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An Experimental Investigation of Mass Transfer Coefficient of CO2 Capture in a Packed Bed

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Abstract

Over the last two decades, the looming catastrophe of climate change and pollution caused by different anthropogenic interventions has drew international attention. However, carbon capture and storage (CCS) systems, which were formerly thought to be a viable technology for averting this alarming future, are now regarded too expensive to implement, and their long-term environmental repercussions remain unknown .The importance of this work in eliminating or reducing carbon dioxide emissions is underlined. In this work, an absorption technology .The mass transfer coefficient of carbon dioxide from a gaseous mixture (air, carbon dioxide) in blended solution Monoethanolamine (MEA), Diethanolamine (DEA), and Triethanolamine (TEA) in a packed bed reactor (PBR) was investigated in this study using absorption technology. The Plexiglas packed bed stood 75 cm high and had a 10 cm internal diameter.At various operating conditions, such as gas flow rate, air flow rate, and liquid flow rate, the overall mass transfer coefficient (K_{Ga}) was studied. Gas flow rates of 5, 10, and 15 L/min, air flow rates of 80,90, and 100 L/h, and liquid flow rates of 150,300,450 mL/min were used. This experiment was carried out utilizing a continuous procedure with the assistance of a centrifugal pump. During the absorption experiment, high-performance gas chromatographic (GC) was used to assess CO_2 loading. The greatest value of total mass transfer coefficient (K_{Ga}) was 0.084 S^{-1}based on the experimental results, which demonstrated that loading CO_2 in the range of 0.511–2.479 (mole CO_2 /mole amine).

Keywords : Monoethanolamine, Diethanolamine , Triethanolamine , mass transfer coefficient (K_{Ga}), Packed bed reactor (PBR) , Taguchi method

1. Introduction

Globally, trapping carbon dioxide from industrial flue gas has become a crucial environmental problem, according to the International Energy Agency (2012) The warming atmosphere resulting from higher rates of greenhouse gases poses a serious danger,energy-related carbon dioxide emissions will reach about 45 giga tons by 2035 in the light of current mitigation strategies and conditions, and work is becoming urgent and cost-effective carbon dioxide capture technologies are being demonstrated **[1]**. Cultures have been impacted in certain situations, and coastal towns have been flooded as a result of increasing sea levels, affecting more than 150 million people. Carbon dioxide is well acknowledged as a major contributor to global warming and climate change. Carbon dioxide, as a greenhouse gas (GHG), may trap and absorb sunlight inside the atmosphere. A power plant, transportation, industrial plants, and cement manufacture all release roughly 5 Gt of carbon dioxide every year. Furthermore, increased CO2 emissions into the environment as a result of fossil fuel burning and human activities has resulted in the development of sustainable and cost-effective chemical synthesis pathways. As a result, the large investment in carbon dioxide capture is projected to make a considerable contribution to reducing emissions, which are mostly from power plants. Carbon usage entails scavenging and transportation**[2]**.There are three choices for reducing carbon dioxide emissions, reducing energy intensity, reducing pollution intensity and rising insulation with carbon dioxide. The first option requires energy efficiency, while the second option requires the use of non-fossil fuels, such as renewable energy and hydrogen. The third option comprises the development of carbon dioxide capture and capture techniques **[٣]**. Increasing carbon dioxide emissions into the atmosphere has already resulted in a number

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of negative consequences, such as global warming and climate change, which are thought to be linked to a number of environmental difficulties, such as rising sea levels and glacier melting, among others **[٤]** .The average CO_2 emission from power plants accounts for around 40% of total CO_2 emissions globally, and it is expected to climb by up to 60% in business as usual by the end of this century **[٥].** As a result, carbon dioxide separation technology is gaining in popularity as a result of the pressing need to address both global warming and energy consumption. Meanwhile, chemical absorption employing innovative absorbents with improved capture effectiveness and lower energy consumption, such as mixed amine solution, is the most extensively used and effective approach for CO_2 collection **[٦].** In a prior investigation, alkanoamine solvents were combined, with the primary being monoethanolamine (MEA) and the secondary being triethanolamine (TEA). **[٧,٨,٩] .** TEA aqueous solutions are used in a hybrid membrane contactor**,** diethanolamine is the most significant secondary amine which is utilized in both lab as well as industry, and this has decreased the energy of regeneration which is required for reusing the solutions of the amine **[١٠,1١].** The findings indicate major changes in CO_2 capture with respect to packed columns that function at room temperature.

Work falls within the thirteenth goal of sustainable development (climate action), where the technology of capturing carbon dioxide gas contributes to reducing its emissions and thus reducing pollution and purifying the climate.The purpose of this research is to investigate carbon dioxide absorption in order to produce the optimum total mass transfer modulus in a packed bed absorbent (PBA) using various mixed amine solutions, including monoethanolamine (MEA), diethanolamine (DEA), and triethanolamine (TEA). These amines were combined in various concentrations.This study focused on improving amine solvents to achieve high CO_2 capture efficiency and low operating cost, as well as the mass transfer coefficients (KGav) determination. performance of the CO_2 absorption process.

2.Determination Overall mass Transfer Coefficient

K_{Ga} is a crucial component in our study. A simulated mix of gas including A (CO_2) and B(air) that flows to a packed column from the bottom constantly touches the amine solution that flows from the top of the column in the scrubber. All current touches the opposing current column at the same time. There has been a reasonable theory in this investigation. **[12,13]:-**

$$(F_{A1} - F_{A2}) - R_{A1}\, V_L = 0 \quad \textbf{Eq. (1)}$$

where RA represents the average rate of absorption in packed bed that can't be obtained in a direct way. Due to the fact that the FA_2 may be obtained with the use of the inert gas as the tie element, the evaluated value of the FA_2 is obtained from:

$$F_{A2} = F_{A1}\left[\left(\frac{1-y_1}{y_1}\right)\left(\frac{y_2}{1-y_2}\right)\right] \qquad \textbf{Eq. (2)}$$

As a result, as Eq. (٢) indicates, the rate of the absorption R_A equals CO_2 consumption through packed bed. Eq. (٢) is re-written in the following form:

$$R_A(mols^{-1}\,L^{-1}) = \frac{F_{A1}\,(\frac{mol}{s})}{V_L\,(L)}\left[1 - \left(\frac{1-y_1}{y_1}\right)\left(\frac{y_2}{1-y_2}\right)\right] \qquad \textbf{Eq. (3)}$$

FA_1 stands for the molar flow rate of the CO_2 that is evaluated when Q_g (i.e. the gas flow rate), T (i.e. the liquid temperature in the column of the reactor), and PA_1 (i.e. the partial CO_2 pressure at the inlet), are available. Moreover, V_L stands for the liquid volume in scrubber, Y_1 represents the molar fraction of CO_2 gas at inlet, and Y_2 stands for the molar fraction of the CO_2 gas at outlet. Which is why, the rate of the absorption R_A may be specified with the measurable quantities. Based on a 2-film architecture and balance of the material in isothermal conditions, the equation of the balance may be expressed in the following form:

$$u\frac{dC_A}{d_Z} + (K_{Ga})_{loc}\,(C_A - HC_{AL})_{\varepsilon_L} \qquad \textbf{Eq. (4)}$$

F 1/F 2 can be replaced by (P_1/P_2) $(T_{٢}/ T_{١})(y_{١}/ y_2)$, taking into account Ideal gas rules for inlet and exit gases at various temperatures. As a result, the general volumetric mass transfer coefficients become

$$K_{Ga}\,(s^{-1}) = \frac{Q_g\,(\frac{L}{s})}{V_L\,(L)}\ln\frac{F_1(\frac{mol}{s})}{F_2(\frac{mol}{s})} \qquad \textbf{Eq. (5)}$$

Where :
Qg=Gas flow rate, (L/S)
F_1= CO_2 molar flux at inlet, $[\frac{mol}{S}]$
F_2= CO_2 molar flux at outlet**,** $[\frac{mol}{S}]$
V_L = is the absorber volume of the liquid.

3. Experimental Design

In order to limit the number of tests, the Taguchi method was utilized as an experimental design. The selection of independent variables was the initial step. The process parameters considered in this study are four continuous parameters: gas flow rate, air flow rate, liquid flow rate, and absorption time. Tables (1) indicate that each element has three levels. The orthogonal array L9(34) exhibited nine studies using the Taguchi experimental design, lowering the number of experiments required and the research cost by nearly 80%. Table (2) which we obtained using Taguchi method, shows the orthogonal array's combination of experiments for the continuous process**[14,15].**.

One of the key parameters, which can affect the mass transfer performance, is the gas flow rate. Many researchers showed that when the gas flow rate increased, K_{Ga} increased as well.The influence of the gas flow rate on the overall mass transfer coefficient has been studied for Continuous process using (MEA+DEA +TEA). Three different levels of gas were used, 5, 10 and 15($Lmin^{-1}$) On the basis of them, in addition to other variables, Taquchi experiments were designed.

4.Experimental work

Because of its simple construction, higher heat and mass transfer coefficients, higher removal efficiency, and effective regulation of liquid residence time, a continuous packed column is a potent carbon dioxide removal procedure when compared to other scrubbers. As a result, some researchers have chosen to use a continuous packed column reactor as an absorber. Table 1 lists the chemical solvents that were used Table(3)

De-ionized water was used to make aqueous solutions. MEA, DEA, and TEA had amine concentrations of 10% volume percent, 5% volume percent, and 5% volume percent, respectively, in the mixes. All of the tests were carried out under atmospheric pressure and at a temperature of 298.15 K. **Figure 1** depicts the experimental setup apparatus for carbon dioxide absorption.

A packed bed reactor (PBR) with the liquid phase in recycling mode was employed in this experiment. The reactor was composed of plexiglas with an inner diameter of ten centimeters and a height of seventy-five centimeters.

Pure CO_2 and air from (compressor) were mixed before injecting the blended amine solution into the packed column reactor, with the air flow rate adjusted to an acceptable value in the range 80-100 L/h. The feed gas (CO_2) flow rate provided from the gas cylinder was balanced and regulated by gas flow (CO_2) rate in the range 5-15 L/min, and then it was fed via the down of the packed column to maintain a particular flow rate. One of the most notable advantages of using aluminum balls with a length of 10 mm and a diameter of 10 mm as random packing within the column is that it increases the surface area available for mass transfer and increases the contact time between gas and liquid.

Table (1) In this investigation, the following factors and levels were used

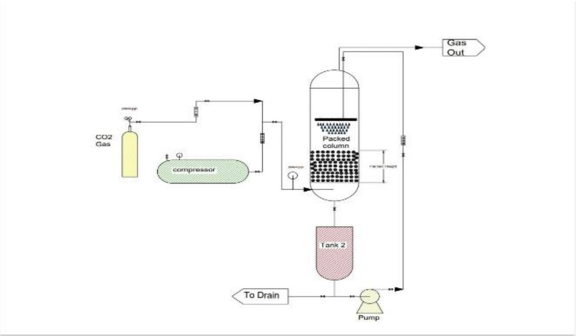
Factor	**Gas Flow $Lmin^{-1}$**	**Air Flow Lh^{-1}**	**Liquid Flow $mLmin^{-1}$**	**Amine concentration Volume percent (%)**	**Absorption time Min**
1	5	80-100	150-450	10%MEA+5%DEA+5%TEA	8-12
2	10	80-100	150-450	10%MEA+5%DEA+5%TEA	8-12
3	15	80-100	150-450	10%MEA+5%DEA+5%TEA	8-12

Table (2) Orthogonal array's combination of experiments for the continuous process.

Experiment No.	**(gas flow) $Lmin^{-1}$**	**(air flow) Lh^{-1}**	**(Liquid flow) mLmin-1**	**(Time) Min**
A	15	100	150	12
B	15	90	300	8
C	15	80	450	10
D	10	100	300	10
E	10	90	450	12
F	10	80	150	8
G	5	100	450	8
H	5	90	150	10
I	5	80	300	12

Table (3) Chemical materials used in this work

Chemical Name	**Abbreviation**	**Chemical formula**	**Molecular weight [g/mol]**	**Density g/cm3**
Monoethanolamine	MEA	C_2H_7NO	61.084	1.0117
Diethanolamine	DEA	$C_4H_{11}NO_2$	105.137	1.097
Triethanolamine	TEA	$C_6H_{15}NO_3$	149.190	1.124



Figure(1) A schematic diagram of gas absorption experimental setup

The gas absorption process is carried out in detail as follows. Initially, flue gas was simulated by combining individual streams of CO_2 from gas cylinder and air from air compressor. Rotameters of the unit Liter per minute ($Lmin^{-1}$), (Lh^{-1}) and ($mLmin^{-1}$) were installed for controlling the gas(CO_2)flow rates, air flow rate and liquid flow rate respectively. For CO_2 gas the range of (CO_2 flow rate) was 5-15 L min^{-1}, air it was 80-100 Lh^{-1} and for liquid it was 150-450 ml min^{-1}.The experiment setup were carried out in absorption column shown in **Figure (1)** The amino solution that was prepared in advance is pumped from the tank to the top of the absorption column by the pump and the amount of liquid is controlled by the flow rate of the liquid that ranges between (150-450) $mLmin^{-1}$. This process lasts between (8_12) minutes for experiments, then after that the solution rich in carbon dioxide is collected in the tank.A drain valve input at the bottom of the column for discharge the column and collecting liquid samples.Liquid samples were possessed from the bottom of the column and analyzed for each concentrations and CO_2loading.

De-ionized water was used for 10 minutes before and after each test to remove contaminants from the reactor. They made all of the amine solutions with de-ionized water and volumetric glassware, and they made aqueous solutions with 1L of water for each experiment. With the help of a liquid flow rate that was set to an appropriate via 150,300,450 mL/min, the prepared absorbent liquid (solvent) was injected at the upper region of the absorption column. A needle valve was installed at the top of the column to generate counter-current contact between gas and liquid, with the exit liquid being recycled at the bottom using a Shimge centrifugal pump. A 10 ml flask bottle was used to collect samples of the circulating liquid from the packed column reactor at various periods. The analysis process was used after multiple samples were taken.

5.Results and discussion

CO_2 absorption into blended solution from MEA-DEA-TEA, which is in the range of (0.511–2.479) moles of CO_2 absorbed per mole of amine, was used to study mass transfer in a packed bed. CO_2 and amine content were measured in samples taken after absorption studies. To calculate the CO_2 loading in terms of (moles of CO_2/moles of amine). The concentration of CO_2 was measured using gas chromatography (GC). By subtracting the mol of CO_2 inlet from the mol of CO_2 outlet, the overall mole of CO_2 absorbed in the absorbent can be estimated, and the CO_2 loading may be calculated .According to the results obtained, the effect of gas flow rate and liquid flow rate was found to be essential in the continuous process, while the airflow rate and the absorption time were simple effect. **Figure(٢,3)** shows the effect of gas(CO_2)flow rate and liquid flow rate on CO_2 loading achieved by 10% MEA , 5% DEA and 5% TEA in continuous process.

$$n_{co_2,abs} = n_{CO_2,IN} - n_{CO_2,out} \qquad \textbf{Eq. (6)}$$

$$\alpha = \frac{mol\ of\ CO_2}{mol\ of\ amine} \qquad \textbf{Eq.(7)}$$

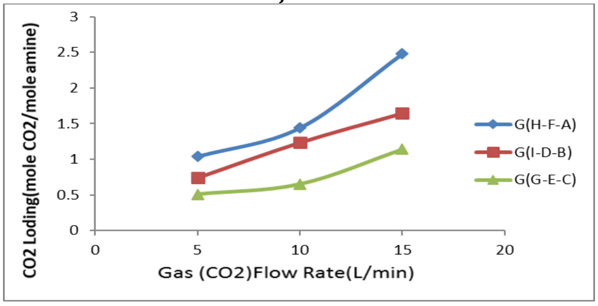


Figure (2) effect of gas(CO_2)flow rate on CO_2 loading

For **Figure (2)** showed the best CO_2 loading capacity in group (H-F-A) the liquid flow was constant at 150 mL/min. CO_2loading (mole CO_2/mole amine) capacity for aqueous amine solution blended increases with increasing gas flow rate, at point A the max value of CO_2loading was (2.497) mole of CO_2per mole of amine at 12min, air flow 100 L/h, and gas flow 15L/min.

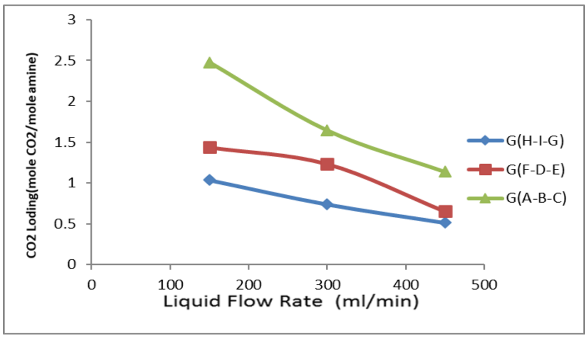


Figure (3) effect of liquid flow rate on CO_2 loading

For **Figure (3)** showed the CO_2loading capacity achieved by 5% concentration by V/v % from MEA , 5% DEA and 10%TEA was in group (A-B-C) the gas flow was constant at 15 L/min. CO_2loading (mole CO_2/mole amine) capacity for aqueous amine solution blended increases with decreasing liquid flow rate , at point A the max value of CO_2loading was (2.497) mole of CO_2 per mole of amine at 12min, air flow 100 L/h, and liquid flow 150 ml/min.

5.1The influence of CO2 loading capacity on the overall mass transfer coefficient, K Ga

The main effect of CO_2 loading on overall mass transfer coefficient K Ga in each group is depicted in the diagram below. Calculate the overall mass transfer coefficient K Ga S^{-1} for a continuous process using equation (1). **Figures (4)** show that increasing CO_2 loading in amine solutions causes the present active amine concentration to decrease, resulting in a decrease in the total weight transfer coefficient. The substantial CO_2 loading in the amine solution is principally responsible for this result. The mass transfer driving force from the gas phase to the liquid phase will decrease when (MEA+DEA+TEA) blended amine solution is employed. This effect is consistent with each of the researchers' findings. Because multiple levels of gas flow rate were utilized, different beginning amounts of carbon dioxide were used, and the absorption process differed from one level to the next.

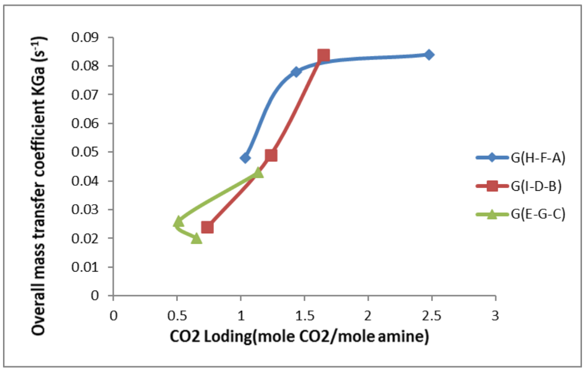


Figure (4) Progression of K_{Ga} in a function of CO_2 loading for continuous processes

Continuous process (0.084) at 150 mL/min liquid flow and 15 L/min gas flow in group A for 12 minutes yielded the highest overall mass transfer coefficient. While **[١٦]** discovered that when absorption CO_2 employing MEA solution, K_{Ga} was (0.0342 $S1^{-1)}$. **[١٧]** CO_2 absorption using an aqueous ammonia solution (K Ga) was(0.051 S^{-1}).

5.2The effect of liquid flow rate on overall mass transfer coefficient, K_{Ga}

The liquid flow rate is one of the most important factors that might influence mass transfer efficiency. Many studies have demonstrated that as the liquid flow rate increases, K_{Ga} increases as well. **Figure (5)** depicts the evolution of K_{Ga} over time for a variety of liquid flows.

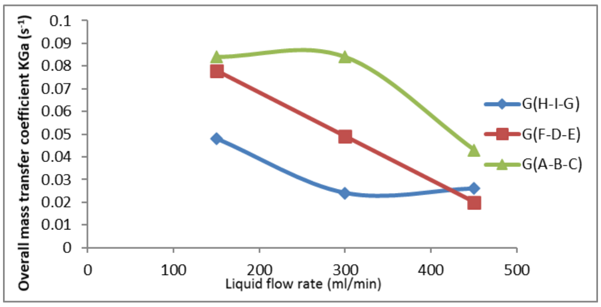


Figure (5) Progression of K_{Ga} in a function of liquid flow for continuous processes

for **figure (5)** observation is that increasing of the liquid flow rate, The absorption loading decreasing Subsequently the overall mass transfer coefficient decreasing with decreasing time.

The tests assumed a linear shape and declined consistently at points A, B, and C, as the carbon dioxide absorption process would be slower at greater liquid flow rates. As a result, the mass transfer coefficient would be greater. The maximum mass transfer coefficient were observed at point A, when the flow rate was liquid 150 ml/min.

After minutes of experimentation,the overall mass transfer coefficient achieved for Figure(5) at sites A and B was ($0.084S^{-1}$) at a flow rate of 150,300 mL/min. The first finding is that when the liquid flow rate increases, the absorption loading decreases. As a result, the overall mass transfer coefficient decreases as time passes.

5.3The effect of gas flow rate on overall mass transfer coefficient, K_{Ga}

The gas flow rate is one of the important elements that can affect mass transfer performance. Many studies have shown that when the gas flow rate increased, so did the K_{Ga}.

The effect of gas flow rate on the overall mass transfer coefficient in a continuous process was investigated using (MEA+DEA +TEA).The blended amine solution was composed of volume percent concentrations of 10%, 5%, and 5%, respectively. **Figure (6)** shows the evolution of the total mass transfer coefficient as a function of gas flow at various time intervals and a constant liquid flow rate.

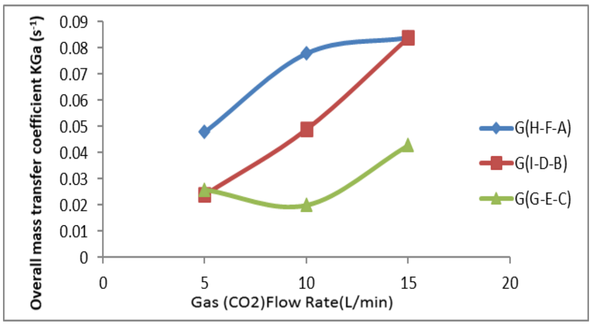


Figure (6) Progression of K_{Ga} in a function of gas flow for continuous processes

For Figure (6) shown at points A and B, after minutes of experiment the overall mass transfer coefficient obtained was ($0.084 S^{-1}$) at gas flow 15 L/min. This means that as more gas passes through the column, more is absorbed at the saturation step.

The curve gradually rises at points b, d, and I as the increase in the gas flow rate is directly proportional to the increase in the mass transfer coefficient, where the higher the level of gas flow for a longer time and the lower the level of liquid flow, the higher the efficiency of the process of capturing carbon dioxide gas, and according to**Eq (5)**, we get The material transfer coefficient with the best value

However, numerous researchers' experiments, as well as predictions by (Fu et al. 2013) and (Chen et al. 2016) work. They demonstrated that the liquid film can control CO_2 absorption in an amine solution, and that the gas flow rate has no effect on K_{Ga} in such a system.The overall mass transfer coefficient (K_{Ga}) is higher for a higher flow rate due to the faster continuous intake in CO_2 from the flue gas. Indeed, more CO_2, flowing through the column implies a better absorption rate of the device.

6. Analytical method of Taguchi

The capture was studied in a packed bed reactor. The concentration of mixed amines was 5V/v %MEA+5V/v % DEA +10V/v %TEA. To limit the number of tests, we employed the Taguchi technique as an experimental design **[١٨,١٩]**. The factors in this study were divided into three levels. When applying the Taguchi technique, the following equation should be used to estimate a minimal number of experiments:

$$N = 1+\sum_{i=1}^{NV}(Li-1) \qquad \text{Eq.(8)}$$

In the fundamental series, the key parameters impacting the rate of absorption are (liquid of absorption) > (Gas Flow rate) > (time Flow Rate) > (air Flow Rate), implying that the time of absorption has the greatest impact on the rate of absorption, followed by the rate of gas flow. **Figure (7)** shows a main effect for four variables that gave maximum values from KGa at 60 minutes when gas flow was 15 L/min, air flow was 90 L/h, and liquid flow was 450 ml/min. Table (4) shows the response of the removal efficiency factors to the S / N ratio**[٢٠,٢١]**.

Table (4) Factors' responses to the S/N ratio for elimination efficiency

Level	gas (CO_2)flow rate	Air flow rate	Liquid flow rate	Time
1	-27.16	-24.29	-20.35	-22.13
2	-24.44	-24.29	-23.70	-23.63
3	-20.45	-23.47	-28.00	-26.29
Delta	6.70	0.82	7.65	4.16
Rank	2	4	1	3

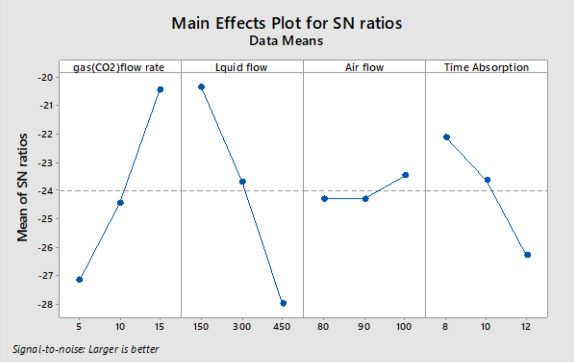


Figure (7) The optimum point of mass transfer coefficient of blended amine with 4-factor in Taguchi analysis program

9.Conclusion

The use of a packed bed in continuous operation allowed for the most CO_2 collection. The significance of this research is in discovering novel ways to achieve maximal absorption in the column and high carbon dioxide concentrations after dissolving it in a packed column. A laboratory-scale packed bed was used to quantify KGa of carbon dioxide absorption into mixed MEA-DEA-TEA solutions. Gas flow, liquid flow, air flow, and absorption time were the parameters employed in this investigation. The gas flow rate, the liquid flow rate, and the KGa all increased as the investigation progressed. The KGa values rose as the gas flow rate and liquid flow rate increased in this investigation. Increasing the CO_2 loading of amines also reduced the KGa. The maximum value of CO_2 loading was obtained in process 2.479 (mole CO_2/mole amine). The maximum value of overall mass transfer coefficient was obtained in process (0.084) S^{-1}.

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References

1. Liang, Zhiwu (Henry), Wichitpan Rongwong, Helei Liu, Kaiyun Fu, Hongxia Gao, Fan Cao, Rui Zhang, Teerawat Sema, Amr Henni, Kazi

Sumon, Devjyoti Nath, Don Gelowitz, Wayuta Srisang, Chintana Saiwan, Abdelbaki Benamor, Mohammed Al-Marri, Huancong Shi, Teeradet Supap, Christine Chan, Qing Zhou, Mohammad Abu-Zahra, Malcolm Wilson, Wilfred Olson, Raphael Idem, and Paitoon (PT) Tontiwachwuthikul. 2015. "Recent Progress and New Developments in Post-Combustion Carbon-Capture Technology with Amine Based Solvents." *International Journal of Greenhouse Gas Control* 40:26–54.

2. Onyeaka, H., Miri, T., Obileke, K., Hart, A., Anumudu, C., & Al-Sharify, Z. T. (2021). Minimizing carbon footprint via microalgae as a biological capture. Carbon Capture Science & Technology, 1, 100007.
3. Yang, Hongqun, Zhenghe Xu, Maohong Fan, Rajender Gupta, Rachid B. Slimane, Alan E. Bland, and Ian Wright. 2008. "Progress in Carbon Dioxide Separation and Capture: A Review." *Journal of Environmental Sciences* 20(1):14–27.
4. Al-Maamary, H.M., Kazem, H.A., Chaichan, M.T., 2017. Climate change: the game changer in the Gulf Cooperation Council region. Renew. Sustain. Energy Rev. 76, 555–576.
5. Alonso, A., Moral-Vico, J., Markeb, A.A., Busquets-Fité, M., Komilis, D., Puntes, V., Sánchez, A., Font, X., 2017. Critical review of existing nanomaterial adsorbents to capture carbon dioxide and methane. Sci. Total Environ. 595, 51–62.
6. Mehassouel A., Derriche R., Bouallou C., 2016, A New CO_2 Absorption Data for Aqueous Solutions of Nmethyldiethanolamine plus Hexylamine, Chemical Engineering Transactions, 52, 595-600.
7. Pao Chi Chen, Sheng-Zhong Lin. "Optimization in the Absorption and Desorption of CO_2 Using Sodium Glycinate Solution", Applied Sciences, 2018.
8. Puxty, G.; Rowland, R.; Attalla, M. Comparison of the Rate of CO_2 Absorption into Aqueous Ammonia and Monoethanolamine. Chemical Engineering Science 2010, 65, 915-922.
9. Saad, Elsayed S., A. M. Nasser, H. Abd El-Wahab, Waseam A. Hassan, and A. E. Elsayed. 2019. "Effect of Different Surfactant Monomers on Alkali-Soluble Emulsion Polymer as a Binder for Water Based Printing Inks." *Egyptian Journal of Chemistry* 62(1):63–76.
10. Al-Sabagh, A. M., Tahany Mahmoud, Maher Helmy Helal, A. M. Abdelrahman, Amira El-Said, and Mona EL-Rayes. 2019. "Flow Ability Enhancement of Waxy Crude Oil Using New Spirocompound Based on Aromatic Amine System." *Egyptian Journal of Chemistry* 62(12):2289–2301.
11. Mostafa, Hamida Y., Ahmed M. A. El Naggar, Ebaa A. Elshamy, Amal S. Farag, and Ahmed I. Hashem. 2019. "Utilization of Binary Mixtures of Different Solvents for Aromatics Extraction from a Petroleum Wax Distillate Feedstock." *Egyptian Journal of Chemistry* 62(9):1749–59.
12. Pao-Chi Chen et al .,2014. CO_2 Capture Using Monoethanolamine in a Bubble-Column Scrubber.
13. Rushdi, S., & Thamer, E. (2020, June). Investigation of overall mass transfer coefficient of CO2 absorption in to aqueous blended Monoethanolamine (MEA), Diethanolamine (DEA) and Triethanolamine (TEA) measured in Bubble column Reactor solution. In IOP Conference Series: Materials Science and Engineering (Vol. 870, No. 1, p. 012056). IOP Publishing.
14. Shahad, F. H., Salih R, Al-Sharify, Z. T. A Taguchi Approach for optimization of mass transfer coefficient in metronidazole drug delivery process and activated carbon as a carrier. (2021). Journal of Engineering Research, Vol.9 No. (4A) pp. 25-38
15. Pashaei, H., Zarandi, M. N., & Ghaemi, A. (2017). Experimental study and modeling of CO2 absorption into diethanolamine solutions using stirrer bubble column. *Chemical Engineering Research and Design*, *121*, 32-43.
16. Chen, P.C.; Luo, Y.X.; Cai, P.W. Capture of carbon dioxide using monoethanolamine in a bubble-column scrubber. Chem. Eng. Technol. 2015, 38, 274–282.
17. Chen, P.C.; Yu, S.C. CO_2 capture and crystallization of ammonia bicarbonate in a lab-scale scrubber. Crystals 2018, 8, 39
18. Ng, C.M., Chen, P.C., Manickam, S., 2012. Green high-gravitational synthesis of silver nanoparticles using a rotating packed bed reactor (RPBR). Ind. Eng. Chem. Res. 51, 5375–5381.
19. Chen, P.C.; Luo, Y.X.; Cai, P.W. Capture of carbon dioxide using monoethanolamine in a bubble- column scrubber. Chem. Eng. Technol. 2015, 38, 274–282.
20. Abd, Z. N. (2020). An Experimental Study of Mass Transfer coefficient of CO2 absorption using Different Amines in a Packed Column. Egyptian Journal of Chemistry, 63(12), 4875-4881.
21. Abd, Z. N., & Rushdi, S. A. (2020). Investigation of overall mass transfer coefficient of CO2 absorption in packed Column. Al-Qadisiyah Journal for Engineering Sciences, 13(2), 153-157.