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RESEARCH ARTICLE

Optimized CO_2 Capture Using Water-Based Absorbent under Circulated Water Conditions for Carbon Capture and Storage (CCS) Applications

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Abstract

Capturing CO_2 emissions using a recirculating water-based system offers a simple and eco-friendly alternative to conventional Carbon Capture and Storage (CCS) methods for reducing emissions and mitigating climate change. To optimize CO_2 solubility in water, it is essential to integrate and evaluate the key variables that influence the capture process, enabling the identification of ideal operating conditions. This study aims to analyze the phenomena and examine the effects of variables such as CO_2 gas flow rate, water flow rate, water temperature, circulation time, and differential pressure on the effectiveness of the CO_2 capture process, as indicated by the mass of CO_2 dissolved in water within the system. The experiment was carried out using a transparent absorber column filled with packing material. CO_2 gas with 99.9% purity was introduced at flow rates of 2 and 4 dm^3/min, while water was recirculated at flow rates of 0.25 and 0.5 dm^3/min. The system operated at water temperatures between 24 and 30 °C, with circulation durations of 5, 10, and 15 min, and differential pressures of 30 and 50 mmHg. Samples were collected at the end of each circulation period and CO_2 absorption was determined through titration using 0.1 M NaOH and phenolphthalein as the indicator. The results demonstrated that higher water flow rates and increased pressure differentials enhanced the capture performance, as evidenced by greater CO_2 absorption. Conversely, elevated water temperatures and higher CO_2 gas flow rates led to decreased absorption efficiency. The most favorable conditions were achieved at 24 °C, a water flow rate of 0.5 dm^3/min, a circulation time of 15 min, and a differential pressure of 50 mmHg, resulting in 1.672 g of CO_2 absorbed. The results of this study indicate that water has the potential to serve as an environmentally friendly alternative technology for CCS applications. However, further research is needed to develop a process that is effective, efficient, and more cost-effective.

Keywords: Reaction kinetics, Climate change, Diffusivity, Equilibrium, Absorption, CO_2 Capture, Environment

Introduction

Carbon dioxide (CO_2) emissions are a leading cause of global warming [1,2]. The primary sources of CO_2 emissions are the combustion of fossil fuels, including coal [3,4], oil [5], and natural gas [6]. These processes consistently release large quantities of CO_2 into the atmosphere, intensifying the greenhouse effect and driving global temperature increases [7]. Rising global temperatures, in turn, accelerate the melting of polar ice caps [8], contributing to sea level rise and posing serious threats to human settlements, especially in coastal regions. To mitigate the adverse impacts of climate change drive by CO_2 emissions, it is crucial to develop alternative technologies that are not only effective and efficient, but also simple, economical, and easy to implement. While research on CO_2 capture technologies, particularly Carbon Capture and Storage (CCS), has advanced considerably, most current methods still rely on chemical absorbents such as alkaline solutions (e.g., NaOH and KOH), ammonia-based solutions, and other synthetic compounds (**Table 1**). These methods typically produce end-products like sodium bicarbonate (Na_2CO_3) from NaOH [9], potassium carbonate (K_2CO_3) from KOH [10], and ammonium carbonate ($(NH_4)_2CO_3$) from ammonia [11]. In addition to its role in reducing carbon emissions, the utilization of CO_2 capture products is a key component of sustainable carbon management. Captured CO_2 can be converted into a variety of valuable products that serve as raw materials or additives in the food, fertilizer, and chemical industries, as well as in synthetic fuels and construction materials, through various synthesis pathways. For instance, methanol (as a fuel) and polyurethane (for construction) can be produced via thermochemical reactions [12]. While sodium bicarbonate and potassium carbonate (for the food and chemical industries), and ammonium bicarbonate (for the fertilizer industry), can be generated through reactions involving alkaline and ammonium-based compounds [13,14]. Integrating CO_2 capture with utilization processes not only helps mitigate greenhouse gas emissions but also adds economic value to comprehensive carbon management systems [15]. An alternative absorbent that is both abundant and naturally available is water. Water offers several advantages as an absorbent: It is non-toxic, widely available, and affordable. However, its CO_2 absorption capacity is relatively low due to a small Henry's law constant [16]. To enhance the efficiency of CO_2 absorption, it is essential to integrate and optimize key influencing factors within the process. Conceptually, when water meets CO_2 gas, it reacts to form dissolved carbonic acid (H_2CO_3) [17], as illustrated in Eqs. (1) and (2). Despite its potential, research on CO_2 capture using water remains limited, with existing studies largely confined to simulation-based assessments using Aspen Plus V.12.1. These simulations particularly in the context of cement industry applications have demonstrated promising levels of capture efficiency. However, no laboratory-scale or pilot-scale experiments have yet been conducted to validate these findings under real-world conditions (**Table 1**).

$$CO_{2\,(g)} \rightarrow CO_{2\,(aq)} \tag{1}$$

$$CO_{2\,(aq)} + H_2O_{(l)} \leftrightarrow H_2\,CO_{3\,(aq)} \tag{2}$$

Therefore, this study investigates the effectiveness and efficiency of using water as an absorbent for CO_2 capture without the addition of other chemical compounds. If proven successful, water-based CO_2 capture would offer several advantages. First, the process would be more environmentally friendly, as water is a neutral and non-toxic substance. Second, it would be more economical, given water's natural abundance and significantly lower operational costs compared to alkaline solutions, ammonia, or other chemical absorbents.

Table 1 CO_2 capture using various types of absorbents.

Absorbent type	Operational condition	Optimal operating conditions	References
$CaCl_2{\cdot}2H_2O$ solution	CO_2 flow rate of 0.1 dm^3/min and temperature ranging from 30 to 70 °C	The highest Ca conversion was approximately 80 wt.% at a temperature of 30 °C.	[18]
KOH solution	CO_2 concentration of 10% and 90%, temperature of 20 °C, CO_2 gas flow rate of 1 dm^3/min, pH > 10.5, contact time of 330 min, and KOH concentration of 30 and 70.5 g/L	The best condition was achieved at a KOH concentration of 30 g/dm^3, with CO_2 absorption of 0.32 g CO_2/g KOH.	[19]
KOH solution	1 M KOH solution, direct air capture, contact time of 8.5 h, KOH solution flow rate of 75	CO_2 capture efficiency was 14.8%, with a bicarbonate/carbonate ratio of 33%/67%.	[20]

Absorbent type	Operational condition	Optimal operating conditions	References
	cm^3/min, and air flow rate of 12 m^3/h		
Sodium Hydroxide (NaOH) solution	CO_2 directly from air with a gas flow rate of 0.7 dm^3/min, NaOH concentration of 6 wt.%, and absorption temperature of 5 to 20 °C.	The optimal condition was achieved at a system temperature of 20 °C, with 500 ppm of CO_2 absorbed.	[21]
Potassium Hydroxide (KOH) solution	Bubble column reactor type, direct air capture system, air flow rate of 0.075 dm^3/s, temperature range of 14 to 33 °C, KOH concentration of 250 g/L of water, pressure of 100 Pa.	No CO_2 capture occurred at temperatures above 30 °C, and the optimal temperature was 18 °C, with approximately 30% of CO_2 absorbed.	[22]
Potassium Hydroxide (KOH) solution	KOH concentration of 2 M, CO_2 concentration of 10%, room temperature, initial pH of 14.	A pH range of 10 - 11 resulted in optimal absorption capacity, reaching 164 g CO_2/kg.	[23]
N-Methyl cyclohexylamine (MCA) + KCl	Temperature of 313 K, CO_2 partial pressure ranging from 10 to 1,000 kPa.	Increases ionic conductivity with rising pressure but without affecting CO_2 solubility, with CO_2 around 3.5 mol CO_2/kg solution.	[24]
Monoethanolamine (MEA)	Flue gas directly contacted using ethanolamine (MEA).	Able to absorb 40% CO_2	[25]
Water (Simulation using Aspen Plus V.12.1 software).	Air temperature of 15 °C, flue gas temperature of 131.7 °C, CO_2 gas flow rate of 17.54 kg/s.	CO_2 capture reached 90%	[26]

Gas-liquid absorption processes are typically carried out in an absorber equipped with packing materials such as Raschig rings, Berl saddles, Intalox saddles, or structured packing like corrugated sheet metal which serves to enlarge the interfacial contact area between the gas and liquid phases (**Figure 1**). The interaction between gas and liquid within the absorber can be theoretically described by Eqs. (3) - (4) [27].

$$y_1 + L_2 X_2 = G_2 y_2 + L_1 X_1 \tag{3}$$

$$G_1 y_1 - G_2 y_2 = L_1 X_1 - L_2 X_2 \tag{4}$$

where G_1 and G_2 - Inlet and outlet CO_2 flow rates (dm^3/s), L_1 and L_2 - water flow rates (dm^3/s), y_1 and y_2 - Inlet and outlet CO_2 mole fractions in the gas phase (dimensionless), X_1 and X_2 - Inlet and outlet CO_2 mole fractions in the liquid phase (dimensionless).

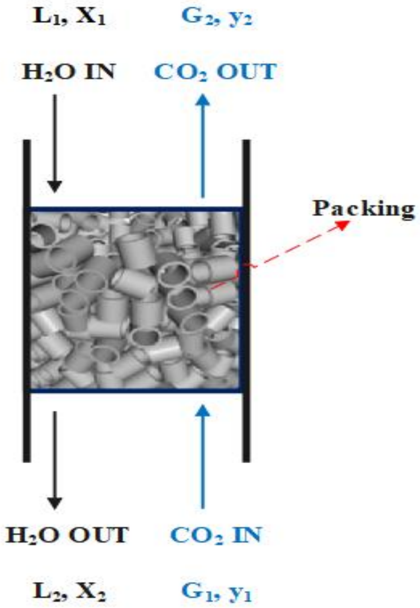


Figure 1 Illustration of the CO_2 capture process in a packed bed using packing material.

The effectiveness of CO_2 capture is influenced not only by the extent of contact between CO_2 gas and water, as shown in **Figure 1** where interaction begins as water absorbs CO_2, but also by the underlying diffusion and reaction mechanisms. As illustrated in **Figure 2**, the stages of the diffusion and reaction process involved in CO_2 capture using water as the absorbent are represented by a series of empirical equations, provided in Eqs. (5) - (9) [28,29]. Diffusion from the center of the CO_2 bubble to the gas-liquid interface layer.

$$\frac{dCO_2}{a\,dt} = k_g\ (Y_{CO2\,g} - Y_{CO2\,i}) \tag{5}$$

CO_2 gas equilibrium at the gas-liquid interface layer

$$Y_{CO2\,i}\ P_s = H_{CO2}\,X_{CO2\,i} \tag{6}$$

Diffusion of dissolved CO_2 from the gas-liquid interface layer into the bulk water phase

$$\frac{dCO_2}{a\,dt} = k_l\ (X_{CO2\,i} - X_{CO2\,b}) \tag{7}$$

Reaction occurring in the bulk liquid between water and CO_2

$$-\frac{dCO_2}{dt} = k_1 C_{CO2}\,C_{H2O} - k_2 C_{H_2CO_3} \tag{8}$$

Under steady-state conditions, the diffusion rate from the gas-liquid interface layer to the bulk water phase equals the rate of the chemical reaction, resulting in Eq. (9).

$$k_l\ (X_{CO2\,i} - X_{CO2\,b}) = k_1 C_{CO2}\,C_{H2O} - k_2 C_{H_2CO_3} \tag{9}$$

where $\frac{dCO_2}{a\,dt}$ – CO_2 flux (mol·dm^{-2} min^{-1}), k_g - gas-phase mass transfer coefficient (mol·dm^{-2} min^{-1}), $Y_{CO2\,g}$ - CO_2 mole fraction in the gas bulk phase (dimensionless), $Y_{CO2\,i}$ - CO_2 mole fraction at the gas-liquid interface (dimensionless), P_s - total system pressure (mmHg), $X_{CO2\,i}$ - CO_2 mole fraction in the liquid at the interface (dimensionless), H_{CO2} = Henry's constant (mmHg), a - surface are of the CO_2 bubble (dm^2), $X_{CO2\,b}$ - CO_2 mole fraction in the liquid bulk phase (dimensionless), and $\frac{dCO_2}{dt}$ - CO_2 mass transfer rate (mol·min^{-1}).

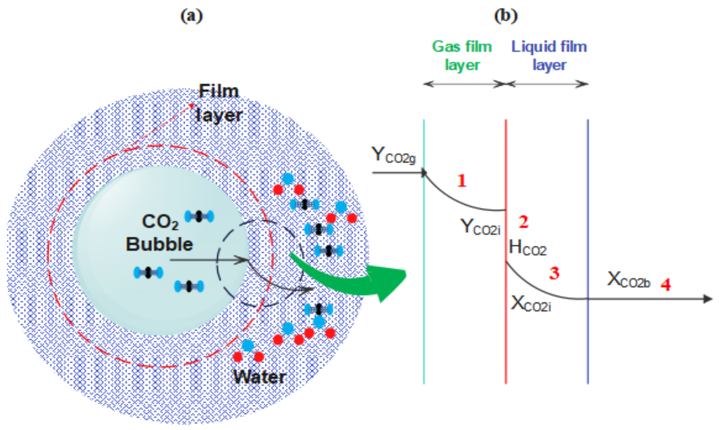


Figure 2 Diffusion-reaction concept in CO_2 capture by water: (a) Illustration of a bubble in water, (b) illustration of the diffusion process from the bubble core to dissolution in water and reaction forming H_2CO_3.

The success of CO_2 capture fundamentally depends on the effective interaction between the absorption process and the diffusion-reaction process. As such, the overall performance of CO_2 capture is governed by the interplay of these 2 mechanisms. To ensure both processes function optimally, it is essential to integrate the key variables that influence CO_2 capture, namely the CO_2 gas flow rate, water flow rate, water temperature, circulation time (contact time), and system pressure. This study aims to integrate these variables to optimize the CO_2 capture process. The rationale for combining them is grounded in several considerations: the flow rates of CO_2 gas and water directly affect CO_2 solubility in water (as indicated in Eqs. (3) and (4)), while system pressure, expressed as differential pressure, influences the CO_2 concentration at the gas and liquid interface (Eq. (6)). Additionally, both temperature and circulation time affect the diffusion rate and reaction kinetics (Eqs. (5), (7) and (8)). To assess the impact of this variable integration and develop a more comprehensive understanding, this study aims to analyze the phenomena and examine the effects of variables such as CO_2 gas flow rate, water flow rate, water temperature, circulation time, and differential pressure on the effectiveness of the CO_2 capture process, as indicated by the mass of CO_2 dissolved in water within the system.

Materials and methods

Materials and research equipment

The raw material used in this study was purified CO_2 gas with a purity level of 99.9%, stored in a cylinder purchased from CV Purnama Jaya Gas, located in Cilegon, Banten, Indonesia. As this research is still in its early stages, the focus was placed on exploring the fundamental phenomena and evaluating the effects of specific variables within controlled ranges on the performance of water-based CO_2 capture. Therefore, CO_2 from Direct Air Capture (DAC), which typically contains around 400 ppm, was not used. Instead, commercially available pure CO_2 was used to simplify the experimental process. The absorbent used was surface water that had been treated beforehand. The observation equipment consisted of a packed bed containing small cylindrical glass, each approximately 6×6 mm^2, with a total bed height of around 27 cm. Transparent glass was selected for both the bed and the packing material to allow clear visualization of the occurring phenomena. To maximize contact between the CO_2 gas and water, the gas was introduced from the bottom of the column. The absorption process was conducted continuously in a counter-current flow. A detailed illustration of the CO_2 capture setup using water as the absorbent is shown in **Figure 3**.

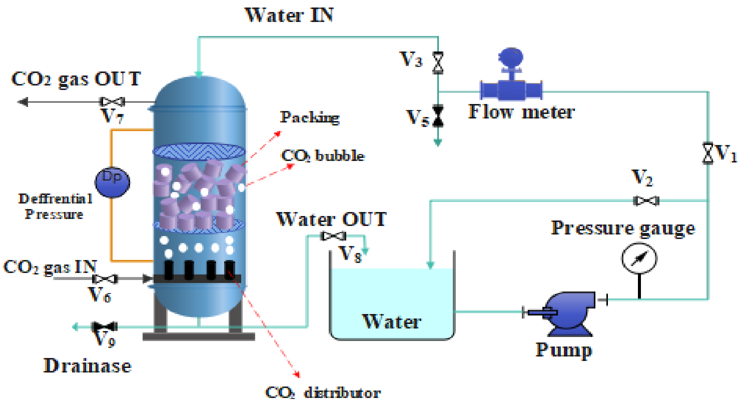


Figure 3 Illustration of CO_2 capture equipment using water as the absorbent.

Experimental procedure

To initiate the procedure, verify that every valve in the system is fully closed. Then, fill the water tank to 3 quarters of its capacity. Add ice to adjust the water temperature to the desired range of 24 to 30 °C. Open valves V_2 and V_3, then start the pump. Check that the pump pressure is above 1 bar to prevent cavitation. While doing so, open valve V_1 and observe the flow meter to ensure the water flow rate reaches the target of 0.25 and 0.5 dm^3/min. Open valve V_8 gradually and adjust it so that the input and output water flow rates are equal. Next, introduce CO_2 gas by opening valve V_6 and adjusting the gas flow meter to the specified rates of 2 and 4 dm^3/min. Then, open valve V_7 and adjust it until the desired differential pressure is reached, approximately 30 and 50 mmHg. Once the system has stabilized, this moment is recorded as time 0 min, and a sample is taken to analyze the initial CO_2 content in the water. After circulating the water absorbent for durations of 5, 10, and 15 min, the process is stopped, and a sample is collected from the V_8 outlet. This sample is then analyzed to determine the amount of CO_2 absorbed in the water during the process. The samples are analyzed using a titration method with 0.1 M NaOH as the titrant and phenolphthalein (PP) as the indicator. The mass of CO_2 absorbed into the water is calculated using Eq. (10).

$$m_{Co2} = M_{NaOH} \times V_{NaOH} \times W_{Co2} \qquad (10)$$

where, m_{Co2}- mass of CO_2 (g), M_{NaOH} - molarity of NaOH (M), V_{NaOH} - volume of NaOH (L), W_{Co2} - molecular weight of CO_2 (44 g/mol).

The concept presented in Eq. (10) is derived from the principle in Eq. (2), which states that the amount of H_2CO_3 is directly proportional to the amount of CO_2. During titration with NaOH, H_2CO_3 undergoes the reaction illustrated in Eq. (11).

$$H_2CO_3 + NaOH \rightarrow Na_2CO_3 + H_2O \qquad (11)$$

According to Eq. (11), the number of moles of H_2CO_3 is equivalent to the number of moles of NaOH, which in turn is equal to the number of moles of CO_2. By multiplying this value by the molecular weight of CO_2, the mass of CO_2 absorbed into the water at each sampling interval can be calculated. The titration was carried out in triplicate, and the results were averaged to enhance the reliability and accuracy of the data.

The selection of variables in this study was guided by several key considerations. The CO_2 gas flow rates of 2 and 4 dm^3/min were chosen based on the studies of Nuryoto *et al.* [14]; Nuryoto *et al.* [30], which showed that flow rates within this range enable effective interaction between CO_2 and absorbents such as calcium hydroxide and potassium hydroxide. The water flow rates were intentionally set at relatively low values, 0.25 and 0.5 dm^3/min, to allow for clear visual observation through the transparent glass column. The CO_2 capture process was carried out at temperatures ranging from 24 to 30 °C to evaluate capture behavior within this range and identify optimal operating conditions. Theoretically, CO_2 solubility in water decreases as the temperature increases [31]. However, if the temperature is too low, the reaction rate between CO_2 and H_2O may also decrease [32]. Therefore, a balance between solubility and reaction kinetics is essential. To maintain safe operating conditions, particularly due to the use of glass-based packing material, a low differential pressure of 30 and 50 mmHg was applied in this study. If Dp is too high, it may cause flooding, which prevents gas from flowing through the liquid and can result in process failure, ultimately reducing the efficiency of CO_2 capture. By selecting variables within these specified ranges, this study aims to develop a comprehensive understanding of the absorption process and its controlling factors.

Mathematical model testing

The mathematical approach applied in this study is based on a straightforward formulation using a pseudo-homogeneous model, as outlined in Eq. (2). The model was evaluated to facilitate its potential application in future technical scenarios and to support further development. Testing of the mathematical model was conducted only under the identified optimal operating conditions. For this purpose, the CO_2 concentration at time zero was measured using the same titration method, to obtain a more accurate value for the reaction rate constant. Several assumptions were made in the kinetic calculations. CO_2 was assumed to be continuously supplied and this present in excess. Under these conditions, the reverse reaction was considered negligible. Based on Eq. (2), the model can then be further developed into Eq. (12).

$$-\frac{dC_{CO_2}}{dt} = k_1\, C_{CO_2}\, C_{H_2O} - k_2\, C_{H_2CO_3} \tag{12}$$

Eq. (12) is identical to Eq. (8) and is then modified using the previously stated assumptions, resulting in Eq. (13).

$$-\frac{dC_{CO_2}}{dt} = k_1'\, C_{CO_2} \tag{13}$$

By multiplying Eq. (13) by the sample volume, the reaction rate is expressed as the rate of change in the number of moles of CO_2, as shown in Eq. (14).

$$-\frac{dn_{CO_2}}{dt} = k_1'\, n_{CO_2} \tag{14}$$

where: $k_1' = k_1\, n_{H_2O}$

Eq. (14) is then modified into a second order equation, resulting in Eq. (15).

$$-\frac{dn_{CO_2}}{dt} = k_1'\, {n_{CO_2}}^2 \tag{15}$$

Eqs. (14) and (15) are integrated to obtain Eqs. (16) and (17).

$$\ln n_{CO_2} = \ln n_{CO_2o} + k_1'\, t \tag{16}$$

$$\frac{1}{n_{CO_2}} = \frac{1}{n_{CO_2o}} + k_1'\, t \tag{17}$$

Eqs. (16) and (17) were fitted with a trendline using Microsoft Excel to obtain the value of k_1'. A mathematical model that produces an R^2 value close to one is considered appropriate for predicting the reaction rate in the CO_2 capture process examined in this study, across broader range of parameters. However, the model must still be validated against actual experimental data to confirm its reliability.

Results and discussion

Effect of CO_2 gas flow rate on CO_2 capture

At a differential pressure of 5 mmHg, the results presented in **Figure 4** show that increasing the CO_2 gas flow rate actually leads to a decrease in CO_2 capture performance. The mass of CO_2 absorbed at circulation times of 5, 10, and 15 min was 0.0072, 0.0077, and 0.0094 g, respectively for a gas flow rate of 2 dm^3/min, and 0.0061, 0.0072, and 0.0077 g for a flow rate of 4 dm^3/min. Assuming a constant CO_2 density of 1.977 gr/L [33], the total CO_2 mass entering the system at 5, 10, and 15 min is approximately 19.77, 39.54, and 59.31 g for the 2 dm^3/min flow rate, and 39.54, 79.08, and 118.62 grams for the 4 dm^3/min flow rate. These values indicate that while the total amount of CO_2 in the system increases the absorbed CO_2 does not rise proportionally. In fact, the opposite occurred. When the gas flow rate increased while circulation time remained the same, the amount of CO_2 capture decreased. Theoretically, increasing the CO_2 gas flow rate raises the gas velocity, which reduces the contact time or residence time between the gas and liquid in the packed area. This condition results in shorter gas and liquid interaction

[34,35], ultimately lowering the amount of CO_2 dissolved in water.

$$v = \frac{Q}{A} \tag{18}$$

where, v - CO_2 gas velocity (dm/s), Q - gas flow rate (dm^3/s), and A - cross sectional area of the column (dm^2).

As shown in **Figure 4**, the difference in CO_2 capture between gas flow rates of 2 and 4 dm^3/min is relatively minor. This is particularly evident at the 10 min circulation time, where the captured CO_2 mass was 0.0077 g for 2 dm^3/min and 0.0072 for 4 dm^3/min. However, when considering the other data points at 5 and 15 min, the CO_2 capture results exhibit a consistent trend, where longer circulation times tend to increase the amount of CO_2 absorbed. Based on these findings, further observations across a wider time range are necessary to establish a more reliable trend.

The phenomenon observed in this study was also reported in previous research (see **Table 2**).

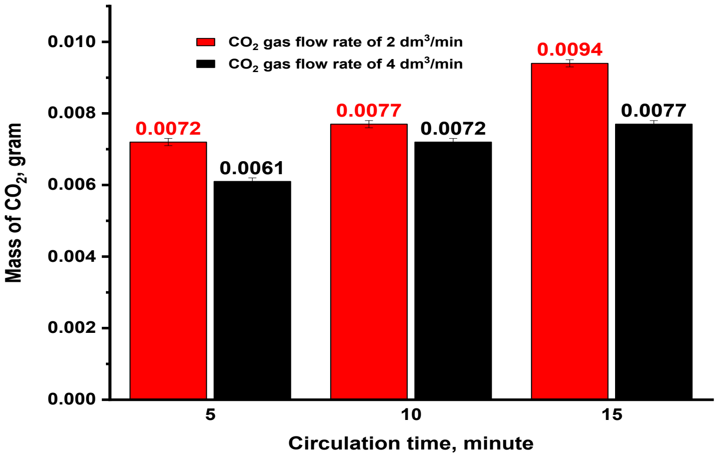


Figure 4 Effect of gas flow rate at a water temperature of 24 °C, water flow rate of 0.25 dm^3/min, and differential pressure of 50 mmHg.

Table 2 Effect of carbon dioxide gas flow rate on CO_2 capture.

Absorbent Type	Gas flow rate	Research findings	References
-	Methane gas flow rate of 1 to 20 standard liters per minute, using an adsorbent instead of an absorbent, specifically activated carbon.	An increase in the gas flow rate resulted in a decrease in the amount of methane gas adsorbed by activated carbon, from 467.4 to 419.1 dm^3.	[36]
Ethylenediamine (EDA)	The flow rate of CO_2 gas mixed with methane was set at 100 and 800 cm^3/min.	When the flow rate of the CO_2 and methane gas mixture was increased, gas capture efficiency decreases from an average of 95% at 100 mL/min to approximately 30% at 800 mL/min.	[37]
Water	CO_2 gas flow rates of 2 and 4 dm^3/min.	An increase in CO_2 gas flow rate affected CO_2 capture, with the best result obtained at a flow rate of 2 dm^3/min, yielding a CO_2 mass of 0.0094 g.	This research

As shown in **Table 2**, increasing the gas flow rate leads to a shorter interaction time between the gas and the absorbent, which acts as the capturing medium. This reduction in circulation time results in a decrease in gas capture efficiency. Hence, the phenomenon observed in this study is consistent with theoretical expectations. Based on both the current findings and previous research, it is advisable to carefully regulate gas flow rates, as excessively high values may compromise the effectiveness of the gas capture process.

Effect of water flow rate on CO_2 capture

As the water flow rate into the column increases, the mass of CO_2 absorbed into the water also rises significantly (**Figure 5**). At a flow rate of 0.25 dm^3/min, the amount of CO_2 dissolved in the water is relatively low when compared to the amount at 0.50 dm^3/min. Specifically, at circulation times of 5, 10, and 15 min, the CO_2 mass absorbed at a water flow rate of 0.25 L/min was 0.0072, 0.0077, and 0.0094 g (atau 0.0288, 0.0308, and 0.0376 $g/dm^3 \cdot min^{-1}$), respectively. In contrast, at a flow rate of 0.5 dm^3/min, the corresponding values were 1.045, 1.078, and 1.672 g (atau 2.09, 2.156, and 3.344 $g/dm^3 \cdot min^{-1}$). These findings clearly show that raising the water flow rate substantially enhances the CO_2 capture process. This improvement occurs because a higher water flow from the top of the column increases the likelihood of interaction between CO_2 gas and water in the packed section (**Figure 3**). As further supported by **Table 3** and previous studies, the flow rate of the absorbent entering the absorber column plays a crucial role in determining the efficiency and success of CO_2 capture.

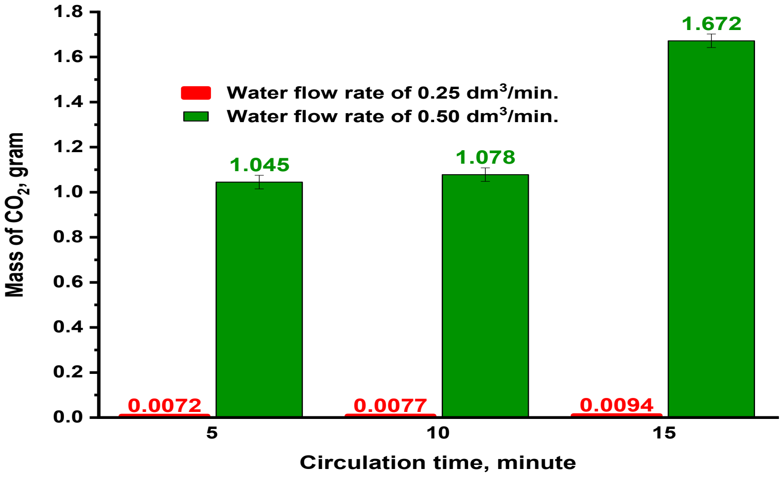


Figure 5 The effect of water flow rate conducted at a water temperature of 24 °C, CO_2 gas flow rate of 2 dm^3/min, and differential pressure of 50 mmHg.

A comparison of the observations in **Figures 4** and **5** clearly shows that variations in CO_2 gas flow rate had little effect on the increase in absorbed CO_2 mass. In contrast, the water flow rate had a significantly greater impact on the efficiency of the CO_2 capture process. This effect is attributed to the increased volume of water in the packing area at higher flow rates, which expands the contract surface between the CO_2 gas and the liquid phase [38,39], thereby enhancing the absorption process. On the other hand, increasing the CO_2 gas flow rate tends to reduce residence time, and excessive flow may cause channeling, which limits the effectiveness of gas and liquid interaction [38]. Based on the data in **Figure 5**, it can be concluded that in a packed column CO_2 capture system, the flow rate of the absorbent, namely water, plays a critical role in the overall success of the absorption process.

Table 3 Effect of absorbent flow rate on carbon capture.

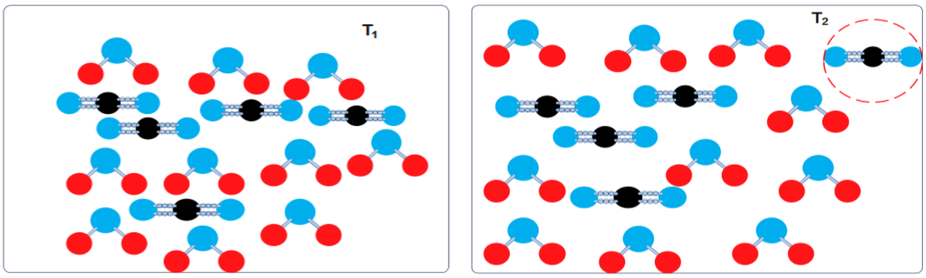
Absorbent Type	Liquid flow rate	Research findings	References
Ethylenediamine (EDA)	EDA flow rate increased from 100 to 800 cm^3/min.	The CO_2 removal increased from approximately 18% to 30%.	[37]
Ammonia solution	Ammonia solution flow rates of 0.6 and 0.9 dm^3/min.	The CO_2 removal achieved at flow rates of 0.6 and 0.9 dm^3/min was approximately 35% and 45%, respectively.	[40]
Monoethanolamine (MEA)	An increase in the liquid-to-gas (L/G) ratio from 2.5 to 10.	There was an increase in CO_2 removal efficiency as the L/G ratio rose, from approximately 27% to approximately 50%.	[41]
Water	Water flow rates of 0.25 and 0.5 dm^3/min.	An increase in water flow rate led to an improvement in CO_2 capture, with the best result obtained at a flow rate of 0.5 L/min, yielding 1.672 g of CO_2.	This research

Effect of water temperature on CO_2 capture

Increasing water temperature during the CO_2 capture process has a negative effect on absorption performance, as indicated by the decreasing mass of CO_2 absorbed by water (**Table 4**). **Table 4** shows that for every 3 °C increase in temperature, the amount of CO_2 absorbed decreases by approximately a factor of 100. This finding highlight that, in addition to gas flow rate, water temperature is a critical variable that significantly influences the efficiency of CO_2 capture when using water as the absorbent. According to the data, water-based CO_2 capture is more effective at temperatures below 24 °C. From a thermodynamic perspective, higher temperature increases the kinetic energy of water molecules while reducing their molecular density [42]. As a result, the capacity of water to absorb CO_2 diminishes. This principle is illustrated in **Figure 6**. On a microscopic level, this behavior can be explained using the concept of molecular kinetics of water [29,42]. At lower temperatures, water molecules have lower kinetic energy, causing them to be more tightly packed and orderly. This arrangement facilitates stronger interactions between water molecules and CO_2, increasing the likelihood that CO_2 will dissolve and remain trapped within the liquid structure. In contrast, at higher temperatures, water molecules gain more kinetic energy, leading to greater spacing and a more disordered structure. This makes it harder to retain CO_2 molecules and may even promote their release through desorption. This phenomenon is illustrated in **Figures 6(a)** and **6(b)**. In the lower temperature scenario shown in **Figure 6(a)**, water molecules are more densely arranged and more effective at capturing CO_2. Meanwhile, in the higher temperature scenario in **Figure 6(b)**, the likelihood of CO_2 being released increases. The illustration in Figure 6(b) highlights this with a circled CO_2 molecule that is no longer surrounded by water molecules, indicating a greater potential for desorption. Similar findings were reported in studies by Yang *et al.* [43]; Chen *et al.* [3] examined CO_2 capture using absorbent made from a mixture of water and an aromatic solvent. When the absorption temperature increased from 30 to 60 °C (303 to 333 K), the amount of CO_2 absorbed decreased from approximately 0.42 to 0.23 mol/mol. In a study by Chen *et al.* [3], carbon capture was investigated using amino acid salts (AAS). When absorption temperature was increased from 57 to 77 °C, the amount of CO_2 absorbed declined from 1.1 mol of CO_2/mol AAS to 0.9 mol/mol. These results suggest that gas absorption processes should be avoided at elevated temperatures, as such conditions may substantially reduce the efficiency of CO_2 capture.

Table 4 Effect of water temperature on CO_2 capture at 50 mmHg differential pressure, CO_2 gas flow rate of 2 dm^3/min, and water flow rate of 0.5 dm^3/min.

Time, minute	**Mass of CO2, gram**		
	Temperature		
	24oC	**27oC**	**30 oC**
5	1.04500	0.01437	0.00013
10	1.07800	0.01752	0.00033
15	1.67200	0.03553	0.00089



(a) (b)

Figure 6 Illustration of the movement and density of CO_2 and H_2O molecules: (a) at a lower temperature (T1), (b) at a higher temperature.

Effect of differential pressure (Dp) on CO_2 capture

As shown in **Figure 7**, increasing the differential pressure (Dp) from 30 to 50 mmHg positively influences CO_2 capture. At circulation times of 5, 10, and 15 min, the captured CO_2 masses at 30 mmHg were 0.44, 0.55, and 1.1 g, respectively, whereas at 50 mmHg, they increased to 1.045, 1.078, and 1.672 g. This corresponds to percentage increases of 136.36%, 96.36%, and 51.28%, respectively. These results indicate that elevating Dp in a gas-liquid absorption system can substantially improve CO_2 capture performance, provided that the pressure remains within safe operational limits to avoid flooding.

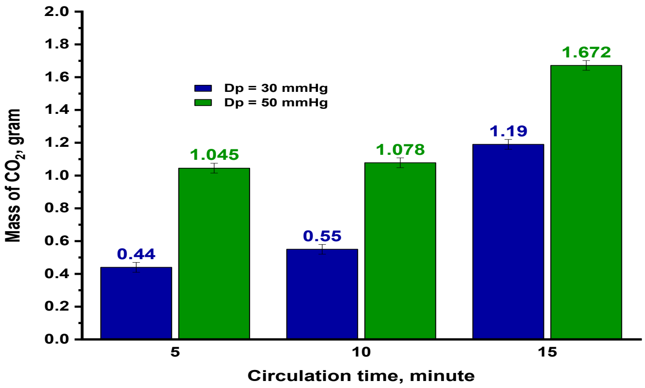
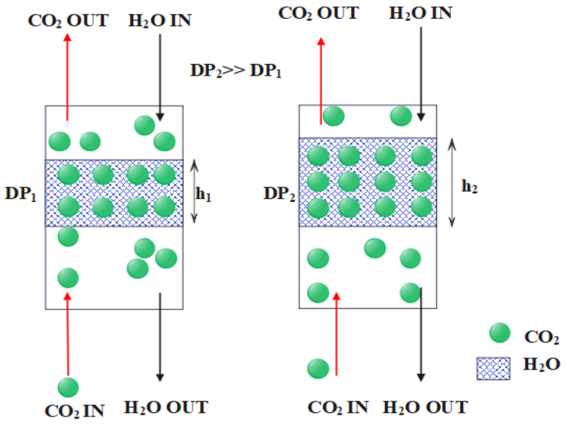


Figure 7 Effect of differential pressure at a water temperature of 24 °C, CO_2 gas flow rate of 2 dm^3/min, circulation time of 15 min., and water flow rate of 0.5 dm^3/min.

An increase in differential pressure (Dp) and its impact on CO_2 capture is conceptually illustrated in **Figure 8**. When Dp in the system is raised from 30 to 50 mmHg, the volume of water retained in the packing area visibly increases compared to the condition at 30 mmHg. This indicates that at Dp 50 mmHg (Dp_2), the amount of water absorbent in the packing region is greater than at Dp 30 mmHg (Dp_1), resulting in an expanded contact area between CO_2 and water. This phenomenon aligns with the area equation (Eq. (18)). As the volume of water in the packing area increases, the velocity of the CO_2 gas decreases, allowing for more effective gas liquid contact. Under these conditions, a greater number of CO_2 molecules can be absorbed into water, as illustrated in **Figure 8**. A similar finding was reported by Soo *et al.* [44], who investigated CO_2 capture using an amine based absorbent solution. When the system pressure was increased from approximately 1 to 10 bar, the amount of CO_2 captured rose from around 72 g of CO_2/kg of solution to 115 g of CO_2/kg of solution.

$$V = \frac{1}{4}\pi D^2 h \tag{18}$$

where, V - volume of the packed column filled with water where CO_2-water contact occurs (dm^3), π - 3.14, D - diameter of the column (dm), and h - height of the water in the column (dm).



(a) (b)

Figure 8 Illustration of the effect of differential pressure on the absorption of CO_2 in H_2O: (a) at low Dp, (b) at higher Dp.

To validate the CO_2 capture results obtained in this study, calculations were carried out using Eq. (6). As referenced in Smith *et al.* [29], the Henry's constant for CO_2 is 1.670 bar, equivalent to approximately 1,252,604 mmHg. By applying this equation and assuming a rapid diffusion process, the resulting CO_2 mole fractions were calculated and are presented in **Table 5**.

Table 5 CO_2 fraction absorbed under operating conditions of water flow rate at 0.5 dm^3/min and CO_2 gas flow rate at 2 dm^3/min with water temperature at 24 °C.

Input CO_2 gas fraction	System pressure	Sample mass (g)	CO_2 mass (g)	$H_{CO2\text{-}H2O}$ (mmHg)	CO_2 fraction (%)		**Deviation (%)
					Data*	Theoretical	
0.999	760	18	1.045	1,252,604	0.0580	0.0606	4.31
0.999	760	18	1.078	1,252,604	0.0600	0.0606	1.01
0.999	760	18	1.672	1,252,604	0.0930	0.0606	53.43

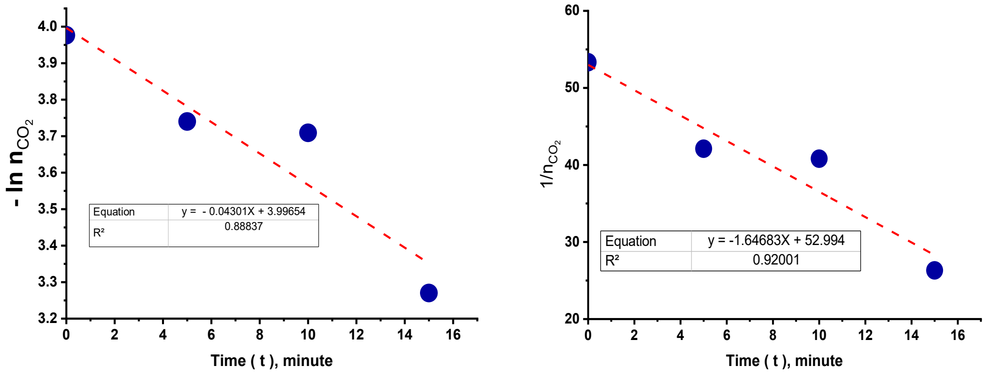
Note: * % data = (mass of CO_2/sample mass)×100%, ** % deviation = {(theoretical − data)/theoretical}×100%.

As shown in **Table 5**, the deviation between the experimental and theoretical data is minimal, particularly at the 10 min circulation time, where the deviation is only 1.01%. In comparison, the deviations at the 5 and 15 min circulation times are 4.31% and 53.43%, respectively. These results indicate that the phenomena observed in this study are generally consistent with theoretical expectations. The variation observed, indicated by a significant increase in deviation at the 15 min circulation time, is attributed to the accumulation of CO_2 mass in the water due to the recirculation process. In this system, the water exiting the absorber (from V_8) is recirculated using a pump and reintroduced into the system at intervals of 5, 10, and 15 min. As a result, the amount of CO_2 dissolved in the water increases with longer circulation times. The largest deviation occurred at the 15 min mark, reaching 53.43%. This deviation arises because the theoretical calculations, based on Eq. (6), assume ideal conditions without accounting for recirculation. In contrast, the actual experimental setup involves repeated circulation, which leads to a higher concentration of dissolved CO_2 than predicted theoretically. The data at the 15 min circulation time (**Table 5**) suggest that the water in the system had not yet reached its saturation point, meaning it still had the capacity to dissolve more CO_2, although at a gradually decreasing rate. Once the water reaches its maximum solubility, additional CO_2 will no longer be absorbed and may simply pass through the system and exit the packed column.

Based on existing literature, CO_2 capture technologies have advanced rapidly through a range of methods, including solid sorbents such as metal-organic frameworks, membrane-based systems [45], electrochemical direct air capture (DAC) [46], and absorption using potassium hydroxide (KOH) or monoethanolamine (MEA). These technologies offer high selectivity and efficient regeneration. However, their application often requires complex infrastructure and significant capital investment. In contrast, water is an abundant, low-cost, and environmentally friendly absorbent, making it a promising alternative for specific CCS applications. Given its many advantages, water has strong potential as an absorbent, and future research is expected to identify optimal operating conditions for its effective use.

Reaction kinetics testing

The calculation of reaction kinetics, using a pseudo-homogeneous approach and assuming that the circulation time equals the contact time, indicates that the R^2 value from the second-order model is higher than that of the first-order model. In the second order kinetic model, the R^2 value was 0.92, while the first order model yielded a value of 0.884 (**Figure 9**). Based on these results, the reaction rate in the CO_2 capture using water as the absorbent in this study follows a second order kinetic model, with a calculated rate constant k_1' of 1.6468 $mol^{-1}min^{-1}$. The resulting kinetic model, a second order mathematical expression, is useful for estimating the reaction rate of CO_2 mass once the CO_2 bubble has been absorbed into the water. However, further validation is required under different temperature conditions, particularly at temperatures below 24 °C.



(a) (b)

Figure 9 Reaction kinetics calculation results: (a) first order and (b) second order.

Critical analysis and industrial perspective

The data from this study show that increasing water flow rate, gas flow rate, reaction temperature, and differential pressure (ΔP) can improve CO_2 absorption performance in a packed column system operating with counter-current flow using water as the absorbent. These results provide useful initial insights and a foundation for further development. However, the study also has several limitations that need to be addressed. One limitation is the relatively low CO_2 capture achieved. Additionally, the gas used in the experiment had very high purity of 99.9% and was not sourced from direct air capture (DAC) with CO_2 levels around 400 ppm or from flue gas streams. The study also did not examine the regeneration or desorption process of CO_2 and relied on a basic mercury-based differential pressure measurement method. For future research, it is recommended to use lower concentration CO_2 sources (around 400 ppm) and standard measurement equipment to generate results that more closely reflect real industrial conditions. Based on the findings of this study, although the CO_2 capture efficiency using water is relatively low, it shows potential for application in industrial settings, particularly for pre-purification units or emission treatment processes with low CO_2 concentrations.

To enable large-scale industrial implementation, a comprehensive evaluation is necessary. This should include detailed analysis of energy consumption, equipment design, cost-benefit assessments, mathematical modelling that incorporates diffusion and reaction processes, and long-term operational feasibility. Additionally, broader experimental observations across a wide range of variables are required to develop a reliable water-based CO_2 capture system. These efforts are crucial to ensure that the system can serve as a cost-effective and environmentally friendly alternative for CO_2 capture. Although this research is still at an early stage, it has provided important foundational insights that can support the future development of water-based CO_2 capture technologies.

Conclusions

Increasing the water flow rate into the absorber and elevating the differential pressure (Dp) in the absorption system had a positive effect on CO_2 capture, as demonstrated by a substantial rise in the mass of CO_2 absorbed. When the water flow rate increased from 0.25 dm^3/min, the mass of CO_2 absorbed during a 15 min circulation time rose from 0.0094 to 1.672 g. Likewise, increasing the differential pressure from 30 to 50 mmHg increased the absorbed CO_2 mass from 1.10 to 1.67 g at the same circulation time (15 min). Conversely, the findings revealed that higher CO_2 gas flow rates and elevated water temperatures reduced absorption performance. At the same circulation time of 15 min, increasing the CO_2 gas flow rate from 2 to 4 dm^3/min resulted in a decrease in the mass of CO_2 absorbed, from 0.0094 to 0.0077 g. In addition, increasing the water temperature from 24 to 27 and 30 °C resulted in a drastic decline in absorbed CO_2 mass, falling from 1.6720 to 0.03553 and 0.00089 g, respectively. The key contribution of this study is its depth analysis of how operational parameters affect the performance of CO_2 absorption using water as the absorbent. These findings provide a valuable starting point for advancing more efficient CO_2 absorption technologies in industrial settings. As a preliminary study, this research has not yet examined key operation conditions such as sub-ambient temperatures (for example, 10 to 20 °C), higher differential pressures, or industrially relevant operating parameters that are theoretically known to enhance CO_2 solubility and thus improve absorption efficiency. Moreover, economic considerations such as cost-benefit analysis were not included and should be addressed in future studies.

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Declaration of generative AI in scientific writing

This article was written independently by the author without assistance from generative AI tools.

CRediT author statement

Rafiif Nur Tahta Bagaskara: Writing - Original draft preparation; Review & Editing. **Indah Lestari, Ester Tampubolon, and Faiz Muamar**: Data curation;

Investigation; Validation. **Nuryoto Nuryoto**: Conceptualization; Methodology; Supervision.

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