Effect of Flow Rate NaOH on CO_2 Absorption Efficiency Using a Column Tray Absorber

Rizal Arifin[a*], Nurul Faizah[a], Ardista Izdhihar Kaloka[a], Anisa Fatma Aulia[a], Gladys Sukma Thufailah[a], Muhammad Adnan Syukur[a]

[a]*Department of Industrial Chemical Engineering, Faculty of Vocation, Sepuluh Nopember Institute of Technology, Surabaya 60111, Indonesia*
Corresponding author: rizal.arifin@its.ac.id

Abstract
CO_2 in industrial gas streams reduces process efficiency, corrodes equipment, and affects product quality. Additionally, CO_2 emissions contribute to climate change and global warming. To mitigate these effects, CO_2 removal through absorption is essential. Absorption involves contacting a gas mixture with a liquid absorbent to dissolve the gas component. This study examines the effect of CO_2 flow rate (V) and NaOH flow rate (L) on CO_2 absorption efficiency. The experiment involved preparing 33 liters of 0.1N NaOH and 250 ml of 0.1N HCl, followed by solution standardization using methyl orange. CO_2 was introduced through valve V-4 while NaOH was pumped into the absorption column. Samples were taken after steady state was reached, and titration with 0.1N HCl determined residual NaOH concentration. Flow rate variations of 1, 3, 5, 7, and 9 L/min were tested. Results align with literature, indicating that as CO_2 flow rate increases, NaOH flow rate also rises. However, the L/V ratio and absorbed CO_2 amount decrease due to reduced contact time, lowering absorption efficiency. This study highlights the importance of optimizing flow rates to enhance CO_2 capture.

Keywords : Absorption; Carbon dioxide; Separation; Sodium hydroxide

1. Introduction

The main factor in the onset of the global warming phenomenon is carbon dioxide emissions, which is a greenhouse gas[1]. According to the Intergovernmental Panel on Climate Change (IPCC), there are 5 sectors that are the main sources of CO_2 emissions, namely energy use, industrial processes, PKPL, and waste. So that mitigation efforts are needed in the form of controls that have the potential to produce CO_2. Low concentrations of CO_2 have a noticeable effect on the health of people in it and high concentrations can increase fatigue inhibit concentration and also reduce mental health[2]. Various CO_2 absorption methods that have been widely applied include membrane, cryogenic, adsorption, and the most common is absorption using chemical solutions[3]. Among these technologies, absorption with chemical solvents has been researched more in-depth and proven to be the most effective and suitable for CO_2 gas separation[4]. Absorption is the process of absorption or separation of certain materials from a gas mixture through physical bonds or chemical bonds[5].

Absorption is widely used to purify impure feed gases, especially in removing acid gases such as hydrogen sulfide and carbon dioxide[6]. The main principle in absorption is the achievement of perfect contact between the two fluids in the absorber column, which is influenced by the fluid flow rate, gas pressure, and the contact area between the fluids[7]. The most used solvents in the CO_2 absorption process are alkanolamines, such as monoethanolamine (MEA), diethanolamine (DEA), and methyl diethanolamine (MDEA)[8]. In addition, CO_2 absorption can be absorbed by an absorbent, one of which is NaOH because the reaction time is relatively fast, the price is low and can be cheaply regenerated[9]. The mechanism of CO_2 absorption with NaOH is a chemical reaction that produces carbonate salts and water with the mechanism that CO_2 gas is physically absorbed so that it directly reacts with hydroxide ions (OH^-) to produce bicarbonate ions (HCO^-) which then reacts back to produce carbonate ions (CO_3^{2-}). The two-stage solvent absorption process increases efficiency and reduces operational costs. However, this natural gas also contains various contaminants, such as H_2S and CO_2. The CO_2 content in natural gas can cause problems in its use, as the corrosive nature of CO_2 can damage pipes and equipment in the plant[10].

Carbon dioxide is an undesirable component in natural gas because it can cause various operational and economic issues, such as ice formation in pipelines, equipment corrosion, and increased maintenance costs for manufacturing facilities[5]. The presence of CO_2 in industrial processes not only affects efficiency but also compromises the quality of end products. Due to these challenges, industries commonly utilize gas absorption techniques to remove CO_2, ensuring smoother operations and enhanced product purity. This absorption process is widely applied in sectors such as ammonia production, petroleum refining, and natural gas processing. In the ammonia industry, for instance, CO_2 is considered a contaminant that poisons catalysts used in ammonia synthesis, making its removal essential before the gas enters the synthesis unit[11].

As industries strive to align with environmental sustainability goals, carbon capture technologies have become increasingly important. These technologies aim to reduce CO_2 emissions at the source, serving as a proactive measure to mitigate climate change and global warming caused by greenhouse gas (GHG) emissions [12]. The integration of carbon capture systems not only supports global decarbonization efforts but also opens opportunities for CO_2 utilization, such as enhanced oil recovery (EOR) and the production of synthetic fuels and chemicals. By adopting innovative CO_2 management strategies, industries can strike a balance between operational efficiency and environmental responsibility, contributing to a more sustainable future.By looking at the dangers of CO_2 in the environment, an absorption practicum was carried out with the aim of knowing the ratio of CO_2 flow rate (V) and NaOH flow rate (L) to absorbed CO_2 gas.

2. Method

2.1. Simmulation Process with Aspen HYSYS

The gas absorption process was simulated using Aspen Hysys to evaluate the removal efficiency of CO_2 and H_2S. The system consisted of natural gas feed and a solvent stream containing NaOH and water. The simulation was conducted at 30°C and 0.25 atm, with varying solvent flow rates to observe their impact on gas removal efficiency. The procedure involved defining the system components, selecting the appropriate fluid package, configuring the process flowsheet, and inputting operational parameters. After running the simulation, the results were analyzed to determine the absorption performance based on the composition changes in the output streams.

2.2. Preparation of Solution

The preparation stage begins with making a 0.1N NaOH solution in 33 liters and making 0.1N HCl in 250 ml. First weigh 132 grams of NaOH solids using a watch glass. Then dissolve the solid by adding distilled water in a beaker glass while stirring. Finally, dilute with distilled water up to 33 liters in a holding tank (TK). Furthermore, to make 0.1N HCl solution in 250 ml by taking 2.42 ml of concentrated HCl solution (32% with 1.19 g/ml) and diluting with pure water to 250 ml.

2.3. Standardization of Solution

The solution standardization stage is carried out by taking a 0.1N NaOH solution from the reservoir then adding 1 drop of MO indicator. Finally, titrate with 0.1N HCl until it turns purple red. Finally, record the titration volume results to calculate the concentration.

2.4. Absorption Process

The experimental steps began by filling the holding tank (TK) with 3 liters of 0.1N NaOH solution. After that, flow CO_2 gas by opening valve V-4 according to the specified variables. Next, turn on the pump and open valve V-3 to drain the NaOH solution into the absorption column. After the system reaches steady state, take samples from the bottom product through valve V-1. The experiment was repeated using different flow rate variables.

2.5. Analysis

The analysis stage is carried out by adding 1 drop of methyl orange to the sample taken for each variable. Then titrate the sample with 0.1 N HCl solution until it becomes a purple red color. After that, record the volume of titration results and calculate the remaining NaOH concentration. The process of absorption can be seen in Figure 1.

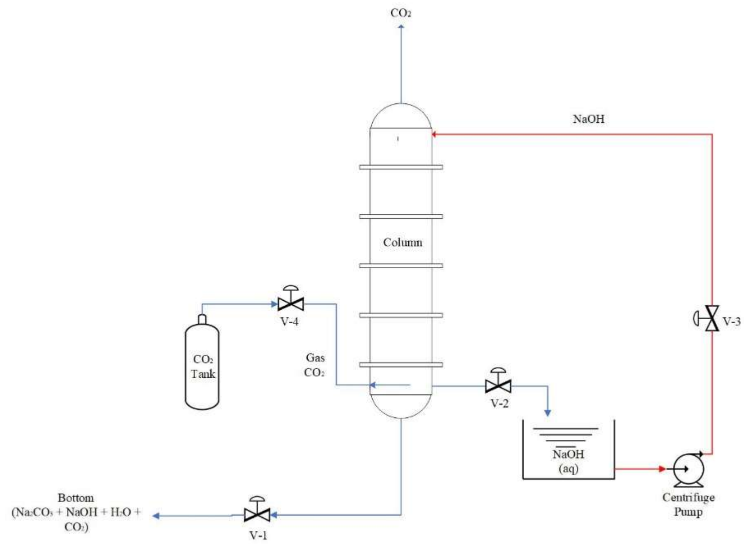

Figure 1. Process flow diagram of CO_2 capture with NaOH.

3. Results and Discussion

3.1. Simulation

The system consists of an absorber column (T-100) where the gas feed (Stream 2) enters from the side, while the solvent (Stream 1) is introduced from the top. The absorption process occurs inside the column, separating the gas components. The treated gas exits as the top product (Stream 3), while the solvent containing the absorbed components exits as the bottom product (Stream 4). As can be seen in the following Figure 2.

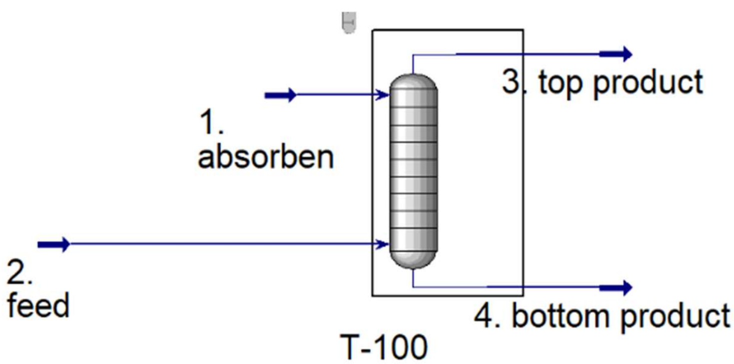

Figure 2. Flowsheet simulation of CO_2 capture using NaOH.

Based on the absorption simulation experiment that has been conducted, the results obtained are:

Table 1. Relationship between solvent rate and absorbed gas.

Rate Solvent (kg/h)	Absorbed Gas (kg/h)
5000	164.46
10000	185.60
15000	256.73
20000	327.86
25000	398.87

Based on the simulation results provided in Table 1, a relationship was observed between the amount of absorbed gas and the solvent flow rate. This relationship is proportional, meaning that as the solvent flow rate increases, the amount of absorbed gas also increases. More detailed data and explanations regarding the absorption simulation results are presented as follows.

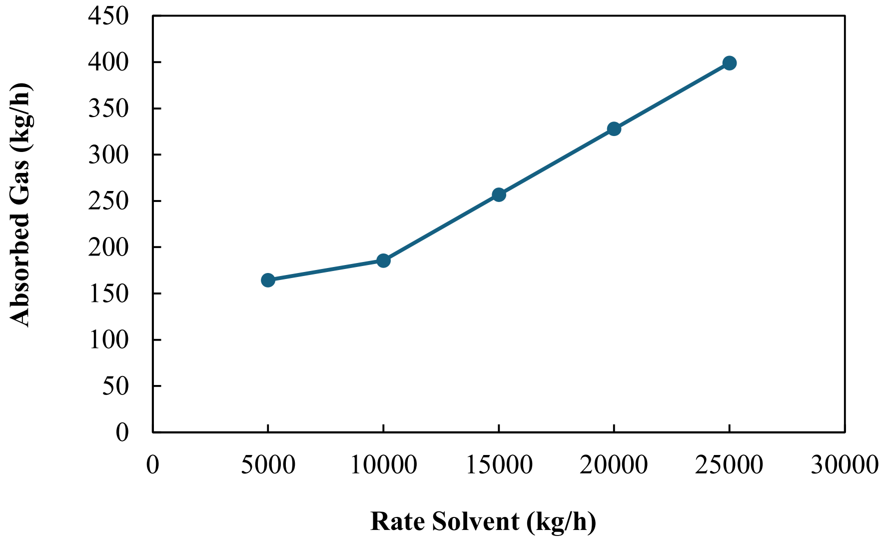

Figure 3. Relationship between solvent flow rate and absorbed gas.

Based on Figure 3, the relationship between solvent flow rate and absorbed gas mass is evident. At a solvent rate of 5000 kg/h (feed ratio 1:5), 164.46 kg/h of gas was absorbed. Increasing the solvent rate to 10,000 kg/h (1:10 ratio) resulted in 185.60 kg/h of absorbed gas. Further increasing the solvent flow to 15,000 kg/h (1:15 ratio) significantly enhanced gas absorption to 256.73 kg/h. At 20,000 kg/h (1:20 ratio), 327.86 kg/h of gas was absorbed, and at the highest tested solvent rate of 25,000 kg/h (1:25 ratio), gas absorption peaked at 398.87 kg/h. This trend shows a strong correlation between solvent flow rate and gas absorption efficiency. Higher solvent flow rates facilitate more effective acid gas absorption due to increased contact time between the gas and solvent. This finding aligns with, which states that a higher solvent flow rate significantly improves CO_2 and H_2S removal efficiency by increasing gas solubility and absorption capacity, particularly under high partial pressures. Unlike chemical solvents, physical solvents are not limited by stoichiometric constraints, allowing for better absorption efficiency with increased flow rates[13].

However, optimizing the solvent rate is crucial for balancing gas removal efficiency and energy consumption. While higher solvent circulation enhances gas solubility and mass transfer, excessive flow can reduce the solvent residence time in the stripping column, leading to increased heat demand for regeneration. Conversely, lower circulation rates improve heat and mass transfer efficiency but may limit absorption performance. Therefore, an optimal solvent rate must be determined to achieve efficient acid gas removal while maintaining energy efficiency. A key limitation of this simulation is that it does not account for gas flow rate variations. Gas flow rate significantly affects CO_2 absorption. Their study found that higher gas flow rates reduce CO_2 removal efficiency by shortening the gas-liquid contact time, despite an increase in gas-phase mass transfer coefficients. Additionally, increasing the gas flow rate decreases the amine-to-CO_2 molar ratio, ultimately reducing CO_2 absorption capacity. Future experiments should consider gas flow rate as a variable to obtain more comprehensive results[14].

3.2. Discussion

Absorption is the process of absorbing or separating certain materials from a gas mixture through physical or chemical bonds[5]. The method used in this research is the chemical absorption method using NaOH solution as an absorbent. The principle of CO_2 absorption with NaOH is based on the chemical reaction between carbon dioxide (CO_2) and sodium hydroxide (NaOH), where CO_2 dissolved in water reacts with hydroxide ions (OH^-) from NaOH. This reaction produces bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-})[15]. So the purpose of this research is to determine the comparison of the CO_2 flow rate (V) and the NaOH flow rate (L) to the absorbed CO2 gas. Where the results will be obtained related to information regarding the most efficient flow conditions to increase CO_2 absorption.

The experimental procedure was carried out with the stages of solution preparation, solution standardization, absorption process and analysis stage. The preparation stage begins with making a 0.1N NaOH solution in 33 liters and making 0.1N HCl in 250 ml. First, weigh 132 grams of solid NaOH using a watch glass. Then dissolve the solid by adding distilled water in a beaker glass while stirring. Finally, dilute with distilled water up to 33 liters in a storage tank (TK). NaOH functions as a strong absorbent for acid gases such as CO_2 because when it reacts it will produce carbonate and bicarbonate ions in solution, resulting in a cleaner compound [9]. Next, to make a 0.1N HCl solution in 250 ml by taking 2.42 ml of concentrated HCl solution (32% with 1.19 g/ml) and diluting it with pure water to 250 ml. HCl was chosen because it is a strong acid solution that is often used as a titer solution in the titration process. A concentration of 0.1N was chosen because with this number it can provide stability in the reaction and provide well-measured results as a volumetric analysis[16]. The solution standardization stage is carried out by taking 0.1N NaOH solution from the reservoir then adding 1 drop of MO indicator. Standardization of the NaOH solution is needed to ensure that the concentration is correct and in accordance with the desired concentration, namely 0.1N. NaOH is a chemical compound that has hygroscopic properties or a compound that can absorb moisture from the atmosphere and CO_2 gas to produce a new compound, namely Na_2CO_3 [17]. This reaction indicates that NaOH has a reagent level that is not pure enough and is used directly. So the NaOH solution must be standardized[18]. Finally, titrate with 0.1N HCl until it turns purple. Finally, record the titration volume results to calculate the concentration. The methyl orange indicator was chosen because of the reaction that occurs between HCl (strong acid) with NaOH (strong base) and Na_2CO_3 resulting from the absorption process with a pH transition range between 3.1 to 4.4 with a change in the indicator from yellow (at basic pH) to purple red (at acidic pH) so that the color change will be clearly visible at the end point of the titration[19].

The experimental steps begin by filling the storage tank (TK) with 3 liters of 0.1N NaOH solution. After that, flow CO_2 gas by opening valve V-4 according to the variables 1; 3; 5; 7; 9 L / min. Variations in CO_2 gas flow at different rates aim to see the effect of gas flow rate on the absorption rate of CO_2 in NaOH solution which shows how gas speed affects the amount of CO_2 that can be absorbed by the solution[5]. Next, turn on the pump until it reaches a steady state by waiting for 3 minutes. Steady state is a condition in which the properties of a system do not change or are constant over time. So that the balance of the absorption reaction process is needed to determine the actual condition of the process without any unstable reaction changes[20]. Then, open the valve V-3 to flow the NaOH solution with valve openings of 45° and 60° into the absorption column.

After the system reaches steady state, take a sample from the bottom product through valve V-1. Variations in the NaOH flow rate opening into the absorption column are carried out to determine changes in the solution flow rate affecting the absorption efficiency. Where, different flow rates can change the contact area between the gas and the solution, thereby affecting the amount of CO_2 absorbed[7]. The reaction that occurs between NaOH and CO_2 produces a product in the form of Na_2CO_3. The concentration of Na_2CO_3 has a direct relationship with the concentration of dissolved CO_2 [9]. After that, take a sample from the bottom product by opening valve 1. Finally, the analysis stage is carried out by adding 1 drop of methyl orange to the sample taken for each variable. Then titrate the sample with 0.1 N HCl solution until it becomes purple. After that, record the volume of the titration results and calculate the remaining NaOH concentration.

3.3. Effect of NaOH Flowrate on CO_2 Mass Absorbed

Based on the process, Table 2 presents the results of the calculation of NaOH flowrate on absorbed CO_2 gas. It shows the relationship between CO_2 flowrate, NaOH valve angle, NaOH concentration, and the amount of CO_2 absorbed.

Table 2. Results of calculation of NaOH flowrate on absorbed CO_2 gas.

Flowrate CO_2 (L/min)	NaOH Valve		NaOH concentration	CO_2 Absorbed
1	45°	Flowrate 16.9 ml/s	0.1	22.33
3				22.77
5				22.88
7				23.65
9				23.87

1	60°	Flowrate 93.98 ml/s	0.1	22.99
3				23.21
5				23.54
7				23.76
9				24.09

Based on the experimental results in Table 2, a graph of the relationship between NaOH flowrate and CO_2 Mass Absorbed was obtained and presented in Figure 4, where the variation in absorbent flowrate in this experiment used Sodium Hydroxide (NaOH) which aimed to determine the effect of CO_2 absorption efficiency.

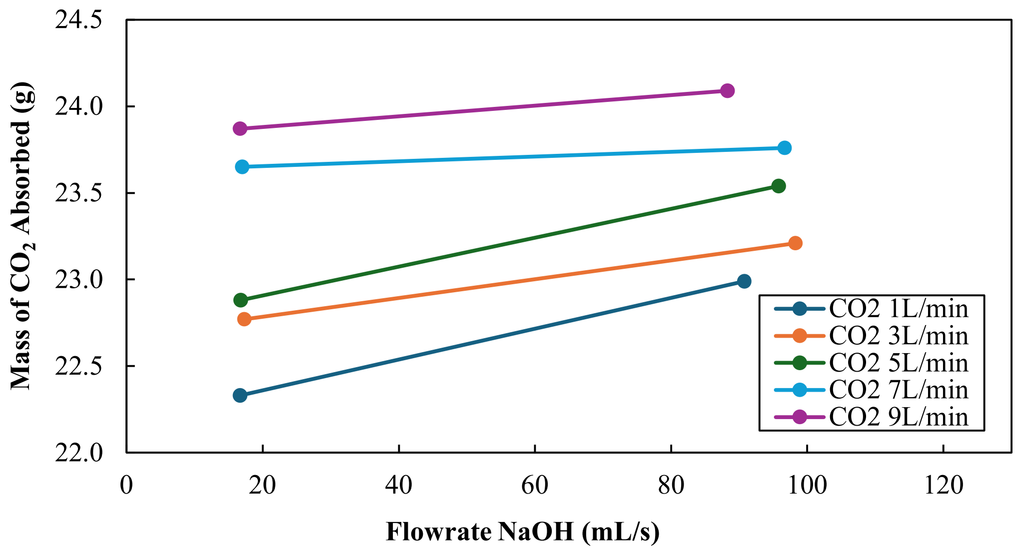

Figure 4. Relationship between NaOH flowrate and absorbed CO_2 gas.

In Figure 4. which shows the relationship between NaOH flowrate (mL/s) and the mass of CO_2 absorbed, it was carried out at two angles of inclination, namely 45° and 60°. At a rotation angle of 45° at a NaOH flowrate of 16.7; 17.3; 16.8; 17; 16.7 mL/s, the mass of CO_2 absorbed was 22.33; 22.77; 22.88; 23.65; 23.87 grams with fluctuating results. While at an angle of 60°, the mass of CO_2 absorbed was higher than at an angle of 45°, with a NaOH flowrate of 90.8; 98.3; 95.8; 96.7; 88.3 mL/s, the mass of CO_2 absorbed was 22.99; 23.21; 23.54; 23.76; 24.09 grams, which are visualized in Figure 1. Based on the experimental results, the greater the NaOH flowrate will increase the formation of bicarbonate under large CO_2 flowrate operating conditions, so that the mass of CO_2 absorbed is greater. This is because the operating conditions of the NaOH and CO_2 flowrates affect the efficiency of mass transfer and the mass of CO_2 absorbed. The mass transfer rate can be affected by increasing the contact area between the solution and the gas so that more CO_2 will be absorbed [21]. Where in the chemical reaction between CO_2 and OH^- ions will produce bicarbonate as in the following reaction:

$$CO_{2\,(g)} + NaOH_{\,(aq)} \rightarrow NaHCO_{3\,(aq)} \quad (1)$$

The mechanism of bicarbonate formation begins with the movement of CO_2 molecules from a high concentration in the gas phase to the gas-liquid surface driven by the concentration gradient of the absorbent. Where the difference in concentration between the two gas and liquid phases will create a driving force that will push CO_2 molecules towards the solution. When CO_2 reacts with the surface of the NaOH solution, it will pass through the liquid boundary layer through the diffusion process. Furthermore, CO_2 will react with OH^- ions in the solution to form bicarbonate. Driving force occurs due to the concentration gradient or difference in CO_2 concentration between the gas and liquid phases, thus encouraging CO_2 molecules to continue to diffuse from the gas phase to the liquid to react with OH- ions [22]. These results are in accordance with the literature stating that the solution flow rate and angle of inclination can affect the gas-liquid contact area and the efficiency of CO_2 absorption [22]. Based on previous research conducted by L.

Trisnaliani et al [23], CO_2 absorption was carried out using NaOH absorbent with variations in flow rates of 6, 7, 8, 9, and 10 liters/minute and variations in NaOH solution concentrations of 0.5 M, 1.0 M, 1.5 M, 2.0 M, and 2.5 M. From the results of the experiment, the optimal flow rate and NaOH concentration for CO_2 reduction were 9 liters/minute and a concentration of 2 M which resulted in the CO_2 content dropping from 27.6% to 20.44%. The results of this study indicate that the setting of operating parameters is not only on the flow rate, but also the concentration of the solution in the absorption process. The optimal flow rate will create a constant gas-liquid contact area without excessive turbulence while the right NaOH concentration will increase the capacity of chemical reactions with the CO_2 molecules to be absorbed.

When compared to previous studies, the experimental results in Figure 1 represent that the 60° valve opening produces a greater NaOH flow rate compared to the 45° valve opening. When the valve opening is not optimal, it can cause contact between CO_2 gas and NaOH solution to be less than optimal. With a large flow rate, the absorbed CO2 mass will increase as the CO_2 flow rate used increases. So the limitation of this experiment is the variation in the concentration of NaOH used as an absorbent. So it is recommended to vary the concentration of NaOH because NaOH plays a direct role in determining the amount of OH^- ions available to react with CO_2. By varying the concentration, the experiment can show the optimal concentration that can absorb CO_2 maximally. In addition, temperature and pressure can affect the efficiency of CO_2 gas absorption. So there is another limitation, namely the absence of temperature and pressure control. Temperature needs to be monitored because it has a major effect on exothermic reactions that can increase the reaction rate as well as evaporation or changes in absorbent properties [24]. While pressure is needed because the pressure of CO_2 gas affects the number of gas molecules that can interact with the NaOH solution. In the absorption process, higher pressure will increase the amount of dissolved CO_2 because it increases molecular contact between phases [25].

3.4. Effect of CO_2 Flowrate on CO_2 Mass Absorbed

Based on the experimental results in Table 1, a graph of the relationship between CO_2 flowrate and CO_2 mass absorbed was obtained to evaluate the effect of flowrate variations on CO_2 absorption efficiency under different operational conditions as follows.

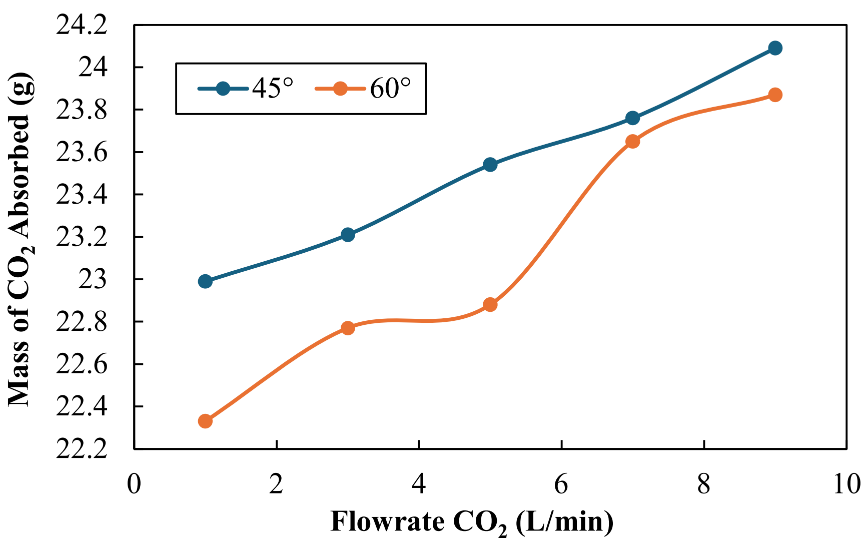

Figure 5. Relationship between CO_2 flowrate and CO_2 absorbed at valve openings of 45^0 and 60^0.

Figure 5 shows the relationship between CO_2 flowrate (L/min) and the mass of CO_2 absorbed (g) at two different valve openings, namely 45° and 60°. The graph shows that increasing CO_2 flowrate tends to increase the mass of CO_2 absorbed at both angles. At an opening angle of 45°, with a flowrate of CO_2 1; 3; 5; 7; 9 L/min, the mass of CO_2 absorbed is 22.33; 22.77; 22.88; 23.65; 23.87 grams. While at an opening angle of 60°, with a flowrate of CO_2 1; 3; 5; 7; 9 L/min, the mass of CO_2 absorbed increases more significantly, namely 22.99; 23.21; 23.54; 23.76; 24.09 grams. From these results, the mass of CO_2 absorbed at an opening angle of 60° is higher than 45° at the same flow rate with a difference in Reynolds number[26]. At a low CO_2 flow rate, it will produce a low fluid velocity or have a smaller Reynolds number value so that the contact between the gas and NaOH is less effective which ultimately results in a lower absorbed CO_2 mass. At a high flow rate, the flow velocity will increase and the Reynolds number will be higher. The flow will become more turbulent, especially at an opening angle of 60°. This turbulence event increases the efficiency of CO_2 contact with NaOH, so that the absorbed CO_2 mass is greater than 45°. These results indicate that increasing the flow rate tends to increase the absorbed mass, but at high rates the increase in flow rate tends to slow down the absorbed CO2 mass. This occurs because at low flow rates, the contact time of CO_2 gas with NaOH is longer and at high flow rates, the contact time of CO_2 gas with NaOH is shorter, making the absorbent approach its saturation capacity, which makes the increase in the amount of CO_2 available no longer produce the efficiency of the CO2 mass absorbed or approaching the asymptotic event. The asymptotic event or when the variables approach a certain limit occurs when the mass of CO_2 absorbed reaches its maximum value even though the flow rate continues to increase[27]. This shows that a larger valve opening angle (60°) increases more efficient gas and liquid interactions, so that the CO_2 absorption process becomes more optimal[28]. Based on previous studies, it has been shown that the configuration of the liquid jet flow in the bubble column significantly affects the CO_2 absorption rate. Liquid jet flow is the condition of the nozzle position and the direction of the angle to the volumetric rate of gas flow. When the configuration reaches the optimal stage, the CO_2 concentration can be reduced to 0.01-0.07% in less than 5 minutes, with NaOH solution as the absorption medium. Variations in the angle and liquid flow rate have a major effect on the absorption efficiency through the formation of small bubble clouds that increase gas-liquid contact[29]. In addition, there is a study on CO2 absorption from flue gas using NaOH regeneration electrolysis from carbonate solution, where the results obtained the CO_2 desorption rate reached 100% and the energy consumption for regeneration was estimated at around 2.4 GJ/ton CO_2[30].

When compared with previous studies, the results of the experiments that have been carried out in Graph 4.2, namely the relationship between CO_2 flowrate and the amount of CO_2 absorbed at valve openings of 45° and 60° show a directly proportional relationship. It can be seen that as the flow rate increases due to the increase in valve opening, the amount of CO_2 absorbed increases. However, this experiment has limitations other than the variation in NaOH concentration as the absorbent used, namely the absence of absorbent saturation capacity testing and the absence of absorbent regeneration. Therefore, it is recommended to determine the saturation capacity of an absorbent and design a regeneration system to renew the absorbent so that it can be reused. Methods that can be used to regenerate NaOH are extraction by adding certain solutions using physical separation methods, low-pressure distillation to remove water and other volatile impurities, with low pressure (decompression distillation), crystallization to purify NaOH by separating it from the remaining solution containing impurities, and filtration. Effective methods that have been used include using thermal regeneration with a rotary kiln method to heat the bicarbonate formed so that the regenerated NaOH solution can be reused or using a chemical method, namely adding $Ca(OH)_2$ to get NaOH back[31].

3.5. Effect of L/V Value on CO2 Mass Absorbed

Table 3 provides the results of the L/V (liquid-to-gas) ratio calculation for absorbed CO_2 gas. The L/V ratio is obtained by dividing the NaOH liquid flowrate by the CO_2 gas flowrate.

Table 3. Results of L/V ratio calculation of absorbed CO_2 gas.

Flowrate CO2 (L/min)	NaOH Valve		L/V	CO2 Absorbed
1	45°	Flowrate 16.9 ml/s	1.002	22.33
3			0.346	22.77
5			0.2016	22.88
7			0.1457	23.65
9			0.1113	23.87
1	60°	Flowrate 93.98 ml/s	5.448	22.99
3			1.966	23.21
5			1.1496	23.54
7			0.8288	23.76
9			0.5866	24.09

Based on the experimental results in Table 3, a graph of the relationship between L/V and the Mass of CO2 Absorbed was obtained. A comparison of L/V values was carried out to determine the effect of CO2 absorption efficiency as follows:

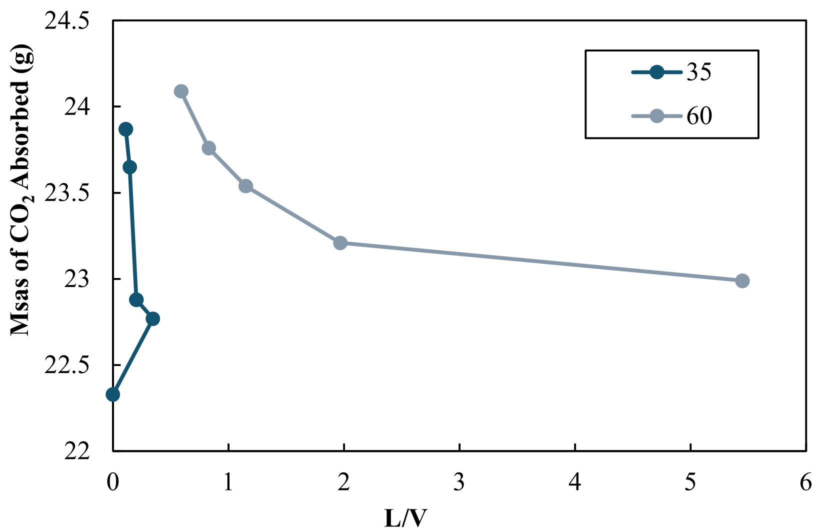

Figure 6. Relationship of L/V to CO_2 absorbed at valve openings of 45^0 and 60^0.

In Figure 6, which is the relationship between absorbed CO_2 and L/V in the CO_2 absorption experiment with NaOH solution which was tested at two valve openings, namely 45° and 60°, the variation affects the L/V ratio and the mass of absorbed CO_2. At a valve opening of 45°, the L/V values were respectively 1.002, 0.346, 0.2016, 0.1457, and 0.1113, resulting in a mass of absorbed CO2 of 22.33; 22.77; 22.88; 23.65; 23.87 grams. Then at a valve opening of 60°, the L/V values were respectively 5.448, 1.996, 1.1496, 0.8289, and 0.5887 resulting in a CO_2 mass absorbed of 22.99; 23.21; 23.54; 23.76; 24.09 grams. From these results, the smaller the L/V value, the greater the CO_2 mass absorbed. The L/V ratio or liquid-gas ratio is the comparison between the liquid flow rate (L) and the gas flow rate (V) in the absorption process which is often used to determine the efficiency of gas absorption such as CO_2 [32]. The factors that affect the L/V ratio are temperature, pressure, and the type of absorbent solution used [33]. A high L/V ratio will indicate that the absorbent solution can interact more with the gas, which means it will increase the efficiency of CO2 absorption. Conversely, a low L/V ratio indicates that the gas volume is greater than the solution so that the contact time for the absorbed gas is more limited[34].

Based on research conducted by Kavoshi [35]it states that increasing the L/V ratio under spray drying conditions increases the efficiency of CO_2 absorption in NaOH-based solutions. This shows that a larger amount of liquid increases the gas-liquid contact area, which is beneficial for increasing CO2 absorption. The results of the study were that the addition of NaOH solution as an absorbent could increase its ability to absorb CO_2. Data obtained that the addition of 100 mL of NaOH solution with a concentration of 1 mol/L per 1000 mL of lime slurry resulted in a removal efficiency of 70.5%. In addition, there is a study using a contact membrane to increase the efficiency of CO_2 absorption with NaOH solution. Increasing the L/V ratio results in higher efficiency in CO_2 absorption, indicating that a larger fluid flow can increase the CO_2 absorption capacity. Based on the results of the experiments that have been carried out in Graph 4.3, namely the relationship between the L/V ratio and the amount of CO_2 absorbed at valve openings of 45° and 60° shows an inverse relationship. It can be seen that as L/V increases, the amount of CO_2 absorbed decreases. So this is not in accordance with the literature and research which states that the relationship between the L/V ratio and the amount of CO_2 absorbed is directly proportional[36].

When compared to previous studies, the results of the experiments that have been carried out in Graph 4.3, the value of the absorbed CO_2 mass is not directly proportional to the increase in the L/V ratio caused by the two-phase flow (liquid-vapor) in the system experiencing instability or maldistribution, thereby reducing effective contact between the liquid and gas phases because flow instability can reduce mass transfer efficiency, because gas and liquid are not evenly distributed throughout the column or reactor volume[37] and under certain conditions, increasing the L/V ratio can reduce the partial pressure of CO_2 in the gas phase. This means that CO_2 absorption is slower because the partial pressure gradient between the gas phase and the liquid phase required for optimal mass transfer is not achieved[38]. So the limitations of this variable are unstable flow or maldistribution which reduces effective contact between the liquid and gas phases, thereby reducing mass transfer efficiency because the gas and liquid are not evenly distributed in the column volume. Due to the instability of the two-phase flow which can reduce the contact between the NaOH solution and CO_2 gas, it is recommended to modify the NaOH solution with a catalyst or supporting compound to produce an absorbent with better capacity and reactivity to slow down saturation and increase the efficiency of the CO_2 absorption process[39]. This study has several limitations that should be addressed in future research. The use of a fixed NaOH concentration (2 M) limits insight into concentration-dependent effects. Additionally, the system operated under ambient temperature and pressure without control, and regeneration of the NaOH solution was not investigated. Future studies are encouraged to explore variable NaOH concentrations, regeneration methods, and controlled operation parameters to enhance process optimization.

4. Conclusions

Based on the results of the CO_2 absorption experiment using NaOH as an absorbent, it was found that both the NaOH flowrate and the valve opening angle significantly influenced the mass of CO_2 absorbed. Higher NaOH flowrates, particularly at a 60° valve opening, resulted in greater CO_2 absorption due to the increased contact area between the gas and the solution, optimizing mass transfer efficiency. Similarly, increasing CO_2 flowrates led to greater absorption, with the effect being more pronounced at a 60° valve opening, where the higher Reynolds number induced a more turbulent flow, enhancing the absorption process. Furthermore, the relationship between the L/V ratio (liquid-to-gas ratio) and CO_2 absorption demonstrated a trend where the mass of CO_2 absorbed decreased as L/V increased. This suggests that beyond a certain point, increasing liquid flow does not proportionally enhance CO_2 absorption, highlighting the importance of optimizing the balance between gas and liquid flowrates. These findings have important implications for gas absorption system design, particularly in optimizing operating conditions to maximize CO_2 capture efficiency. The results align with previous studies on mass transfer in gas-liquid absorption systems, reinforcing the role of turbulence and contact area in improving absorption rates. Future research could explore different absorbent concentrations or alternative chemical solutions to further enhance CO_2 capture efficiency, contributing to more effective carbon capture technologies.

Acknowledgment

This research supported by Biotechnology Laboratory of Department of Industrial Chemical Engineering, Institut Teknologi Sepuluh Nopember.

References

[1] D. Labiba and W. Pradoto, “Sebaran Emisi CO2 Dan Implikasinya Terhadap Penataan Ruang Area Industri di Kabupaten Kendal,” *Jurnal Pengembangan Kota*, vol. 6, no. 2, p. 164, 2018.

[2] M. A. Fanani, D. R. Nurmaningsih, and S. Nengse, “Meninjau Efisiensi Penurunan Kadar CO2 oleh Living Moss Wall: Studi tentang Potensi dan Tantangan dalam Mengatasi Pencemaran Udara di dalam Ruangan,” *Dampak*, vol. 20, no. 2, p. 55, 2023.

[3] Y. Kurniati and L. Qomariyah, “Prediksi Solubilitas (Absorpsi) Gas CO 2 dalam Larutan Potasium Karbonat (K 2 CO 3) dan MDEA Menggunakan Simulasi ASPEN-K 2 CO 3-MDEA-H 2 O system, electrolyte NRTL model, vapor-liquid equilibrium,” vol. 2, no. 1, pp. 1–10, 2018.

[4] Y. Hartanto, A. Putranto, S. Cynthia, K. Kunci, and: CO2, "Simulasi Absorpsi Gas CO2 dengan Pelarut Dietanolamina (Dea) Menggunakan Simulator Aspen Hysys," 2017.

[5] A. Kurniawan, M. Fatimura, and R. Masriatini, "Pengaruh Variasi Laju Alir Gas Alam Terhadap Absorbsi Gas CO2 dan Waktu Pembakaran Gas Alam."

[6] O. I. Maile, E. Muzenda, and H. Tesfagiorgis, "Chemical Absorption of Carbon Dioxide in Biogas Purification," in *Procedia Manufacturing*, Elsevier B.V., pp. 639–646, 2017.

[7] S. Ardhiany and K. Kunci, "Proses Absorbsi Gas CO 2 dalam Biogas menggunakan Alat Absorber Tipe Packing dengan Analisa Pengaruh Laju Alir Absorben NaOH," 2018.

[8] G. da Cunha, J. de Medeiros, and O. Araújo, "Carbon Capture from CO2-Rich Natural Gas via Gas-Liquid Membrane Contactors with Aqueous-Amine Solvents: A Review," *Gases*, vol. 2, no. 3, pp. 98–133, Sep. 2022.

[9] R. Robiah *et al.*, "Kajian Pengaruh Laju Alir NaOH Dan Waktu Kontak Terhadap Absorpsi Gas CO2 Menggunakan Alat Absorber Tipe Sieve Tray," 2021.

[10] A. M. Nor Azira and A. Umi Aisah, "Purification of biohydrogen from fermentation gas mixture using two-stage chemical absorption," in *E3S Web of Conferences*, EDP Sciences, Apr. 2019.

[11] A. Chalim and E. Novika Dewi, "Prosiding Seminar Nasional Kimia dan Pembelajarannya (SNKP) 2019 Malang," 2019.

[12] J. Xu, "Research progress in CO 2 capture technology," 2023.

[13] A. S. Farooqi, R. M. Ramli, S. S. M. Lock, N. Hussein, M. Z. Shahid, and A. S. Farooqi, "Simulation of Natural Gas Treatment for Acid Gas Removal Using the Ternary Blend of MDEA, AEEA, and NMP," *Sustainability (Switzerland)*, vol. 14, no. 17, Sep. 2022.

[14] K. Fu, P. Zhang, and D. Fu, "Absorption capacity and CO2 removal efficiency in tray tower by using 2-(ethylamino) ethanol activated 3-(dimethylamino)propan-1-ol aqueous solution," *Journal of Chemical Thermodynamics*, vol. 139, Dec. 2019.

[15] A. H. Lahuri and M. A. Yarmo, "Study of CO2Adsorption Time for Carbonate Species and Linear CO2Formations onto Bimetallic CaO/Fe2O3by Infrared Spectroscopy," *Sains Malays*, vol. 51, no. 2, pp. 507–517, Feb. 2022.

[16] M. Ahmadi and S. H. Seyedin, "Investigation of NaOH Properties, Production and Sale Mark in the world," 2019.

[17] R. Rahmawati and M. Tejamaya, "Chemical Dermal Exposure Risk Assessment in the Water Treatment Plant of Fertilizer Industry," *Indonesian Journal of Occupational Safety and Health*, vol. 13, no. 2, pp. 241–251, Aug. 2024.

[18] A. U. Istiqomah, F. Rahmawati, and K. D. Nugrahaningtyas, "Replacing Soda Ash (NaOH) With Kalium Hydroxyde (KOH) In Destilation Of Binary Ethanol-Water Mixture," *Alchemy Jurnal Penelitian Kimia*, vol. 12, no. 2, p. 179, Sep. 2016.

[19] K. Asemave and A. S. Shiebee, "Comparative Analysis of Curcuma longa Rhizome and Tectona grandis Leaves Extracts as Green Indicators versus some Synthetic Indictors in Acid-Base Titration," *Journal of Engineering Research and Sciences*, vol. 1, no. 1, pp. 51–55, Feb. 2022.

[20] N. Siraj and A. Hakim, "Steady-State and Dynamic Simulations of Gas Absorption Column Using MATLAB and SIMULINK Steady-State and Dynamic Simulations of Gas Absorption Column Using MATLAB and

SIMULINK Introduction 2 Process description 3 Absorption tower model development 4 Results and discussion 5 Conclusion and recommendation," 2018.

[21] A. Durgadevi and S. Pushpavanam, "An experimental and theoretical investigation of pure carbon dioxide absorption in aqueous sodium hydroxide in glass millichannels," *Journal of CO2 Utilization*, vol. 26, pp. 133–142, Jul. 2018.

[22] H. Luo and H. Kanoh, "Fundamentals in CO2 capture of Na2CO3 under a moist condition," *Journal of Energy Chemistry*, vol. 26, no. 5, pp. 972–983, Nov. 2017.

[23] L. Trisnaliani *et al.*, "The Effect of flowrate and NaOH Concentration to CO2 Reduction in Biogas Products Using Absorber," in *Journal of Physics: Conference Series*, Institute of Physics Publishing, May 2020.

[24] Y. Tavan and S. H. Hosseini, "A novel rate of the reaction between NaOH with CO2 at low temperature in spray dryer," *Petroleum*, vol. 3, no. 1, pp. 51–55, Mar. 2017.

[25] C. Yao, K. Zhu, Y. Liu, H. Liu, F. Jiao, and G. Chen, "Intensified CO2 absorption in a microchannel reactor under elevated pressures," *Chemical Engineering Journal*, vol. 319, pp. 179–190, 2017.

[26] A. Tollkötter and N. Kockmann, "Absorption and chemisorption of small levitated single bubbles in aqueous solutions," *Processes*, vol. 2, no. 1, pp. 200–215, Mar. 2014.

[27] M. Gunnarsson, D. Bernin, Å. Östlund, and M. Hasani, "The CO2 capturing ability of cellulose dissolved in NaOH(aq) at low temperature," *Green Chemistry*, vol. 20, no. 14, pp. 3279–3286, 2018.

[28] F. I. Dinul, H. Nurdin, D. Rahmadiawan, Nasruddin, I. A. Laghari, and T. Elshaarani, "Comparison of NaOH and Na2CO3 as absorbents for CO2 absorption in carbon capture and storage technology," *Journal of Engineering Researcher and Lecturer*, vol. 2, no. 1, pp. 28–34, Apr. 2023.

[29] S. Setiadi, D. Supramono, and N. Istiqomah, "Pengaruh konfigurasi liquid jet flow kolom gelembung terhadap kemampuan absorpsi gas karbondioksida," *Jurnal Teknik Kimia Indonesia*, vol. 9, no. 2, p. 42, Oct. 2018.

[30] L. Li *et al.*, "Research on integrated CO2 absorption-mineralization and regeneration of absorbent process," *Energy*, vol. 222, May 2021.

[31] F. M. Baena-Moreno, M. Rodríguez-Galán, F. Vega, T. R. Reina, L. F. Vilches, and B. Navarrete, "Regeneration of sodium hydroxide from a biogas upgrading unit through the synthesis of precipitated calcium carbonate: An experimental influence study of reaction parameters," *Processes*, vol. 6, no. 11, Oct. 2018.

[32] V. Rajiman, N. A. H. Hairul, and A. M. Shariff, "Effect of CO2 concentration and liquid to gas ratio on CO2 absorption from simulated biogas using monoethanolamine solution," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing Ltd, Dec. 2020.

[33] C. Dinca, N. Slavu, and A. Badea, "Benchmarking of the pre/post-combustion chemical absorption for the CO2 capture," *Journal of the Energy Institute*, vol. 91, no. 3, pp. 445–456, Jun. 2018.

[34] R. Sutanto, A. Mulyanto, M. Wirawan, I. B. Alit, and N. Nurchayati, "Adsorbsi gas karbon dioksida dalam biogas dengan menggunakan endapan batu kapur," *Dinamika Teknik Mesin*, vol. 9, no. 2, p. 133, Jul. 2019.

[35] L. Kavoshi, A. Rahimi, and M. S. Hatamipour, "Experimental Study of Chemical Absorption of CO2 in a Bench-Scale Spray Dryer Absorber," *Gas Processing Journal*, vol. 6, no. 1, pp. 21–28, 2018.

[36] A. Constantinou, S. Barrass, and A. Gavriilidis, "CO2 absorption in flat membrane microstructured contactors of different wettability using aqueous solution of NaOH," *Green Processing and Synthesis*, vol. 7, no. 6, pp. 471–476, Dec. 2018.

[37] L. Zhang, G. Hu, and X. T. Bi, “Two-phase flow in parallel channels: Mal-distribution, hysteresis and mitigation strategies,” *Chem Eng Sci*, vol. 247, Jan. 2022.

[38] S. Djayanti, B. Besar, T. Pencegahan, and P. Industri, “Optimalisasi Penurunan Konsentrasi SO2 Emisi Menggunakan Larutan NAOH pada Menara Absorber.”

[39] L. Prentza, I. P. Koronaki, and M. T. Nitsas, “Investigating the performance and thermodynamic efficiency of CO2 reactive absorption – A solvent comparison study,” *Thermal Science and Engineering Progress*, vol. 7, pp. 33–44, Sep. 2018.