorption rate)

Chart 2 illustrates the relationship between the concentration of $CaCO_3$ (expressed in grams), the absorption rate, and the concentration of CO_2 in the exhaust gas.

Table -3: Absorption Results (Data table by different amount of Cu)

Inlet Valve (%)	Concentration of $CaCO_3$ (gm)	H_2SO_4 (ml)	Cu (gm)	CO_2 (%)	Absorption Rate (%)	Reaction Time (sec)
100	128	98	5	38	2.73	202
100	128	98	7	41	3.9	195
100	128	198	10	45	6.35	185
100	128	98	12	51	8.59	170

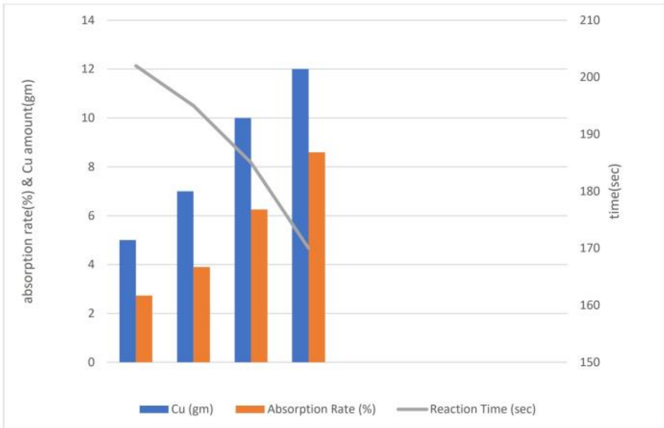

Chart -3: Absorption Rate vs Amount of Cu (parameterized by reaction time)

In Chart 3, The reaction time also decreases with increasing amount of Cu. This indicates that higher amounts of Cu facilitate quicker absorption of SO_2 into the system. The decrease in reaction time can be attributed to the enhanced reactivity of Cu with SO_2 at higher concentrations.

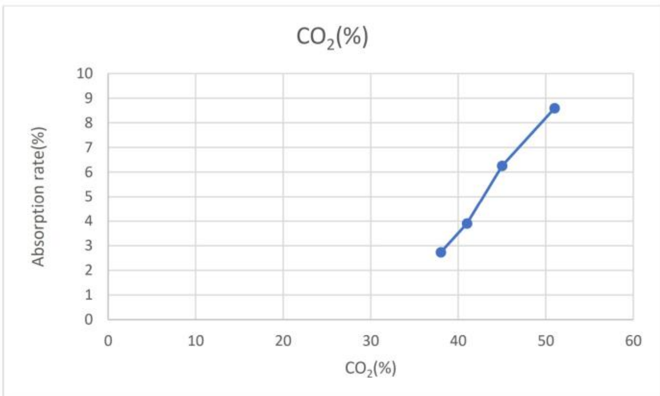

Fig -7: CO_2 vs Absorption Rate

Fig 7 illustrates the relationship between the absorption rate and the concentration of CO_2 in the exhaust gas. As the concentration of Cu increases from 5 gm to 12 gm, there was a clear trend of increasing absorption rate, indicating a more efficient absorption process for removing SO_2 from the exhaust gas. Additionally, the concentration of CO_2 also increases from 38% to 51% as the concentration of Cu increases. This suggests that higher concentrations of Cu lead to both greater absorption of SO_2 and subsequent production of CO_2 through the reaction between Cu and SO_2. The relationship between Cu concentration, absorption rate, and CO_2 concentration indicates the potential role of Cu in enhancing the efficiency of the absorption process and the production of CO_2 in the exhaust gas.

Overall, the results of these reactions suggests that the optimal combination of materials for SO_2 absorption is for the maximum inlet valve opening (100%) keeping all other parameters constant which is 6.25%. For varying $CaCO_3$ keeping other parameters constant concentration the lower the concentration of $CaCO_3$ higher the rate of absorption of SO_2 which is 5.46% for 128gm of $CaCO_3$ and for varying cu amount keeping other parameters constant the higher the amount of cu higher the absorption rate of SO_2 which is 8.59% for 12 gm of Cu & the maximum efficiency of the system is when inlet valve is 100% open, $CaCO_3$ supply is 128gm through the inlet valve & 12gm Cu reacts with 98ml H_2SO_4 for generating SO_2.

4. CONCLUSIONS

In the investigation of a sulfur dioxide (SO_2) capture system using various parameters such as inlet valve opening, calcium carbonate ($CaCO_3$) concentration, and copper (Cu) amount, challenges arose due to the unavailability of pure SO_2. Despite these hurdles, rigorous experimentation yielded valuable insights into system efficiency and provided a foundation for further optimization. Initially, results demonstrated a clear relationship between inlet valve opening and SO_2 absorption rate. As the valve opening increased, allowing for a higher flow rate of $CaCO_3$, a corresponding rise in SO_2 absorption was observed. However, this relationship exhibited diminishing returns at very high flow rates, suggesting the importance of balancing flow rate and contact time with the absorbent for maximizing absorption efficiency. Moreover, investigation into varying $CaCO_3$ concentrations revealed an intriguing trend. Contrary to expectations, higher $CaCO_3$ concentrations led to decreased SO_2 absorption rates, indicating the existence of an optimal concentration for efficient SO_2 capture. The role of copper (Cu) in the absorption process proved significant, with increasing Cu concentrations correlating positively with higher SO_2 absorption rates. This observation was further supported by the decrease in reaction time with increasing Cu concentrations, highlighting the importance of reaction kinetics in optimizing SO_2 capture systems. Analysis of CO_2 concentration further supported these findings, indicating a clear indication in every case that the amount of CO_2 found in Exhaust Gas Analyzer was increasing with increasing absorption rate. Beyond these quantitative findings, the study underscores the critical importance of reaction time in assessing system performance. Shorter reaction times, facilitated by factors such as higher Cu concentrations, not only contribute to increased throughput and system efficiency but also offer practical advantages in real-world applications. Combining the insights from these experiments, the study identified the optimal operating conditions for maximizing SO_2 absorption efficiency, including maintaining the inlet valve fully open, supplying specific amounts of $CaCO_3$ and Cu. Under these conditions, the system exhibited the highest absorption rate. Despite the limitations imposed by the unavailability of pure SO_2 and other experimental constraints, the study provides valuable insights into the factors influencing SO_2 absorption efficiency and lays the groundwork for further optimization of SO_2 capture technology. In conclusion, the findings highlight the potential of the developed SO_2 capture system while acknowledging its current operational limitations. Through continued refinement and optimization, informed by the insights gained from this study, advancements in SO_2 capture technology can be achieved, fostering environmental sustainability and air quality improvement initiatives.

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