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Analysis of the Impact of Nanofluids on the Improvement in CO_2 Absorption using Taguchi Method

Safa Waleed Shakir[1], Sarah Saad Mohammed Jawad[2], Zainab Abdulmaged Khalaf[3,*]

[1] Department of Chemical Engineering, College of Engineering, University of Tikrit, Iraq
[2] Department of Chemistry, College of Education, University of Samarra, Iraq
[3] Department of Electromechanical Engineering, College of Engineering, University of Samarra, Iraq

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ABSTRACT

Capturing Carbon dioxide (CO_2) has been the most crucial issue due to the dangerous impact of emissions of CO_2 on the warming of globe and climate change. A novel class of solvent has been effectively employed in absorption technology in recent decades to eliminate CO_2. The process of employing nanofluids to enhance CO_2 uptake is receiving a lot of attention. However, other studies are needed to enhance the nanofluid absorption rate. The purpose of this study was to use nanofluid (based on amines) to optimize the absorption process for CO_2 from flue gas. The technique was designed to extract CO_2 from exhaust gas. This paper discusses the removal of CO_2 from flue gas and parameter adjustments that increase overall removal efficiency. The nanoparticle concentration, stirring speed, and nanoparticle size were all varied during the tests. The experimental design using Taguchi method was applied to determine the optimal conditions of nanofluid for the process of absorption. Taguchi experimental design to investigate the perfect setting for the highest possible rate of CO_2 absorption. The best settings were found to be a nanoparticle beginning concentration of 0.01 vol%, a stirrer speed of 4 rpm, and a nano size of 60 nm, according to the results of multiple regression and signal to noise ratio (S/N). Additionally, the analysis of variance (ANOVA) was used to determine the relative significance of each factor. The results show that the proportion of contributions were as follows: mixing speed (rpm) 46.56%, nano concentration (vol.%) 4.33%, and nano size (nm) 43.18%. The most useful parameter was the mixing speed (rpm). The experimental and anticipated values agreed well with regression analysis (R2=97.26%), and the findings of the confirmation test demonstrated that the CO_2 absorption rate was 0.0029 g/s; a success that is highly advantageous for industrial uses.

1. Introduction

Recently, the importance of the design, simulation, and optimization of CO_2 separation from flue gas in the fossil fuel used in power plants and numerous businesses has grown dramatically. The rise in CO_2 emissions in the atmosphere is developing ecological problems [1]. The pre-, post-, and oxyfuel combustion methods all produce CO_2 in varying amounts, but only the post-combustion CO_2 capture

* *Corresponding author.*
E-mail address: zainab.abd@uosamarra.eu.iq

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technology is now accessible on a fully commercial scale [2]. In addition, CO_2 can be separated in a variety of ways, depending on the conditions, including adsorption, membrane, cryogenic separation, and chemical or physical absorption [3,4]. One of these techniques is CO_2 capture via a chemical absorption mechanism, which is thought to be highly effective [5]. In CO_2 capture by amine processes, the separation of CO_2 is carried out in an absorption-desorption unit. Chemical absorption using aqueous alkanolamine solutions is the most popular method of CO_2 capture [3,4]. Various alkanolamine solutions, such as monoethanolamine (MEA), diethanolamine (DEA), and triethanolamine (TEA), are used for CO_2 capture. Alkanolamines can be divided into numerous classes, each with unique physical and chemical characteristics. In general, MEA and DEA have high reactivity with CO_2 and require a lot of energy to regenerate. (TEA) has a low energy requirement for regeneration and a gradual reaction with CO_2. They also have a high loading capacity [2-4].

Additionally, these amines are comparable to tertiary amines in terms of the loading capacity of sterically hindered amine (AMP). The aqueous solution of MEA has been widely employed as the predominant amine in the carbon dioxide (CO_2) absorption process. that is due to its favorable reaction kinetics with CO_2, cost-effectiveness, and user-friendly nature. Nevertheless, the primary obstacles associated with the utilization of MEA were the substantial energy requirements for regeneration, its deterioration, and its corrosive nature [2,5]. The biggest obstacle to post-combustion capture technology is, therefore, the search for new solvents that are superior to MEA.

In order to choose a solvent possessing a high absorption capacity and low energy requirements for regeneration, it is important to thoroughly evaluate a range of solvents. Consequently, the primary concern for scientists was the discovery and advancement of novel solvents. The researchers discovered that the addition of multiple types of amines to a single amine compound resulted in the enhancement of its features [2,6-9]. It was also observed that the coexistence of AMP and MEA resulted in a higher absorption capacity compared to the utilization of MEA. The primary amine (MEA, DEA, etc.) exhibits a strong kinetic interaction with CO_2. On the other hand, sterically hindered amine possesses a significant capacity for CO_2 absorption [9,10].

Consequently, the combination of amines has the potential to alleviate the limitations associated with commonly employed solvents. Furthermore, recent research has indicated that the introduction of nanoparticles into the solvent has the effect of accelerating the processes of gas absorption [5,8]. Nanofluids are formed by suspending particles having a diameter of 100 nm or less in a certain solvent [7,11]. Also, further investigation is required to ascertain the impact of nanoparticle size, stirred speed, and nanoparticle volume percent on the rate of mass transfer [5].

Numerous prior studies have addressed the removal of CO_2 from flue gas; however, when varying the size, stirrer speed, and volume percentage of the nanoparticles, the results are noticeably lacking [11]. Therefore, the goal of this work was to investigate how adding nanoparticles improved the bi-blend alkanolamine's ability to absorb CO_2.

Further, the cost of experimentation is taken into consideration when designing experiments, gathering data for analyses, and figuring out the ideal factor levels. Orthogonal arrays are used to determine the values of the controllable factors, ensuring the independent estimation of factor effects. Moreover, the selection of the uncontrolled or noisy elements' levels. This goal can be approached by applying experimental design using Taguchi. Taguchi's method looks for the optimal combinations of the controllable parameters. that, when appropriate, both maximize the S/N ratio and bring the quality characteristic's mean response closer to the goal value [11,12].

The incentive to lower total expenses over the course of the product's life is intrinsic to the Taguchi design. It is therefore believed that any departure of the quality feature from the intended norm will lead to increased expenses or a loss of quality. Depending on the kind of quality feature, appropriate quality loss functions are generated and then applied to define performance metrics like

S/N ratios. Based to the Taguchi method of experiment design, the appropriate orthogonal array that allows studying the influence of the considered parameters and their interaction for these mixed levels would be L18. An L18 orthogonal array will be used for parameter optimization and analysis with the aim of maximizing CO_2 removal by setting the optimum condition. The initial nanoparticle concentration, agitation speed, and nanoparticle size are important factors that need to be examined because they were not adequately taken into account in previous studies. Ideally, a confirmatory trial would also be conducted [12].

2. Methodology

2.1 Chemicals and Equipment

MEA (98%), TEA (98%) and silicon oxide (SiO_2) nanoparticles (60, 80, and 100 nm in diameter) with a purity of (99.9%) were purchased from Sigma Aldrich, India. Every substance is utilized without any further purification. For the flue gas simulation, N_2 (99.99%) and CO_2 (99.99%) gas cylinders were utilized. The CO_2 analyzer, Atmocheck double O_2/CO/U.S.A., Range (0.00–100%), flow meters, Flowtech. /U.S.A., N_2 (25–250) ml/min, CO_2 (25–250) ml/min), ultrasonic, and maximum temperature of 60°C were the specifications of the equipment utilized.

2.2 Preparation of Nanofluid

The nanofluids used in the tests were generated in line with Figure 1, as described in our prior work [13]. To make a homogeneous solution, the base solvent was first prepared by combining 3/3 molar ratios of MEA and TEA. The nanoparticles of SiO2 of various sizes were then added to the blend of MEA and TEA, 3m of each, using ultrasonic irrigation to ensure that they were evenly distributed in the solvent. After 24 hours, the nanofluid container was visually inspected to determine its stability, as shown in Figure 2.

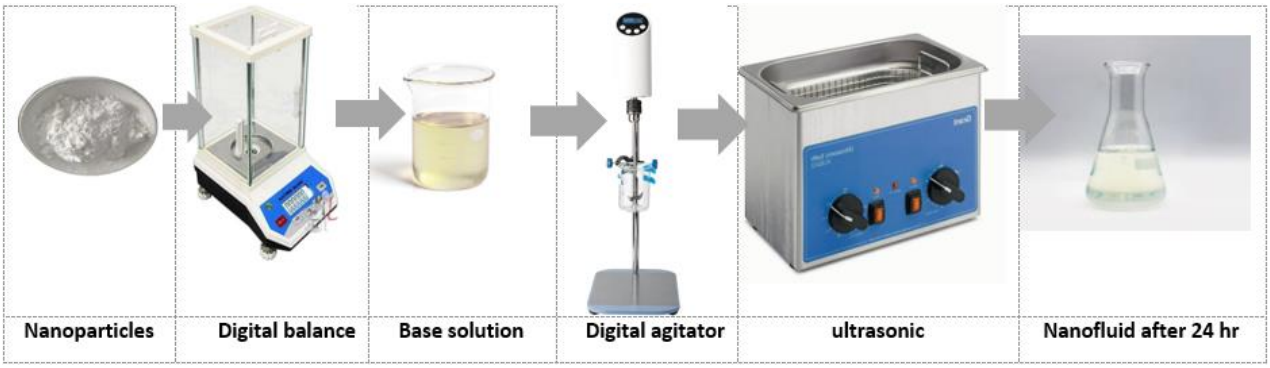

Fig. 1. Nanofluid preparation steps

2.3 Apparatus and Procedures

The CO_2 adsorption studies were carried out in a 100-mL glass reactor, as illustrated in Figure 2. The carbon dioxide (CO_2) and nitrogen (N_2) gas streams were effectively mixed to obtain the desired CO_2 proportion (15 volume) via diligent flow meter management. The nanofluid was then injected into the gas mixture using the absorption cell. Furthermore, the adsorption of all of the scanned nanofluids was tested under equal CO_2 VOL.% conditions. To obtain an accurate estimate, the rate of gas flow and temperature must be considered. The gaseous composition is then injected into the nanofluid through an absorption cell at a flow rate of 200 liters per hour. A CO_2 gas analyzer was used to constantly measure the gas effluent from the absorption unit at one-minute intervals until the nanofluid became saturated with CO_2. Subsequently, research was done to determine the effect of nanoparticles on CO_2 absorption rates. The CO_2 ingestion rate of the solvent can be calculated by quantifying the difference in CO_2 fluxes at the gas-phase absorber's inlet and output using a CO_2 gas analyzer and the following formulas [14,15]:

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

R represents the rate of CO_2 intake in moles per kilogram per minute. The F_{in} variable represents the inlet gas flow rate, which is measured in millilitres per minute. F_{out}: The outlet's gas flow rate in millilitres per minute. The parameter is being discussed.

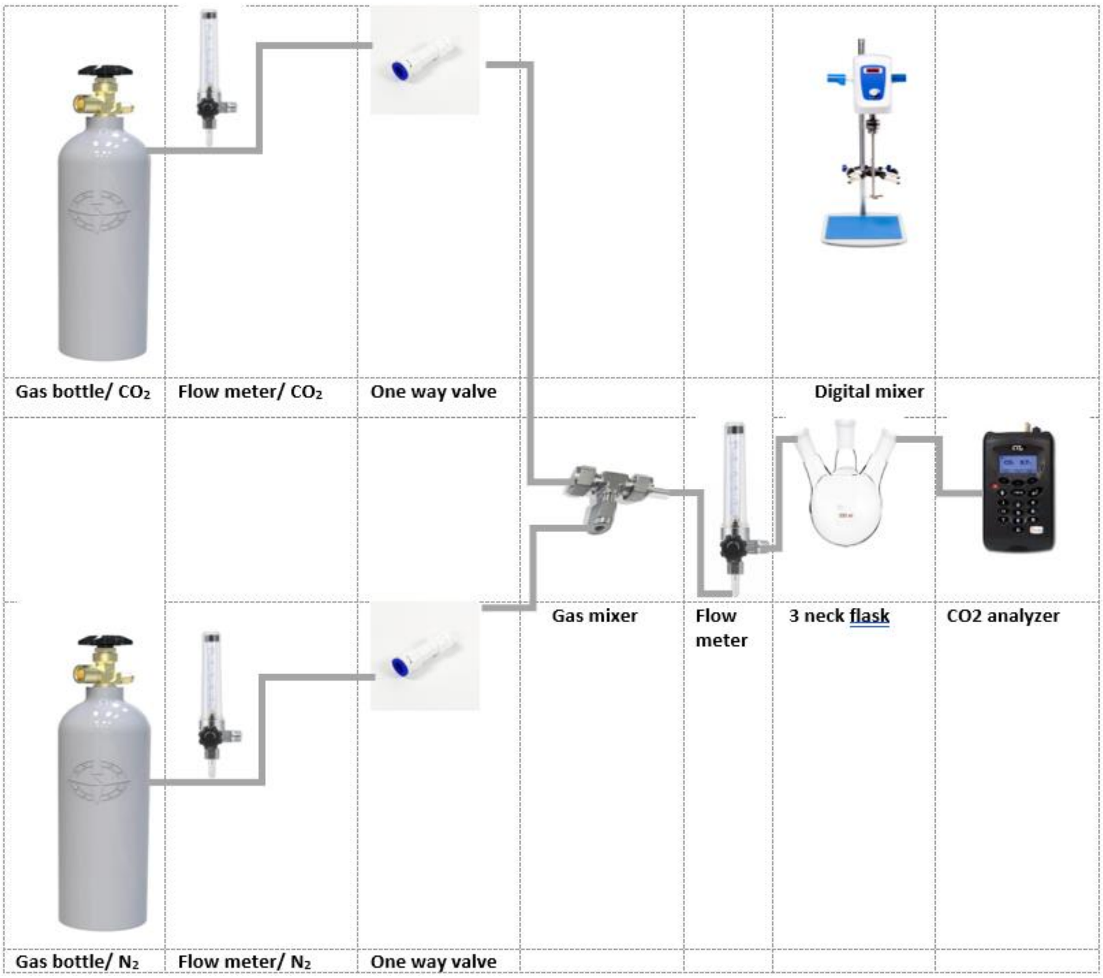

Fig. 2. The experiment of CO_2 absorption procedure

Atmosphere pressure and a room temperature of 298 K were used for the absorption of CO_2. Alkanolamine nanofluid was placed in a 100 mL glass cell reactor that was set at a certain stirring speed of (1,4) rotations per second (rps). Using calibrated flow meters, Carbon dioxide (CO_2) and nitrogen (N_2) gases were obtained from SDI Samarra, Iraq, with a purity of 99.99%. The gases were used as supplied and were given in a recommended volume ratio of 15% CO_2 and 85% N_2. Then, the gas mixture was substituted and introduced into the absorption unit, where it interacted with the solvent at a flow rate of 200 L/h. Upon reaching its saturation point, the solvent could no longer absorb any additional CO_2. Subsequently, the gas discharged from the absorption unit was subjected to analysis via a CO_2 analyzer. The absorption rate was obtained using Eq. (1).

Figure 3 illustrates the conceptual framework of the experimental arrangement employed for the carbon dioxide absorption process [16,17].

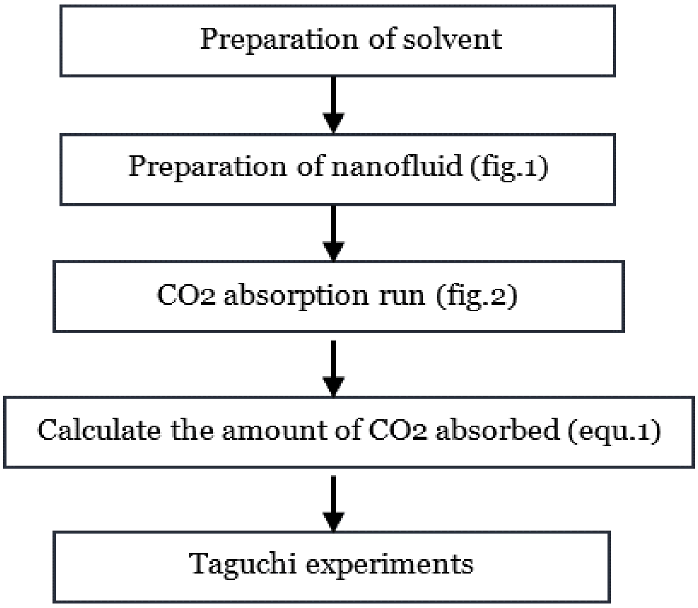

Fig. 3. Outline of the experiment of CO_2 analysis procedure

3. Design of Experiments (DOE)

Applying DOE approaches based on statistical techniques can lead to an effective strategy for analyzing experimental data from research and assessing the different impacts of controlling factors on objective functions. These techniques also enable process optimization and evaluate the improvement in absorption rate. The Taguchi optimization approach is a well-established, unique, and durable discipline that enables optimization with minimal tests [18,19].

In this study, the elements that significantly influenced the rate of CO_2 absorption using nanofluid were identified based on Taguchi's design of experiments. In the current study, three factors were examined: stirrer speed (coded X1) with two levels (1,4 rpm); the other factors with three levels were nanoparticle concentration of SiO_2 (coded X2) with three levels (0.05, 0.1, and 0.15 vol%); and nanoparticle size (coded X3) (60, 80, and 100 nm). The L18 (3 ^3 2^1) array presented in Table 1 would be the appropriate orthogonal array by the Taguchi experiment design This methodology enables the examination of the impact of the parameters in question and their interplay at various levels of mixing. The tests were conducted within these specified conditions.

Table 1
L18 orthogonal array for Coded values

Exp. No.	Coded Values		
	X1/ (stirrer speed)	X2/ (nanoparticles concentration)	X3/ (nanoparticles size)
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

A study on the signal-to-noise (S/N) ratio is necessary to assess the experimental findings. The Taguchi technique categorizes the characteristics of performance (S/N) into three categories: "larger is the better (LB)", "nominal the best (NB)", and "smaller-the-better (SB)". The objective of this analysis was to determine the condition that exhibited the highest rate of CO_2 absorption. Consequently, the present study employed the criterion of higher is better. The signal-to-noise ratio (S/N ratio) in the presence of LB features can be determined by employing Eq. (2) in the following manner [11]: Eq. (5) has been referenced in source [18].

$$S/N_{LB} = -10 \log \frac{[\sum_{i=1}^{n} 1/y_i^2]}{n} \qquad (2)$$

Hence, we can define the sample mean as the sum of all y_i values divided by n experiment. The experimental data were analyzed using the MINITAB 17 program.

4. Results and Discussion

4.1 Analysis of the Signal-to-Noise Ratio and Optimization

The model of multiple linear regression was derived using the MINITAB 17 software to examine the correlation between the rate of CO_2 absorption and the characteristics of the nanofluid. The mathematical model presented in Eq. (3) describes the amount of CO_2 absorption rate as determined by statistical analysis. The correlation coefficient, denoted as R seq., is found to be 97.26%. This high value suggests that the model accurately represents the observed data.

$$\mathrm{CO_2\ absorpt}ion\ rate = 0.003511 + 0.000279 * \mathrm{X}_1 + 0.002176 * \mathrm{X}_2 - 0.000035 * \mathrm{X}_3 + 0.0000002 * \mathrm{X}_3^2 - 0.000002 * \mathrm{X}_1 * \mathrm{X}_3 \qquad (3)$$

The observed and predicted values of the L18 orthogonal arrangement for the absorption rate of CO_2 are presented in Table 2. Table 2 presents the response obtained through the utilization of Eq. (3), which demonstrates the expected levels of the CO_2 absorption rate. Additionally, it showcases the signal-to-noise (S/N) ratios determined by Eq. (2) for all test outcomes.

Table 2
Values of CO_2 rate of absorption and S/N ratios that were measured and projected for all experiments

No.	Stirrer speed (rpm)	nano conc. (vol%)	nano size (nm)	Experimental CO absorption rate (g/s)	predicted CO absorption rate (g/s)	*S/N* Ratio
1	1	0.01	60	0.00226	0.002192	52.586771
2	1	0.01	80	0.0021	0.001972	52.318252
3	1	0.01	100	0.00199	0.001912	51.984975
4	1	0.05	60	0.00235	0.002279	51.581005
5	1	0.05	80	0.00225	0.002059	51.26629
6	1	0.05	100	0.00205	0.001999	50.894789
7	1	0.1	60	0.00244	0.002388	50.400471
8	1	0.1	80	0.0023	0.002168	50.014234
9	1	0.1	100	0.0022	0.002108	49.534035
10	4	0.01	60	0.00275	0.002669	48.940272
11	4	0.01	80	0.00234	0.002329	48.512686
12	4	0.01	100	0.00224	0.002149	47.84301
13	4	0.05	60	0.0029	0.002756	46.970856
14	4	0.05	80	0.00249	0.002416	46.352588
15	4	0.05	100	0.00237	0.002236	45.342444
16	4	0.1	60	0.00295	0.002865	43.860781
17	4	0.1	80	0.00254	0.002525	42.538842
18	4	0.1	100	0.00244	0.002345	39.699478

Figure 4 illustrates a comparison between the experimental results and the projected outcomes obtained from Eq. (3). The model demonstrates a strong ability to accurately forecast the rate of CO_2 absorption. Eq. (3) can be considered a valuable tool for evaluating the process.

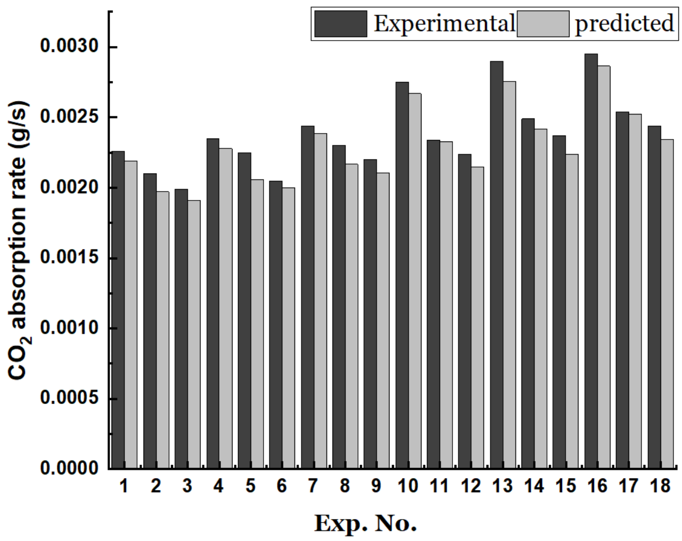

Fig. 4. Experimental and predicted CO_2 absorption rate

Table 3 presents the average response of each element at different levels, whereas this information is visually depicted in Figure 5. The results of the mean analysis indicate that the criteria of utmost significance are presented in the subsequent sequence: The relationship between speed, concentration, and nano size can be described as follows: an increase in speed (measured in revolutions per minute, rpm) leads to an increase in concentration (measured in volume percent, vol.%) which subsequently results in a reduction in particle size (measured in nanometers, nm).

Table 3
Figured out the average reaction from data from CO_2 absorption tests

Level	Speed (rpm)	Concentration (vol.%)	Nano size (nm)
1	0.002216	0.002280	0.002608
2	0.002558	0.002402	0.002337
3		0.002478	0.002215
Delta	0.000342	0.000198	0.000393
Rank	2	3	1

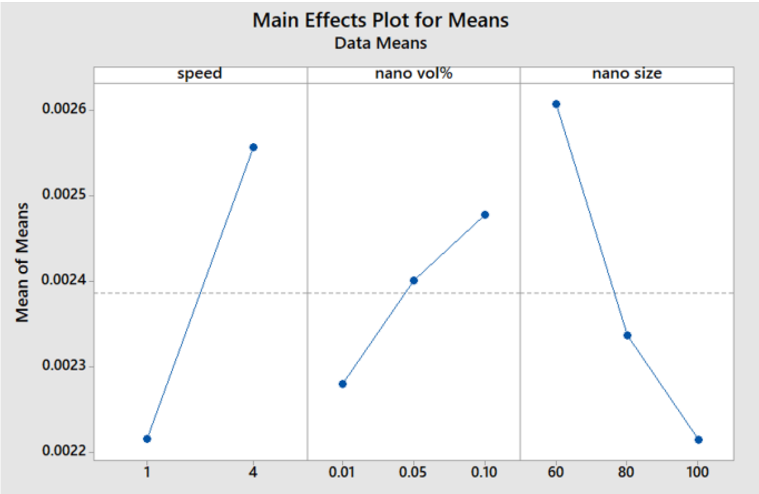

Fig. 5. Main outcome plot for means values of CO_2 absorption

Table 4 presents the response table with the calculated Signal Noise (LB) and the order of importance of the four investigated components. These components are visually shown in Figure 6. The rankings are determined by comparing the proportions of effects using delta statistics. The delta statistics are calculated as the average lowest subtracting from the largest average for the same parameter [17]. The higher the S/N ratio, the faster CO_2 is absorbed. The rankings obtained for each component clearly suggest that the concentration of nanoparticles is the most essential aspect.

Table 4
Response of S/N (larger is better)

Level	Speed (rpm)	Concentration (vol.%)	Nano size (nm)
1	-53.03	-52.44	-51.63
2	-51.79	-52.15	-52.54
3		-52.63	-53.06
Delta	1.25	0.48	1.43
Rank	2	3	1

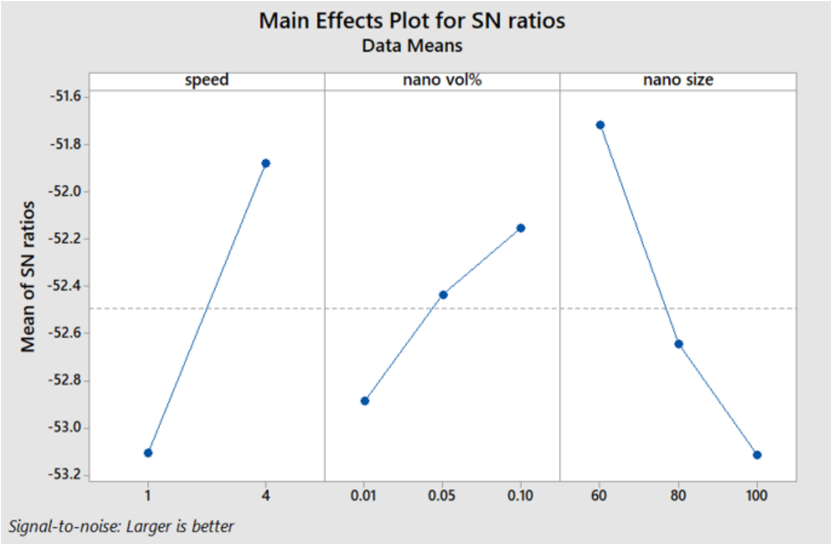

Fig. 6. Main outcome plots of S/N (larger is better) for CO_2 absorption

4.2 ANOVA (Analysis of Variance)

The ANOVA statistical method was employed to evaluate the statistical significance of the control parameters. This was achieved by determining the percentage that reflects the contribution of each component, which represents the percentage of the total measured variation throughout the study attributed to each significant factor. The greater the magnitude of the contribution percentage for each researched parameter, the more significant its influence on the conclusions. This approach can also contribute to a more comprehensive comprehension of the reported outcomes and the potential that the trials were conducted under controlled environments. ANOVA was computed using F-value, and P-value statistical measurements. The ranges for each adjustable element are chosen based on previous studies [18,20].

The ANOVA outcomes for the current experiment are presented in Table 5. Based on the results obtained, the subsequent parameters have been identified as the primary determinants affecting absorption efficiency: The relative importance of various factors in a system can be assessed based on their respective contribution percentages. In this particular case, the factors under consideration are concentration (expressed in volume percentage), speed (measured in revolutions per minute), and nano size (measured in nanometers). The significance of each factor in the answer can also be assessed using the P-value, which quantifies the association between the sum of the squared parameters and the total sum of squares. When the p-value is less than 0.05, at a 95% confidence level, the parameter is considered statistically significant [18,19,21]. The results of the statistical analysis, namely the P-values with a confidence level of 95%, indicate that the concentration factor exhibited statistical significance. However, the variables of Speed (rpm) and nano size (nm) did not demonstrate any significant effects within the selected range of the study. With F values more than 1 for the controlled parameters, it was inferred that the error variance is comparatively smaller than the variances of these variables. This suggests that these variables have a substantial impact on the replies [17].

Table 5
Analysis of Variance (ANOVA) for CO_2 absorption

Source	DF	Contribution	F-Value	P-Value
mixing speed (rpm)	1	46.56%	94.25	0.000
nano concentration (vol.%)	2	4.33%	4.38	0.037
nano size (nm)	2	43.18%	43.7	0.000
Error	12	5.93%	-	-
Total	17	100.00%	-	-

4.3 Effect of Operative Factors
4.3.1 Nanoparticle concentration (vol%) effect

Figure 7 and Figure 8 depicts the influence of nanoparticle concentration (vol%) on CO_2 absorption rate using Eq. (3) at the two-level speed rate. It is clear that raising the concentration of nanoparticles increases the expected absorption rate, which is consistent with earlier research [2]. The chosen range of nanoparticles concentration had a significant influence on the CO_2 absorption rate, The lack of significance of the factor on process performance is supported by the S/N and ANOVA results, where the F-value was found to be less than 1 at a significance level of 0.05, and the impact percentage was determined to be 0.05% which consistence with literatures [14,16,17].

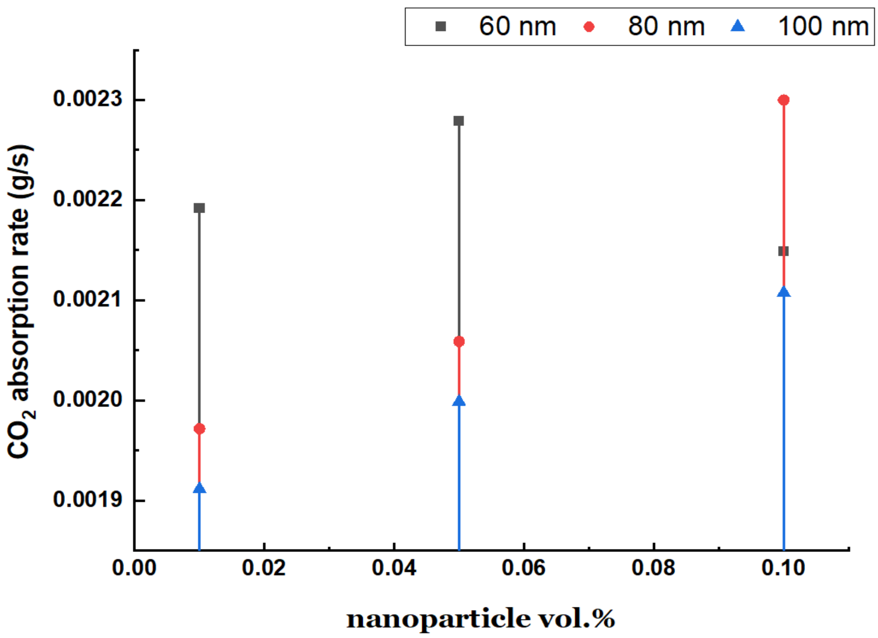

Fig. 7. Influence of nanoparticle concentration on the CO_2 absorption rate at (1 rpm)

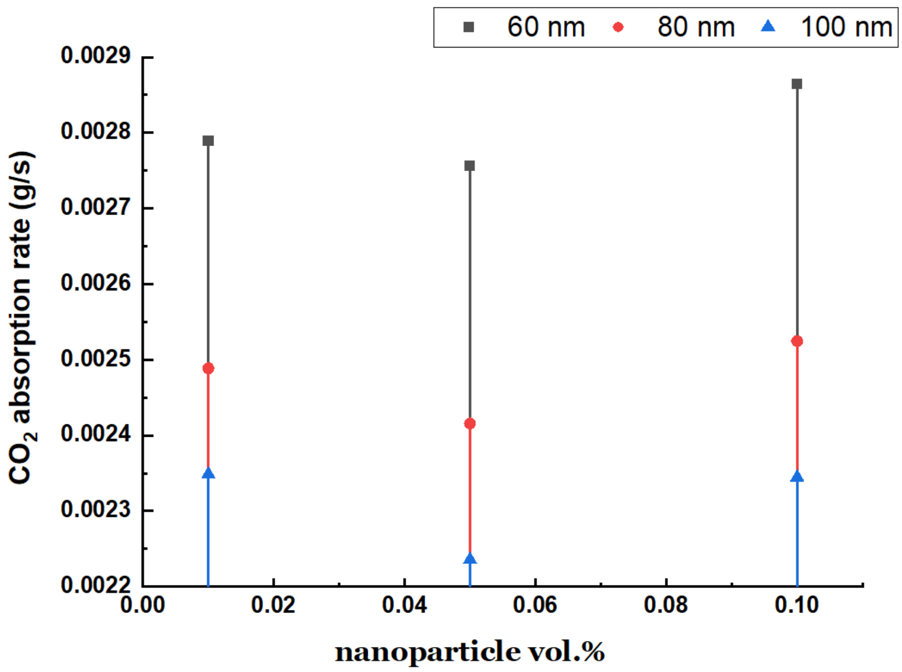

Fig. 8. Influence of nanoparticle concentration on the CO_2 absorption rate at (4 rpm)

4.3.2 Effect of stirred speed

One of the effective characteristics in the application of nanofluid of absorbing CO_2 is stirrer speed (see Figure 9, Figure 10 and Figure 11). The value of this parameter has a direct impact on the amount of CO_2 absorbed. The augmentation of stirring velocity would result in an amplification of the surface area of interaction between the fragmented gas bubbles and the surrounding liquid medium, as well as the nanoparticles. Additionally, it would intensify the random motion of particles, known as Brownian motion, hence leading to an enhancement in the rate of absorption of carbon dioxide [14,20]. In order to examine the influence of elevated stirring speed on the absorption of CO_2, the graphical representation labeled as Figure 9 was shown utilizing the equation denoted as (3). The 0.0019 to 0.0028 g/s. Also evident from the S/N data, increasing current density leads to greater S/N values, implying a higher CO_2 absorption rate.

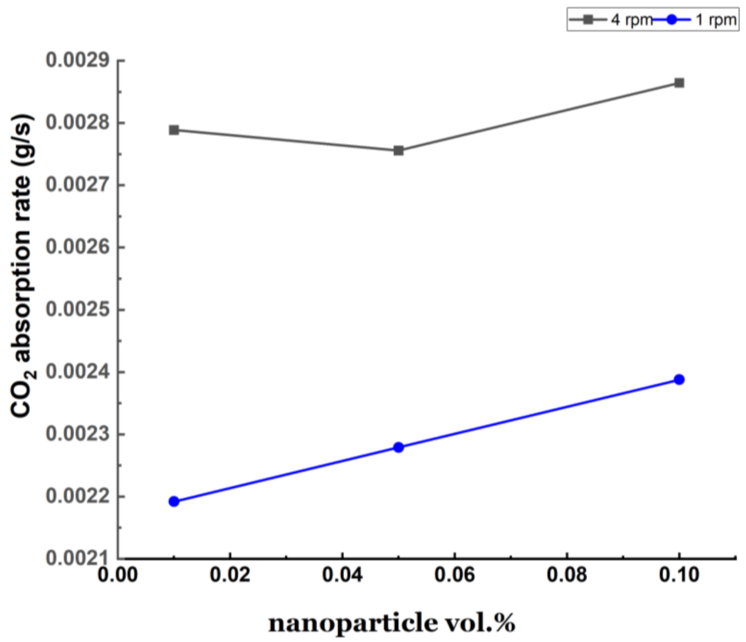

Fig. 9. Influence of stirrer speed on the CO_2 absorption rate for the nano size of 60 nm

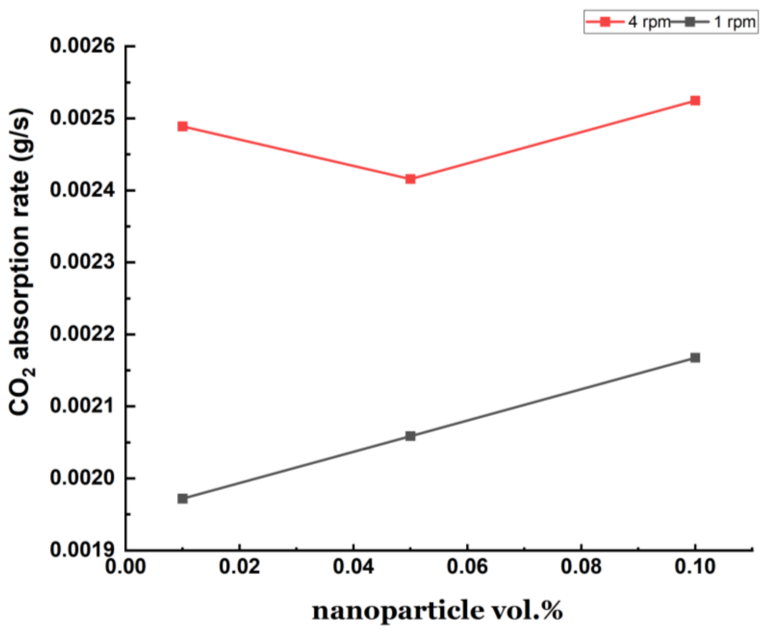

Fig. 10. Influence of stirrer speed on the CO_2 absorption rate for the nano size of 80 nm

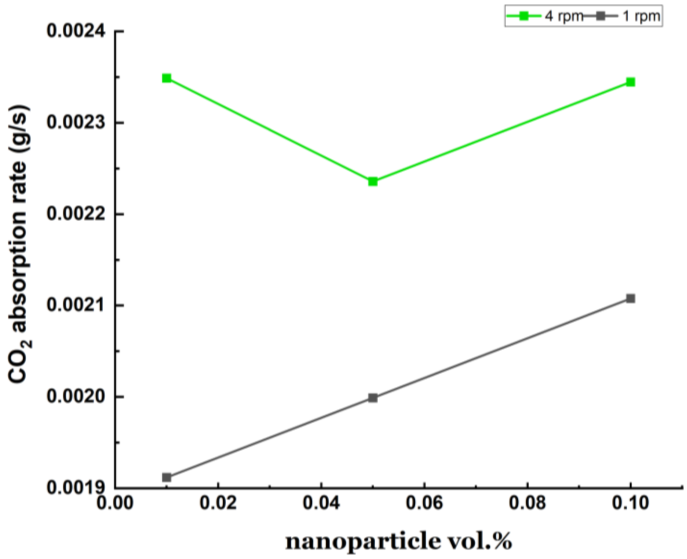

Fig. 11. Influence of stirrer speed on the CO_2 absorption rate for the nano size of 100 nm

4.3.3 Effect of nanoparticles size

The findings of S/N and ANOVA in the current investigation showed that nanoparticle size had the least influence on CO_2 absorption rate performance. The rate of CO_2 absorption decreases as the size of the nanoparticles increases. Figure 12 and Figure 13 clearly show the effect of nanoparticle size. Which was plotted using Eq. (3) at two different speeds of 1 and 4 rpm. It is obvious that increasing the size of the nanoparticles reduces the rate of CO_2 absorption [22].

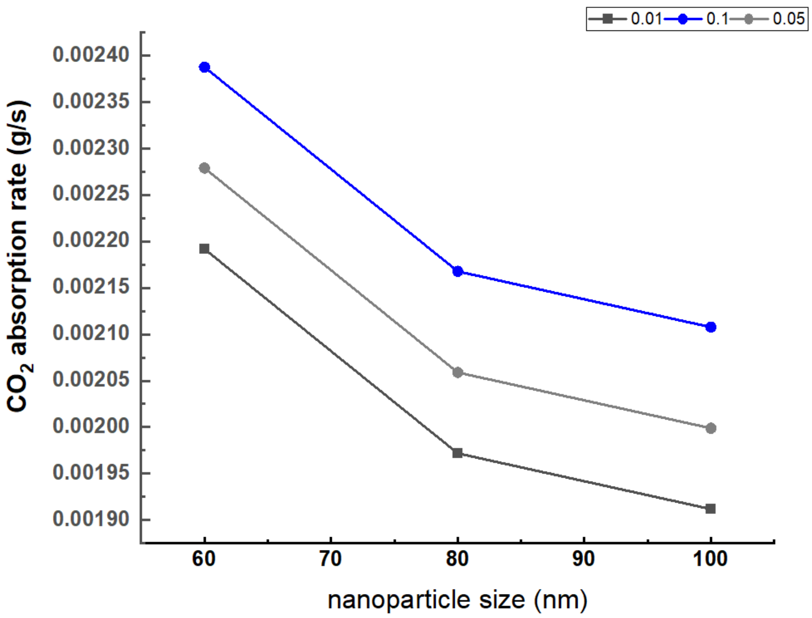

Fig. 12. Influence of nanoparticle size on the CO_2 absorption rate at (1 rpm)

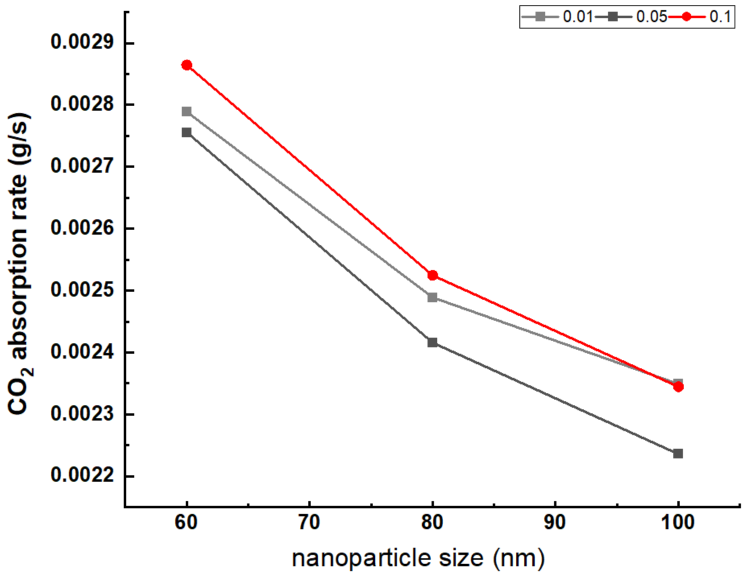

Fig. 13. Influence of nanoparticle size on the CO_2 absorption rate at (4 rpm)

5. Conclusions

The current study focuses on applying nanofluid in the capturing of CO_2 from flue gas. This study investigated the influence of varying concentrations of nanoparticles, stirrer speed, and nanoparticle sizes on the rate of CO_2 absorption. The Taguchi method was used to optimize the characteristics of the nanofluid. The findings from the signal-to-noise ratio (S/N) analysis and analysis of variance (ANOVA) support the conclusion that the significance of nanoparticle parameters can be ranked in the following order: mixing speed > nano size > nano concentration (vol.%) with the proportion of contributions were as follows: mixing speed (rpm) 46.56%, nano size (nm) 43.18% and nano concentration (vol.%) 4.33%. Also, the experimental and predicted values coincided well with regression analysis (R^2=97.26%), and the confirmation test results showed that the CO_2 absorption rate was 0.0029 g/s, a highly beneficial result for industrial applications. The optimal circumstances were determined to be at a concentration of 0.1 volume percent, particle size of 60 nanometers, and rotational speed of 4 revolutions per minute. Based on the findings of the current study, it can be inferred that the concentration of nanoparticles, stirrer speed, and size of nanoparticles were the primary factors with the greatest impact. Previous investigations have demonstrated a significant impact on the rate of CO_2 absorption. Two verification tests were performed under optimal conditions, yielding a carbon dioxide (CO_2) absorption rate above 0.0029 grams per second.

More studies need to be done on the phenomena of mass transfer in the absorption process using nanofluid. Also, the influence of nanoparticles on the heat transfer in the desorption process.

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