Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 120, Issue 1 (2024) 204-216

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Examination and Improvement of the Taguchi-Based Nanofluids Impact on CO_2 Absorption using Al_2O_3 Nanoparticles

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ARTICLE INFO

Article history:
Received 18 April 2024
Received in revised form 15 July 2024
Accepted 28 July 2024
Available online 15 August 2024

Keywords:
Taguchi; design of experiment; Al_2O_3; CO_2 absorption; nanofluid; nanoparticles; stirring speed

ABSTRACT

In this study, a batch absorption reactor was used to evaluate the nanofluid of a binary aqueous solution of monoethanolamine and 2-amino-2-methyl-1-propanol (MEA/AMP) with nanoparticles of aluminium oxide (Al_2O_3) as a solvent used to remove carbon dioxide (CO_2) from simulated flue gas. Furthermore, the application of the Taguchi experiment design method determined the optimal conditions for the absorption process. This research focuses on the CO_2 absorption process and the optimal conditions related to nanoparticle addition. The main effects of using nanofluid were investigated. The concentration of nanoparticles, nanoparticle size, and stirrer speeds were the evaluated factors. It found that the best conditions for using nanofluids in the absorption process were 0.00293 g/s, which is suitable for industrial applications using nanofluids.

1. Introduction

Recently, environmental issues have been exacerbated by the increased concentration of CO_2 in the atmosphere [1]. Though the emissions of CO_2 vary between pre-, post-, and oxyfuel combustion processes, only post-combustion has commercially available CO_2 absorption technology [2]. The importance of modeling and optimizing CO_2 removal from flue gas formed by fossil fuels utilized in power plants and industrial processes has increased significantly. Depending on the conditions and CO_2 emission source and concentration, many techniques can be used to separate CO_2, including adsorption, membrane, cryogenic, chemical, and physical absorption [3,4].

Many people consider the absorption of CO_2 to be a highly effective and popular method [5]. Industries have widely used the aqueous solution of an amine-based solvent to capture CO_2 [3,4-8]. Generally, various alkanolamines, like 2-amino-2-methyl-1- propanol (AMP), diethanolamine (DEA),

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https://doi.org/10.37934/arfmts.120.1.204216

triethanolamine (TEA), and monoethanolamide (MEA), capture CO_2 due to their high reactivity and availability.

However, because of its corrosively at high solvent concentrations and energy requirements for regeneration, this lessens the importance of this method [2,5-10]. Finding a new solvent superior to MEA is the most problematic challenge. We should evaluate a variety of solvents to identify the optimal one which has a high absorption capacity and low regeneration energy requirements. Consequently, many researchers focused on finding and developing a new solvent. They discovered that the combination of two or more types of amines improved their characteristics [2,10-19]. Furthermore, they found that the combination of AMP and MEA had a higher absorption capacity than MEA alone. Primary amines and sterically hindered amines demonstrate strong CO_2 kinetic reactions and high CO_2 absorption capacities [9,10]. So, it is possible to moderate the disadvantages of commonly used solvents by combining different types of amines. Lastly, researchers found that adding nanoparticles to many solvents accelerates both gas absorption and desorption [5,8-22]. They found that a suspension of nanoparticles in a suitable fluid, and loading enhances the solvent ability [7,22-27]. Further research is necessary to fully understand the impact of adding nanoparticles on the rate of mass transport in gas-liquid systems [5,14]. This study aimed to evaluate the influence of adding nanoparticles to bi-blend alkanolamine. Furthermore, the modifiable parameters were investigated in order to improve CO_2 removal efficiency. The optimization was performed using Taguchi's traditional method.

2. Experimental

2.1 Chemicals and Equipment

Sigma-Aldrich, an Indian company, supplied the MEA (98%) and AMP (98%) nanoparticles, as well as 99.9% pure silicon oxide (Al_2O_3) at 60, 80, and 100 nm. The flue gas simulation required no further purification; cylinders containing 99.99 percent N2 and 99.99 percent CO_2 were used. The apparatus included flow meters (Flowtech/U.S.A., N2 (25–250) ml/min, CO_2 (25–250) ml/min), an ultrasonic cleaner, and a CO_2 analyzer (Atmocheck double CO_2/U.S.A., Range (0.00–100%)), as well as a maximum temperature of 60°C.

2.2 Preparation of Nanofluid

Figure 1 demonstrates the experimental nanofluid preparation process. MEA and AMP aqueous solutions of 1.5 and 1.5 molar quantities were mixed to create the base solvent. Then, nanoparticles of Al_2O_3 were sprayed into the solvent (1.5M MEA/1.5 AMP) using ultrasound to ensure distribution [1,27]. Figure 2 depicts the results of a visual examination of the nanofluid container at 24 hours to determine its stability. The experiments' nanofluids were created in accordance with Figure 1.

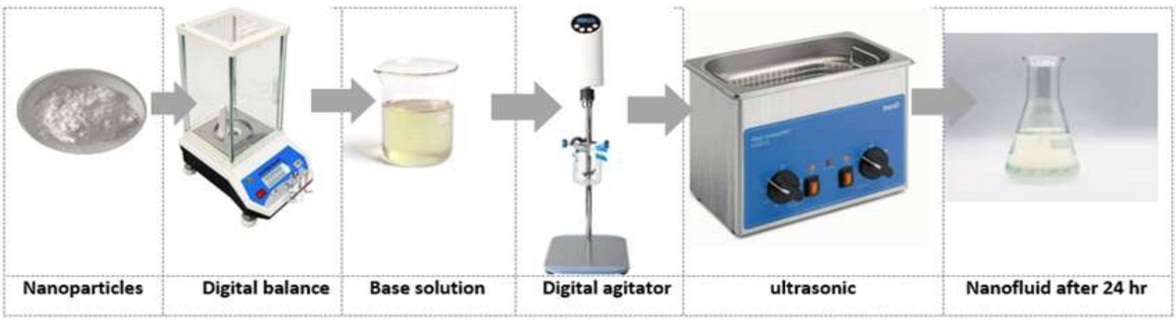

Fig. 1. The procedures for preparing nanofluids

2.3 Absorption Experiment

Figure 2 describes the experiments of CO_2 absorption were conducted at 1 atm pressure and a room temperature of 298 K in a 500-mL three-neck glass reactor. The gas streams of CO_2 and N2 were combined to achieve the required CO_2 ratio (15 volume) using a flow meter. After that, the gas was introduced into the nanofluid via the absorption cell, and a CO_2 analyzer monitored the gas's escape from the absorption cell until the nanofluid reached CO_2-saturation. Eq. (1) shows how to use a CO_2 gas analyzer to measure the difference in CO_2 flow rates at the input and output of a gas-phase absorber [1].

$$\boldsymbol{R = F_{in} - F_{out}/m * 22.4 * 1000} \tag{1}$$

R represents the rate of CO_2 intake in moles per kilogram per minute. The Fin variable represents the inlet gas flow rate, which is measured in milliliters per minute. Fout: The outlet's gas flow rate in milliliters per minute.

The solvent absorption rate is represented by A, in moles per kilogram per minute. In milliliters per minute, '' denotes the rate of gas flow out of the outlet. M: quality of solvent per kilogram. Figure 2 and Figure 3 display the CO_2 absorption experiment.

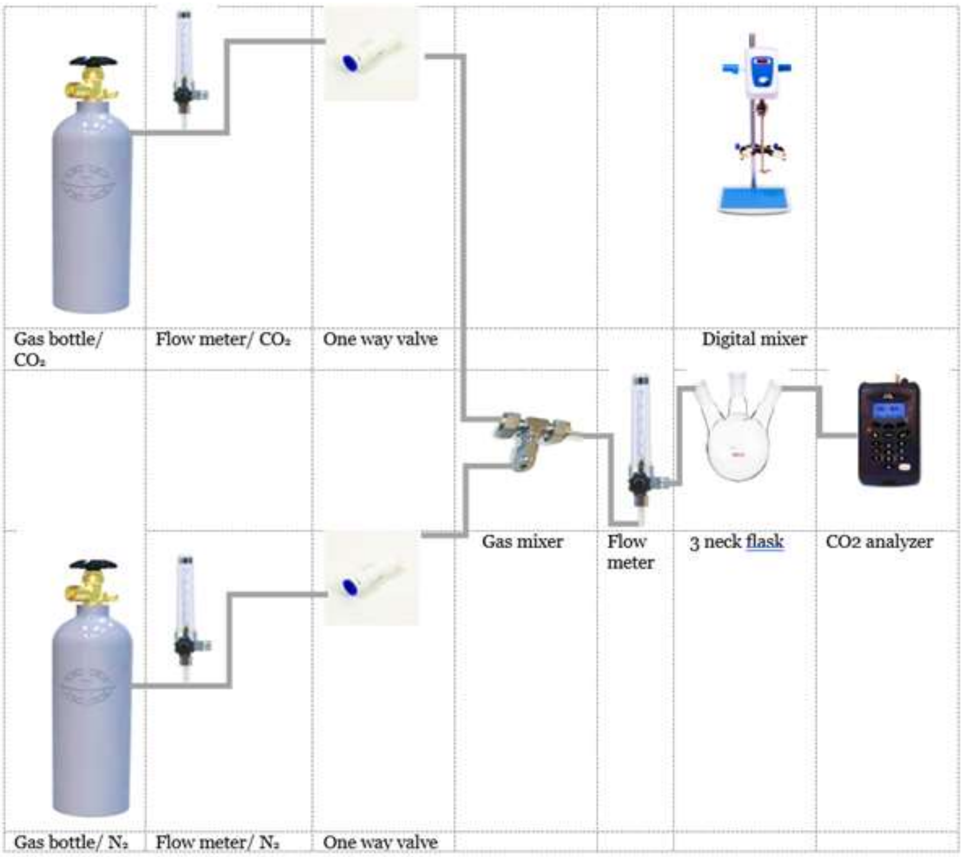

Fig. 2. The experiment process for CO_2 absorption

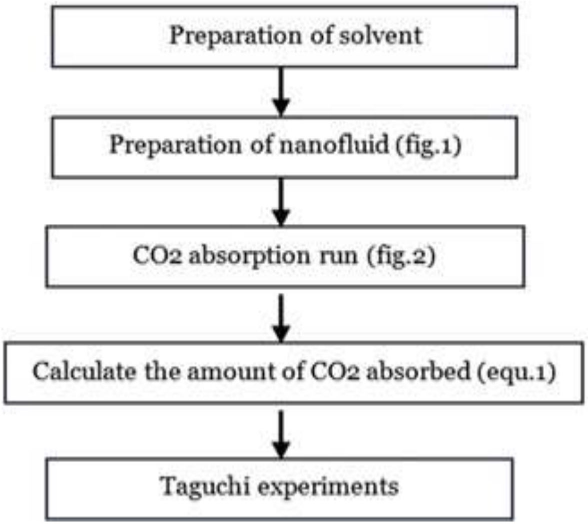

Fig. 3. The schematic of the CO_2 absorption experiment

3. An Experiment Design Process (DOE)

The application of design of experiment (DOE) based statistical methods is an effective approach for analyzing experimental data to observe the influence of various control factors on objective functions. In addition, this technique allows for process optimization and CO_2 absorption rate evaluation. The Taguchi optimization method is a well-established, unique, and long-lasting discipline that allows for optimization with few tests [22,26,27]. The factors that had a considerable influence on the CO_2 absorption rate using nanofluid were identified.

This study examined three factors related to nanoparticles, the stirrer speed (coded A), with levels (1, 4 rpm); the nanoparticle concentration of Al_2O_3 (coded B), with three levels (0.05, 0.1, and 0.15 vol. %); and the nanoparticle size (coded C), which has three levels (60, 80, and 100 nm). The L18 (3^3 2^1) array shown in Table 1 is the right orthogonal array for the Taguchi experiment design because it lets us study how the parameters disturb these mixed levels and the interaction between them.

Table 1
L18 orthogonal array for Coded values

Exp. No.	Coded Values		
	A/ (stirrer speed)	C/ (nanoparticles size)	B/ (nanoparticles concentration)
1	1	0.01	60
2	1	0.01	80
3	1	0.01	100
4	1	0.05	60
5	1	0.05	80
6	1	0.05	100
7	1	0.1	60
8	1	0.1	80
9	1	0.1	100
10	4	0.01	60
11	4	0.01	80
12	4	0.01	100
13	4	0.05	60
14	4	0.05	80
15	4	0.05	100
16	4	0.1	60
17	4	0.1	80
18	4	0.1	100

To evaluate the experimental results, a signal-to-noise (S/N) ratio analysis is required. The Taguchi approach divides the performance characteristics (S/N) into three categories: "larger is the better (LB), nominal is the best (NB), and smaller is the better (SB)." The goal of this study was to use the greater-is-better standard. The S/N ratio with LB features can be calculated using Eq. (2), as follows [26,27]

$$\boldsymbol{S/N_{LB} = -10\log\frac{\left[\sum_{i=1}^{n} 1/y_i^2\right]}{n}} \tag{2}$$

where $\boldsymbol{y_i}$ represents the experiment's effectiveness and n is the number of times the exact same experimental conditions were repeated. The MINITAB 17 software was used to analyze the experimental data.

4. Results and Discussion

4.1 Signal-to-Noise Ratio Analysis and Optimization

MINITAB 17 program was used to find the relation of the CO_2 absorption rate and the nanofluid essential factors. Also, equation of the multiple linear regression was generated to study the influence of each factor statistically. Eq. (3) signifies the percentage of CO_2 absorption rate; the correlation coefficient R seq., which is equal to 94.28%, shows how well the model fits the data.

Table 2 displays the expected and experimental values for the CO_2 absorption rate. As well as the expected CO_2 absorption rates from Eq. (3), which can be seen in Table 2, there are also the S/N ratios for each experimental response from Eq. (2). A comparison of the predicted and experimental results based on Eq. (3) is shown in Figure 4. It is evident that the model accurately predicts the rate of CO_2 absorption, and Eq. (3) may be considered a helpful tool for process assessment.

$$\boldsymbol{CO_2\ absorption\ rate = 0.003022 + 0.000024 * X_1 + 0.001583 * X_2 - 0.000008 * X_3} \tag{3}$$

Table 2
Experimental and predicted values of CO_2 absorption rate and S/N ratios outcomes of all experiments

Exp. No.	Stirrer speed (rpm)	nano conc. (vol%)	nano size (nm)	Experimental CO_2 absorption rate (g/s)	predicted CO_2 absorption rate (g/s)	S/N Ratio
1	1	0.05	60	0.00267	0.00264515	-51.65
2	1	0.05	80	0.00255	0.00248515	-51.41
3	1	0.05	100	0.00235	0.00232515	-51.14
4	1	0.1	60	0.0027	0.0027243	-50.79
5	1	0.1	80	0.00265	0.0025643	-50.50
6	1	0.1	100	0.0024	0.0024043	-50.18
7	1	0.15	60	0.00285	0.00280345	-49.76
8	1	0.15	80	0.00261	0.00264345	-49.44
9	1	0.15	100	0.00254	0.00248345	-49.01
10	4	0.05	60	0.00277	0.00271715	-48.52
11	4	0.05	80	0.00254	0.00255715	-48.05
12	4	0.05	100	0.00247	0.00239715	-47.42
13	4	0.1	60	0.00278	0.0027963	-46.64
14	4	0.1	80	0.00262	0.0026363	-45.90
15	4	0.1	100	0.0025	0.0024763	-44.89
16	4	0.15	60	0.00293	0.00287545	-43.41
17	4	0.15	80	0.00277	0.00271545	-41.89
18	4	0.15	100	0.0026	0.00255545	-39.15

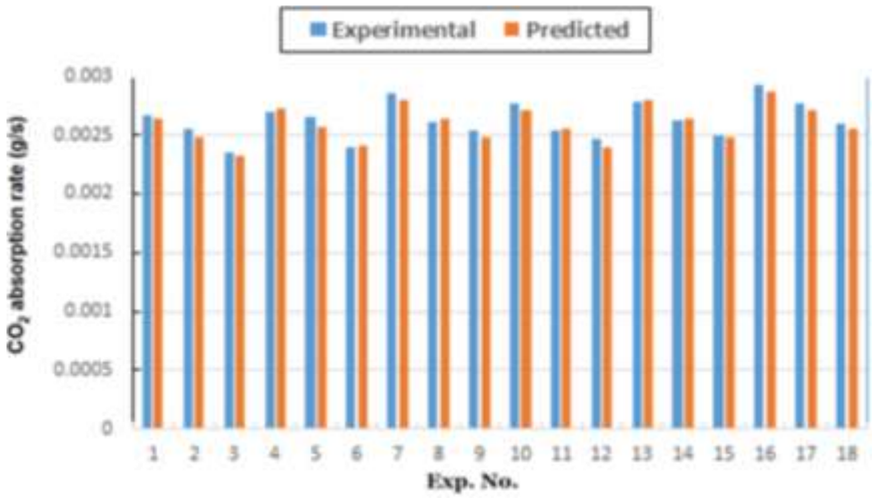

Fig. 4. Displays the actual and predicted rate of CO_2 absorption

The mean of each factor's reaction at each level is shown in Table 3, as seen in Figure 5. The mean's results indicate that the following is the order in which the most crucial factors are listed: Concentration (vol%) > nanosize (nm) > speed (rpm).

Table 3
Computed average response for information gathered from CO_2 absorption

Level	A	B	C
1	0.002591	0.002558	0.002783
2	0.002664	0.002608	0.002623
3	-	0.002717	0.002477
Delta	0.000073	0.000158	0.000307
Rank	3	2	1

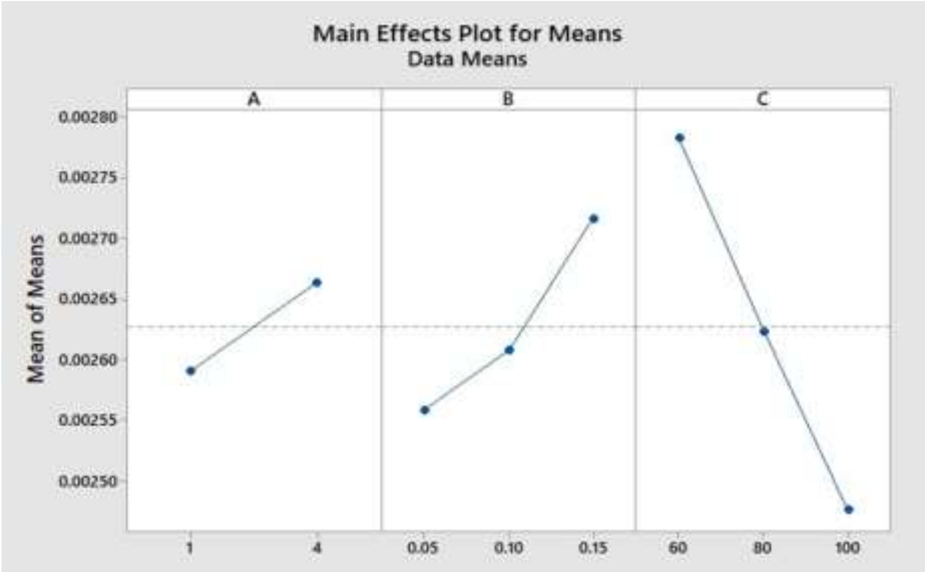

Fig. 5. Main effect plot for CO_2 absorption mean values

Table 4 displays the response table for the four investigated components' ranks and estimated signal noise ratios (LB), which are graphically shown in Figure 6; using delta statistics, the proportions of effects are compared to determine the rankings. The delta statistics are computed by deducting the biggest average for a given parameter from the lowest average [26]. The rate at which CO_2 is absorbed increases with the S/N ratio. The order in which each component was ranked makes it abundantly evident that the concentration of nanoparticles is the most important factor.

Table 4
S/N response table (bigger is better)

Level	Speed (rpm)	Concentration (vol.%)	nano size (nm)
1	-51.74	-51.85	-51.11
2	-51.50	-51.68	-51.63
3	-	-51.33	-52.13
Delta	0.24	0.52	1.01
Rank	3	2	1

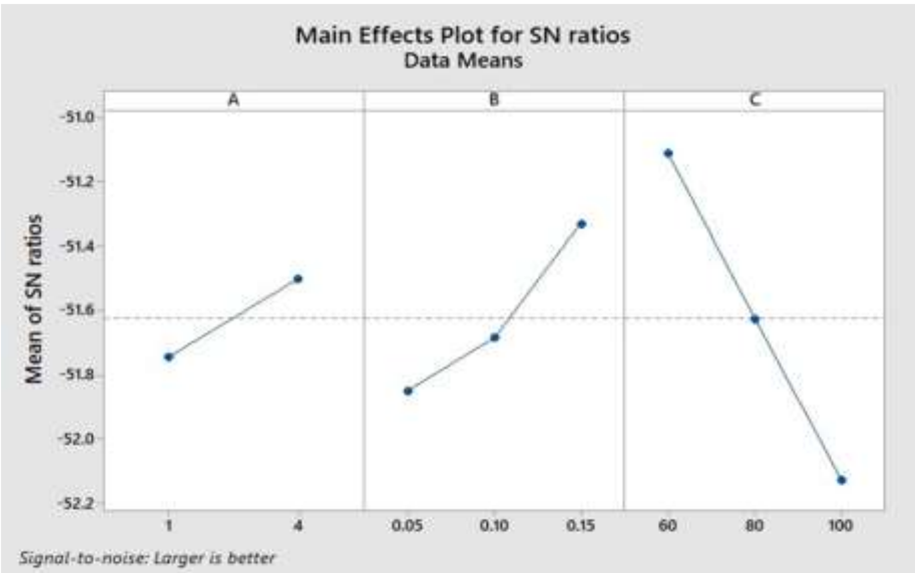

Fig. 6. Major effect S/N plots for CO absorption (higher is better)

4.2 Analysis of Variance (ANOVA)

The statistical method (ANOVA) was used to examine the effect weight of each factor. In the study, each principal component displays the total variance obtained, which is composed of an unobserved difference. “The more you write a section for each parameter studied, the more specifically it will spread. This can also help in better understanding the final results and the probability of performing the test under controlled pressure. ANOVA was calculated using degrees of freedom (DF), sums of circles (SS), the ratio of the effect of each parameter, the adjusted modifier combinations (Adj SS), the adjusted mean squares (Adj MS), the F-value, and the P-value. These are the values saved for each controllable creature [25,26].

Table 5 shows the ANOVA results of all experiments. Based on the following, regarding the most important factors affecting absorption efficiency: According to their contribution ratio, force (volume%) > speed (cycle in detail) > differential (nm). The P value, which is defined as the correlation between the sum of the squares of the parameters and the sum of the squares, can also be used to account for the significance of each component in the compensation. If the p-value is less than 0.05 (at the 95% confidence level), it is considered a significant parameter [25]. P values (based on a 95% confirmed score) indicate that this factor was significant. However, speed (rpm) and variety (nm) have not been much in the scope of scientific research.

Since F > 1 for controlled parameters, there is less error from these connection variances, which means that this factor may have a significant influence on the responses [26].

Table 5
Examining the absorption of CO_2 by Analysis of Variance (ANOVA)

Source	DF	Seq. SS	Contribution %	Adj. SS	Adj. MS	F-Value	P-Value
mixing speed (rpm)	1	0.000000	5.98	0.000000	0.000000	14.82	0.002
nano concentration (vol.%)	2	0.000000	19.42	0.000000	0.000000	24.08	0.000
nano size (nm)	2	0.000000	69.76	0.000000	0.000000	86.47	0.000
Error	12	0.000000	4.84	0.000000	0.000000	-	-
Total	17	0.000000	100	0.000000	0.000000	-	-

4.3 Impact of Operational Factors

4.3.1 Effect of Al_2O_3 nanoparticle concentration (vol. %)

Figure 7 and Figure 8 show the Al_2O_3 nanoparticles concentration (vol. %) influence on the carbon dioxide absorption rate using Eq. (3) at different speed rates. It is clear that increasing the concentration of nanoparticles increases the expected absorption rate as a result of increasing the transfer area of the material, which is consistent with previous studies [27]. When the F value was 0.05 or less than 1 and the contribution ratio was 0.05%, the S/N and ANOVA results showed that the chosen range of nanoparticle concentration had a significant effect on the CO_2 adsorption rate, indicating that it was not an important factor in the process performance.

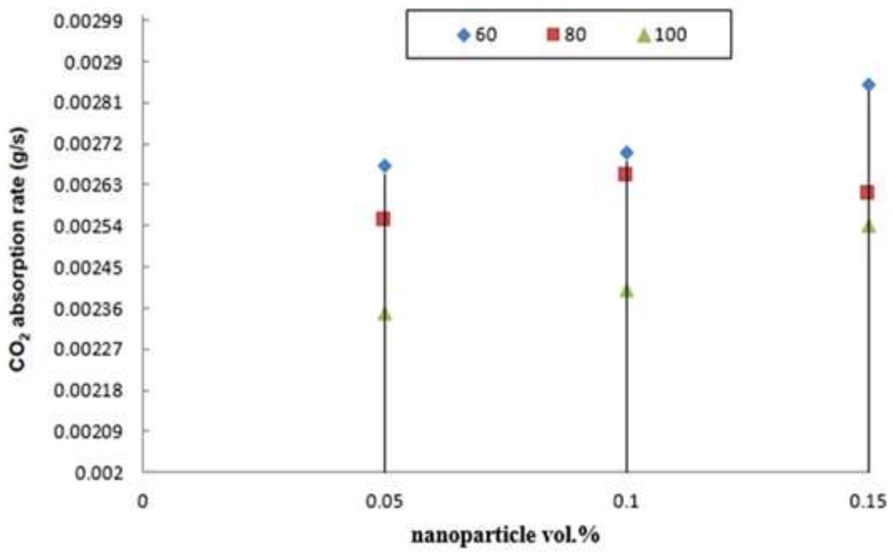

Fig. 7. The impact of Al_2O_3 nanoparticle concentration on the CO_2 absorption rate at (1 rpm)

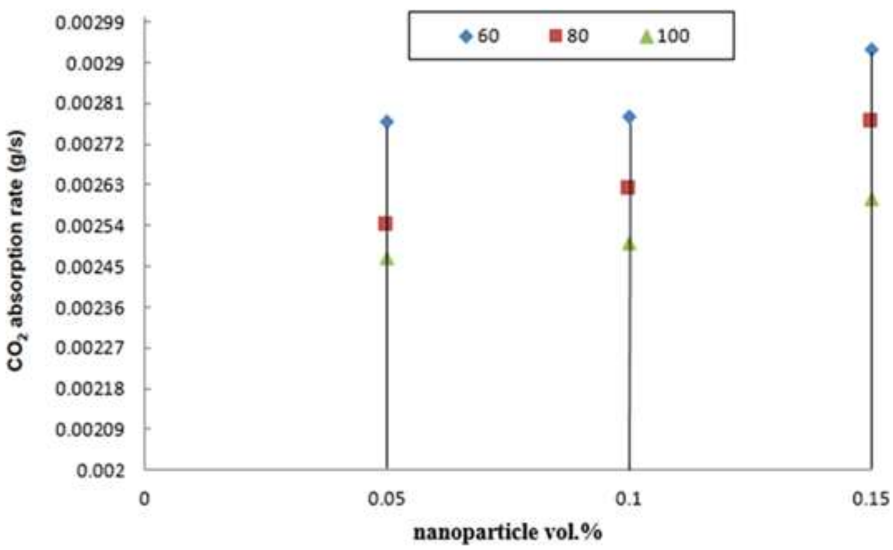

Fig. 8. The impact of Al_2O_3 nanoparticles concentration on the CO_2 absorption rate at (4 rpm)

4.3.2 Effect of stirred speed

Nanofluid stirring speed is one of the most influential characteristics that affecting the absorption of CO_2. Figure 9, Figure 10, and Figure 11 show the effect of stirring speed on the absorption rate. This parameter's value directly affects the amount of carbon dioxide absorption. In addition to Brownian motion, accelerating the stirring process increases the contact area of the ripped gas bubbles with the liquid and nanoparticles, thereby accelerating the rate of CO_2 absorption [1]. Eq. (3) generated Figure 9, Figure 10, and Figure 11 to illustrate the effect of increased stirring speed on CO_2 adsorption using nanofluid. (3). It was found that increasing stirring increases the absorption rate from 0.0026 to 0.00293 g/s. The S/N data indicate that an increase in current density leads to higher an S/N values.

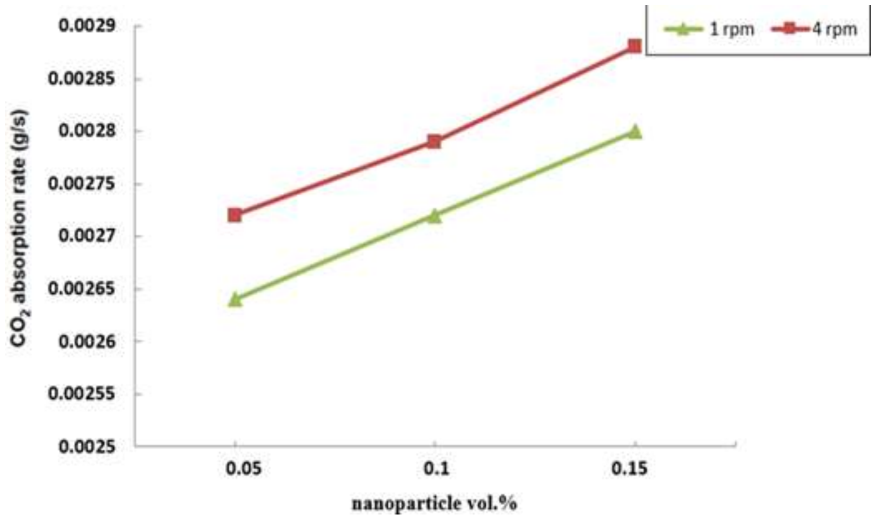

Fig. 9. Shows the impact of stirrer speed on the rate of CO_2 absorption for Al_2O_3 nanoparticles with a size of 60 nm

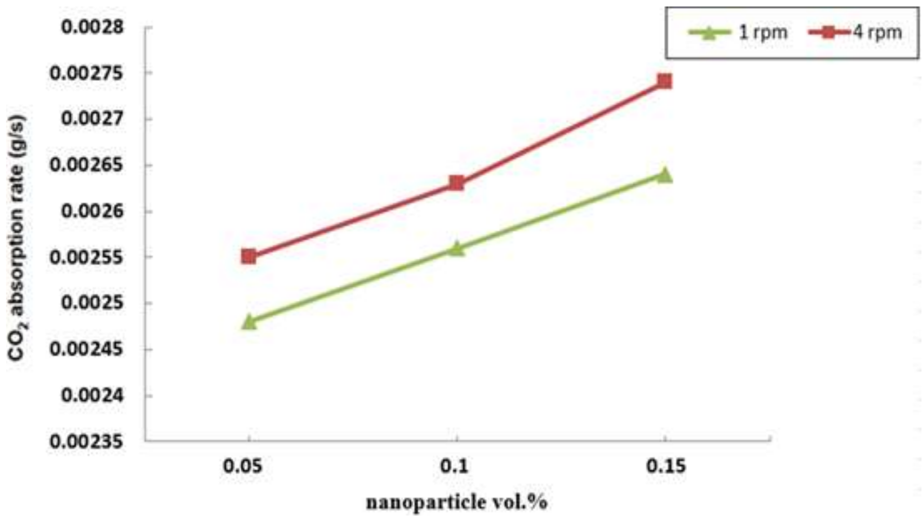

Fig. 10. Shows the impact of stirrer speed on the rate of CO_2 absorption for Al_2O_3 nanoparticles measuring 80 nm

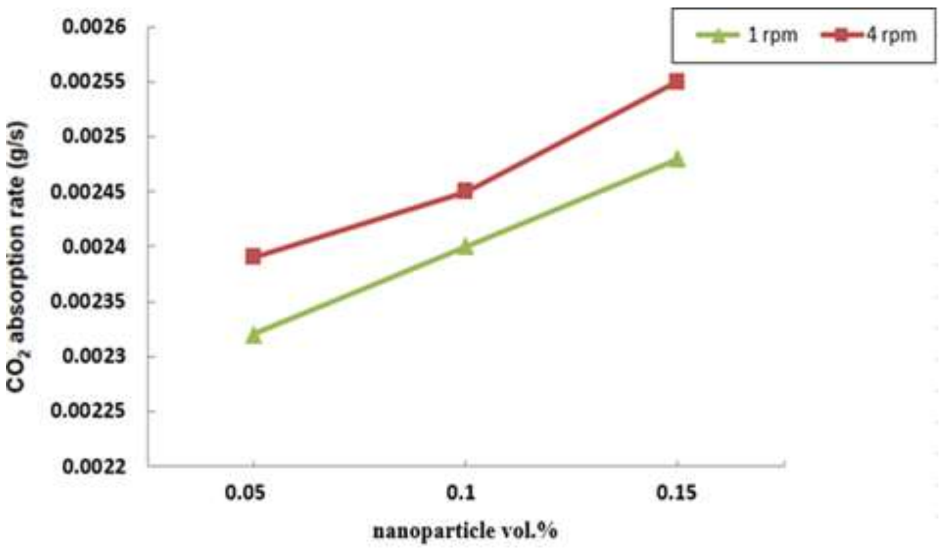

Fig. 11. Shows the impact of stirrer speed on the rate of CO_2 absorption for Al_2O_3 nanoparticles with a size of 100 nm

4.3.3 The impact of Al_2O_3 nanoparticles size

The results of the S/N and ANOVA in this study indicated that the performance of the CO_2 absorption rate was least affected by nanoparticle size. As the size of the nanoparticles increases, the rate of CO_2 absorption decreases. Figure 12 and Figure 13 make the impact of nanoparticle size very evident, which was plotted at two different speeds—1 and 4 rpm using Eq. (3). It is clear that the rate of CO_2 absorption is slowed down when the size of the nanoparticles increases.

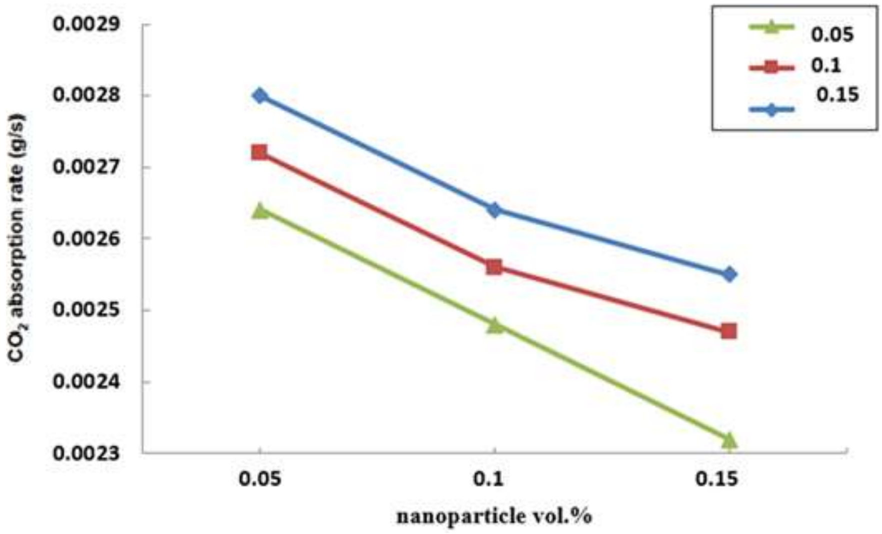

Fig. 12. The impact of Al_2O_3 nanoparticles size at 1 rpm on the rate of CO_2 absorption

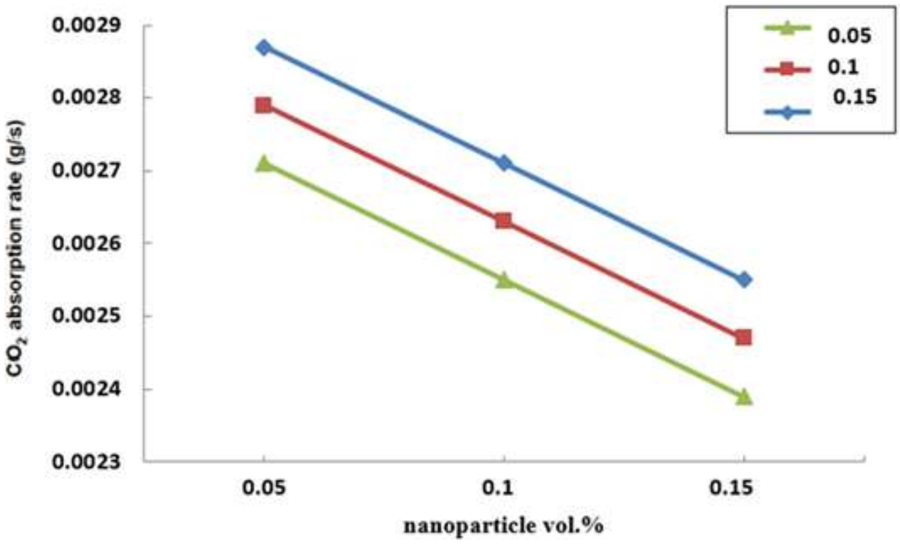

Fig.13. The impact of Al_2O_3 nanoparticles size at 4 rpm on the rate of CO_2 absorption

5. Conclusion

The current study treats flue gas through the use of nanofluid in the CO_2 absorption process. To find out how the size, concentration, and stirrer speed of the nanoparticles affected the rate of CO_2 absorption, these factors were investigated.

The nanofluid parameters were optimized using the Taguchi method. The S/N and ANOVA results, which were in this order: stirrer speed > nanoparticle size > concentration of nanoparticles, confirmed the significance of the nanoparticle parameters. The ideal parameters were 4 rpm, 60 nm, and 0.1 vol. %. The present study's results indicate that the three most important parameters were the size, concentration, and stirrer speed of the nanoparticles. Shown a moderate impact on the rate of CO_2 absorption in earlier research. Under ideal circumstances, two confirmation tests produced CO_2 absorption rates greater than 0.00293 g/s.

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