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Carbon Dioxide Removal Using Blended Amine Solution in a Randomly Packed Bed Column

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Abstract

Many researchers are currently investigating carbon dioxide capture and storage since it is suppressing the global warming phenomenon. Aqueous carbon dioxide chemical absorption is the most effective method. The present study incorporates the applicability and performance of blended alkanol amine solutions monoethanolamine (MEA) with diethylenetriamine (DETA) as a chemical blended absorbent investigated in a pilot scale column packed randomly with Rashing rings. The effect of operating conditions on absorption performance was examined. The performance investigation is given in terms of the overall mass transfer coefficient (KGa_v) and carbon dioxide capture efficiency (η). Typically, DETA: MEA with a mass ratio of 1:1 and total mass concentration of 30 % wt. could provide the highest K_Ga_v with a value of 0.1572 (kmol/(m^3*Kpa*hr)) and η with a value of 98.79 %. While at the same condition in terms of liquid and gas rate, with DETA: MEA in the blending mass ratio 0.25:1, the K_Ga_v and η values equal to: 0.1198 (kmol/(m^3*Kpa*hr)) and 96.37%, respectively. Based on these findings, it is reasonable to assume that diethylenetriamine, a solution of alkanol amines, would serve as an efficient blending absorbent for carbon dioxide removal.

Keywords: Chemical absorption; Carbon dioxide removal; Packed bed column; Alkanol amine blender; Monoethanolamine; Diethylenetriamine.

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1- Introduction

The presence of greenhouse gases within the atmosphere, which is distinguished by their ability to capture infrared rays, which causes the majority of global warming [1]; The most massive greenhouse gases are carbon dioxide sources from coal and oil power generation, manufacturing furnaces, cement factories, automobile exhaust systems, lime furnace vents, sweetening of natural gas, and syngas production are all significant contributors to the atmosphere's carbon dioxide content [2]. Furthermore, relevant greenhouse gases are rising exponentially because of the increasing worldwide demand for energy, so carbon dioxide captured from large stationary sources has drawn a lot of attention. Much attention by researchers as a way of mitigating the harsh environmental and climatic damage caused by such emissions [3]. The corrosion rate significantly rises in the presence of CO_2 gas; thus it is the main species that causes corrosion in the production of sour gas [4]. It requires the development of efficient carbon dioxide capture methods from stationary sources to reduce the negative environmental consequences of greenhouse gases and the corrosion issues in gas processing.

Carbon dioxide capture can be accomplished through a number of different technologies, including adsorption, absorption, membrane, gas separation, and cryogenic separation. These technologies must include adsorbent or absorbent regeneration, and efficient operation under realistic conditions is essential to achieve economic viability [5]. Industrial carbon dioxide capture from post-combustion and natural gas processing is done by the most popular technology at present, which is chemical solvent absorption, because of the lower cost and superior efficiency, especially in comparison to other processes [6]. There are several advantages to the using of chemical solvent absorption for carbon dioxide capture, including (a) The ability to perform the reaction and removal of carbon dioxide in only one processing facility; (b) a considerably higher carbon dioxide capture efficiency; (c) The feasibility of regenerating a richly loaded chemical solvent with carbon dioxide in the absorption step for further reuse as a lean unloaded chemical absorbent; (d) The ability to achieve nearly pure carbon dioxide after desorption of loaded solvent,(e) Technologically-advanced enough to be widely applicable in the industry [7].

Monoethanolamine as a primary alkanol amine, diisopropylamine, and diethanolamine as a secondary alkanol amine, methyl diethanolamine as a tertiary amine, and 2-Amino2-Methyl1-Propanol as specialty amines are some of the most common alkanol amines used for carbon dioxide capture [8]. Among the many benefits of the alkanol amine system is the fact that the occurrence of chemical reactions throughout the liquid phase

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enhances mass transfer during the process of absorption. Carbon dioxide capturing via post-combustion is done via a conventional monoethanolamine absorbent in the industry [9]. Desorption is the following step to the absorption process; done through the desorber column. It is equipment responsible for releasing carbon dioxide that was absorbed from the flue gas in the absorber via a change in pressure or temperature. The main issue in the absorption of carbon dioxide is the amount of energy needed to desorb carbon dioxide in the desorption step. Other major factors influencing the efficiency as well as the process cost include the carbon dioxide capacity of the solvent, its kinetics, the degree to which the solvent degrades, and the degree to which the process is integrated [9].

Developing energy-efficient and effective-cost absorption processes is critical to reducing the overall cost of carbon dioxide capture. This objective could be attained by means of various methods: (a) Enhancing the absorption performance of alkanol amines and by designing gas-liquid contactors used in the process; (b) An appropriate choice of alkanol amines and incorporating their mixing blends into the process has the potential to minimize the size required of process equipment and lower the overall energy utilization; this maintains carbon dioxide capture at a lower cost. Proper alkanol amine selection could significantly reduce the process's capital and maintenance costs [8]. Considering it practically, the performance of the mass transfer investigated in laboratory equipment with the packed column is the most accurate representation of the absorption behavior of gas-liquid contactors. This is due to the fact it takes into account, not just kinetics and thermodynamics as well as hydrodynamics of the entire system, which accurately represents the value of the surface area required to achieve absorption [10].

The present study incorporates the applicability and performance of a different type of alkanol amine solutions as a chemical absorbent investigated in a pilot scale column packed randomly with Rashing rings packing. The present study incorporates the applicability and performance of blended alkanol amine solutions monoethanolamine (MEA) and diethylenetriamine (DETA) as a chemical absorbent investigated in a pilot scale column packed randomly with Rashing rings. Investigating the effect of operating conditions, including amine feed concentrations, alkanol amine flow rates, simulated feed gas flow, feed amine loading, a blended mass ratio of DETA: MEA, inlet carbon dioxide concentration, and feed amine temperature. All experiments were conducted at atmospheric pressure (101.325 Kpa). This paper primarily aims to improve carbon dioxide absorption performance by employing blending amine MEA: DETA with different blending mass ratios. The performance investigation is given in terms of the overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η). After carefully analyzing a large amount of experimental data, it revealed that blending the DETA into the MEA solution exhibited the best possible performance in terms of K_Ga_v and η.

2- Theoretical Aspects

2.1. Determination of the Overall Mass Transfer Coefficient (KGa_v)

The overall mass transfer coefficient (K_Ga_v) is a lumped parameter representing the packed column's absorption performance per unit volume. It is the sum of three factors related to the mass transfer, kinetics, hydrodynamics, and thermodynamics of the carbon dioxide absorption system, a critical parameter because the absorber column height can be determined through it [10]. Flue gas, which is a gas side, and amine solution, which is a liquid side, are the two bulk phases involved in the mass transfer; it occurs when carbon dioxide in a gas side moves through the gas−liquid interface into a liquid side [11]. Based on the two-film theory, overall carbon dioxide flux N_{CO2} moving from the bulk of the gas side to the bulk of the liquid side through the gas−liquid interface could be calculated using Eq. 1. The driving force in Eq. 1 is represented as the difference between the concentration of carbon dioxide in the bulk gas side (y_{CO2}) and the equilibrium concentration of carbon dioxide (y^*_{CO2}) concerning its concentration within the bulk liquid side [12].

$$N_{CO2} = KG * P * (y_{CO2} - y^*_{CO2}) \quad (1)$$

Where KG represents the overall coefficient of mass transfer based on the gas side; P is the operating pressure; thus:

$$KG = \frac{N_{CO2}}{P(y_{CO2} - y^*_{CO2})} \quad (2)$$

KGa_v can be determined through Eq. 2 by multiplying it by the interfacial area $\frac{a_v}{a_v}$ as follows:

$$KG = \frac{N_{CO2}}{P(y_{CO2} - y^*_{CO2})} * \frac{a_v}{a_v} \quad (3)$$

Simplifying Eq. 3 to get Eq. 4

$$KG * a_v = \frac{N_{CO2}}{P*(y_{CO2} - y^*_{CO2})} * a_v \quad (4)$$

Naami et al. experimentally verified that the term $N_{CO2}\, a_v$ can be calculated by analyzing the concentration gradients of carbon dioxide where measured through a packed section of the absorber. Conforming to Fig. 1, assuming an element along the absorber packed section with a height of *dZ*, and by making mass balance based on carbon dioxide over this slice. The resulting equation can be expressed, as in the following [11]:

$$N_{CO2}\, a_v * dZ = G * d\left(\frac{y_{CO2}}{(1 - y_{CO2})}\right) \quad (5)$$

Where, $\frac{y_{CO2,}}{(1 - y_{CO2})}$ represents the molar ratio of carbon dioxide in the bulk gas side, and it can also be expressed as Y_{CO2}; dZ represents a differential height section of the packing; G represents the total molar flow of the untreated

gas without carbon dioxide flow. Eq. 5 can be expressed alternatively, as in the following:

$$N_{CO2} = \frac{G}{a_v dZ} * d(Y_{CO2}) \quad (6)$$

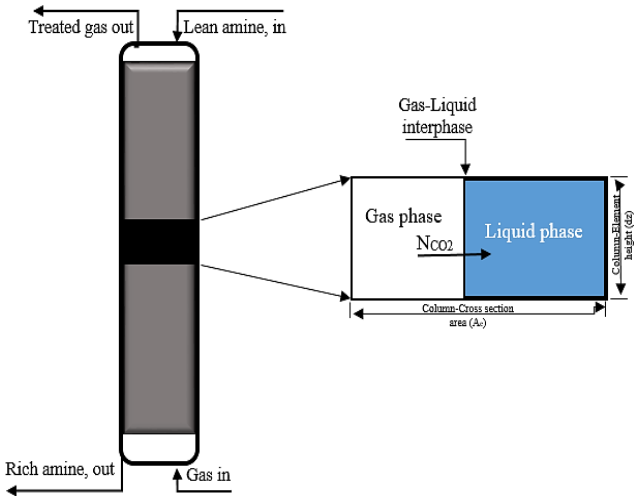

Fig. 1. Mass Transfer Mechanism of Carbon Dioxide Absorption

Then, Eq. 6 can be used in combination with Eq. 4 as in the following:

$$KG * a_v * (y_{CO2} - y^*_{CO2}) * P * dz = G * dY_{CO2} \quad (7)$$

Rearrangement Eq. 7 to get Eq. 8

$$KG * a_v = \frac{G}{P*(y_{CO2} - y^*_{CO2})} * (\frac{dY_{CO2}}{dZ}) \quad (8)$$

Since the chemisorption of carbon dioxide within the alkanol amine absorbent obeys the instantaneous mechanism of the reaction scheme. Resulting in the absence of carbon dioxide concentration on the liquid side, subsequently, y^*_{CO2} achieves zero. The term y^*_{CO2} represents the equilibrium concentration of carbon dioxide in the bulk gas side in equilibrium with the concentration of carbon dioxide in the liquid bulk side [13].

$$KGa_v = \frac{G}{P*\int_0^Z dz} * \int_{Y1}^{Y2} (\frac{1}{y_{CO2}}) dY_{CO2} \quad (9)$$

Since,

$$Y_{CO2} = \frac{y_{CO2}}{1 - y_{CO2}} \quad (10)$$

Substitute Eq. 10 in Eq. 9 and integration Eq. 9 for all changes of carbon dioxide molar ratio along the height of the packing section would lead to the main equation that identifies the overall coefficient of mass transfer (KGa_v), as in the following:

$$KGa_v = \frac{G}{P*Z} * \left[\ln\left(\frac{y_{CO2,in}*(1-y_{CO2,out})}{y_{CO2,out}*(1-y_{CO2,in})}\right) + (\frac{y_{CO2,in}}{(1-y_{CO2,in})} - \frac{y_{CO2,out}}{(1-y_{CO2,out})})\right] \quad (11)$$

Where $y_{CO2,in}$, is the inlet concentration of CO_2 and $y_{CO2,out}$ is the outlet concentration of CO_2, and Z is the height of packing.

2.2. Determination of Carbon Dioxide Capture Efficiency

The carbon dioxide capture efficiency (η) is the amount of carbon dioxide absorbed by an alkanol amine solvent. The equation for this is as follows [10]:

$$\eta = \left(1 - \frac{y_{CO2,out}}{1-y_{CO2,out}} * \frac{1-y_{CO2,in}}{y_{CO2,in}}\right) * 100\ \% \quad (12)$$

2.3. Determination of Carbon Dioxide Loading

The Chittick carbon dioxide analyzer was used to estimate the carbon dioxide loading in an amine solution. The Official Analytical Chemists Association (AOAC) described this [14]. The amount of carbon dioxide captured by the amine absorbent and the concentration of titrated amine was determined using the following equations [15-17]:

$$\alpha(\frac{moles_{CO2}}{moles_{amine}}) = \frac{\left(\frac{(V_{gas}-V_{HCl})*(P)*(273.15K)}{(1013225Pa)(T(K))(22.4\frac{L}{mol})}\right)}{C_{amine}V_{amine}} \quad (13)$$

$$C_{amine} * V_{amine} = C_{HCl} * V_{HCl} \quad (14)$$

Where: V_{gas} is the volume of released carbon dioxide gas (ml), V_{HCl} is the volume of titrant hydrochloric acid (ml), P is the operating pressure (pa), T is the lab temperature (K), C_{amine} is the liquid amine concentration (mole/L), V_{amine} is the sample amine volume (ml), C_{HCl} is the prepared hydrochloric acid concentration (mole/L), V_{HCl} is the titrated hydrochloric acid volume (ml). The assumption on this equation is that neglecting pressure exerted by releasing carbon dioxide gas, and operation pressure is the atmospheric pressure.

3- Experimental Work

3.1. Materials

Monoethanolamine (MEA, Thomas Baker, >98%); Hydrochloric acid (HCl, CDH, 35-38%); Diethylenetriamine (DETA, Fluka, >97%); Distilled water; CO_2 gas (>99.6 v/v%) and N_2 gas) >99.8 v/v%) were supplied from Albilal gas company located in Baghdad to prepare the absorbate gas mixture. The materials were used in the same state in which they were purchased.

3.2. Laboratory Apparatus and Equipment

The laboratory apparatus and equipment used in this research are listed in Table 1 as follows:

Table 1. Laboratory Apparatus and Equipment

No.	Laboratory Apparatus or Equipment	Model and Origin	Function
1	IR gases analyzer	Geotechnical Instruments, BIOGAS 5000, UK	Determine the concentration of carbon dioxide
2	Pressure regulator	China	Reduce the inlet pressure of gas from the cylinder to the desired outlet pressure
3	Liquid flowmeter	ZYIA Instrument Company, AFM-6T, China	Measure the solution volumetric flow rate
4	Gas flowmeter	Bass Instrument, PMBCV.P.A.10.L.M.G2, Turkey	Measure the simulated gas volumetric flow rate
5	Gauge pressure	Excel Instrument, EN 837-1, India	Monitor the top and bottom operating pressure of the absorber
6	Check valve	China	Ensure the flow of gas in one direction
7	Diaphragm pump	TYP-2500NH, China	Transfer solutions from the reservoir to the top of the absorber
8	Magnetic stirrer with heater	Dragon Lab, MS-H-pro, Australia	Homogenizing solution with or without heating
9	Magnetic stirrer bar	China	Stir solutions in a sealed flask
10	Gas cylinder	/	Store carbon dioxide gas and nitrogen gas
11	20-L high-density polyethylene (HDPE) tanks	China	Store rich and lean absorbent solution

3.3. Experimental Setup

3.3.1. Set up of Pilot-Scale of Carbon Dioxide Absorption Unit

A schematic is shown in Fig. 2, illustrating the pilot-scale absorption unit where the absorption experiments are conducted. All experimental apparatus of a packed bed absorption unit is listed in Table 2. The pilot-packed bed absorber's major components were a packed column made from acrylic plastic (transparent plastic material) consisting of 1.8 m effective packing height with a total length of 2 m, and 40 mm inside diameter with 5 mm wall thickness; other specifications of the absorber are listed in Table 3. Rashing rings are the packing used to pack the absorber used for providing a large, wet surface area between the gas-liquid phases; the geometric features of these packing are given in Table 4; the packing is dumped randomly since the absorption columns typically employ a random packing pattern for their internals. Random packing is frequently used in processes where fouling might occur, such as flue gas sweeting, because of the inexpensive cost and ease of installation and removal of the packed for maintenance [18].

The bypass valve and liquid flowmeter were equipped in the feed amine stream to control the pump's head and amine flow. A gas flowmeter was used to regulate the flow rate of the simulated gas feed before it was introduced to the packed bed absorber. The entire gas pipeline had a check valve; which was installed to ensure the flow of gas in one direction. The rich amine at the base of the absorber was distributed via a pipeline connected to the three-way valve at the bottom of the absorber; meanwhile, the liquid outlet stream was divided into a sampling stream and a waste stream; the sampling stream was linked to a valve for removing sampling tests to be analyzed for carbon dioxide loading experiment. The sweet gas was released from the top of the absorber via a pipeline connected to the head of the absorber and sent to a sampling box for the carbon dioxide measuring. The installation of other support devices was also essential for the success of the experiment, a carbon dioxide cylinder, nitrogen cylinder, two gas rotameters, liquid flowmeter, two-gauge pressure, and two of the 20-L high-density polyethylene (HDPE) tanks for rich and lean absorbent.

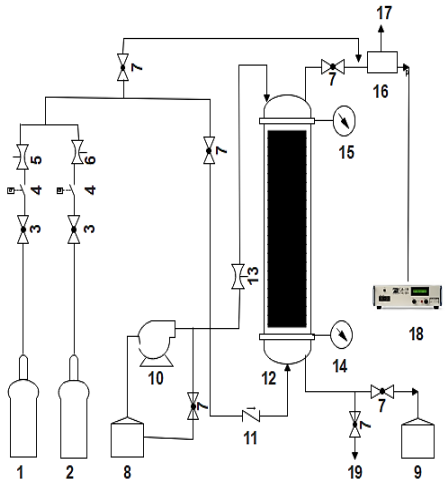

Fig. 2. Schematic of the Pilot-Scale of Carbon Dioxide Absorption Unit

Table 2. Experimental Apparatus of a Packed Bed Absorption Unit

No.	Component	No.	Component
1	Co_2 gas cylinder	11	Check valve
2	N_2 gas cylinder	12	Packed bed absorber
3	Gas pressure- regulator	13	Amine flow meter
4	Valve for gas flow tuning	14	Bottom pressure gauge
5	CO_2 flow meter	15	Top pressure gauge
6	N_2 flow meter	16	Sampling box
7	Valve	17	Treated gas pipeline
8	Lean amine tank	18	Gas analyzer
9	Rich amine tank	19	Rich amine sample point
10	Lean amine diaphragm pump		

Table 3. Characteristics of Packed Bed Column

Parameters	Data
Walls material	Acrylic
Column outer diameter	0.05 (m)
Column inner diameter	0.04 (m)
Column height	2 (m)
Packing height	1.8 (m)

Table 4. Geometric Features of the Random Packing

Parameters	Data
Column packing	Rashing rings
Rashing rings material	Glass
Rashing rings size	6 (mm)
Wall thickness	0.8 (mm)
Number	3,020,000 (/m^3)
Contact surface	794 (m^2/m^3)
Free space	62 %
Packing factor	5250 (m^2/m^3)

3.3.2. Set up of Chittick Device

Fig. 3 displays the apparatus' schematic of the Chittick device used for measuring loaded carbon dioxide in rich amine solution and apparatus listed in Table 5.

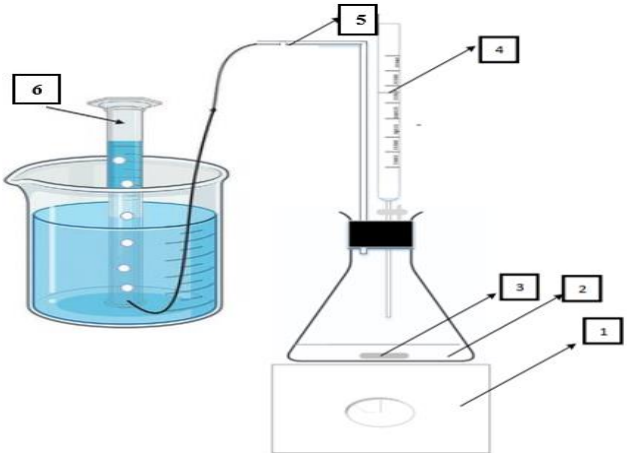

Fig. 3. Schematic of CO_2 Loading Apparatus

Table 5. Carbon Dioxide Loading Apparatus

No.	Apparatus	No.	Apparatus
1	Magnetic stirrer	4	Burette
2	Erlenmeyer flask	5	Deliver pipeline
3	Magnetic stirrer bar	6	Collected volume of CO_2 released

3.4. Experimental Procedure

3.4.1. Operation of Carbon Dioxide Absorption Unit

The absorption unit was designed for a counter-current mode of operation, where the simulated flue gas feed (CO_2 and N_2) where prepared by mixing a known volumetric flow of nitrogen and carbon dioxide gas and enters the packed bed absorber via its base and ascended. Lean amine solutions were prepared by adding a known volume of distilled water to the amine to get the desired concentration of absorbent and pumped to the top of the packed by a pump and descended. The flow pattern is counter-current, which is beneficial to make carbon dioxide contact and react completely with the amine solution. The sweet gas is released from the absorber column's top; while the rich loaded amine solutions are discharged from the absorber column's bottom and stored in the loaded amine tank. The sweet gas enters the IR gas analyzer to analyze the concentration of carbon dioxide. At the end of each experiment power off the lean amine pump and turn off properly of the nitrogen and carbon dioxide gas cylinders. Running the washing process with water to clean the absorber packing properly.

3.4.2. Carbon Dioxide Molar Concentration Test

This test was done for both the treated gas line and simulated feed flue gas line to confirm the feed carbon dioxide molar concentration with the use of the IR gas analyzer with the specifications of response time to analyze the concentration of carbon dioxide gas ≤10 seconds [19]. Typically, it was operated during the experiments to withdraw samples and measure the carbon dioxide volumetric concentrations. When the steady state condition is reached within ten minutes; where the amine solution has already reacted with carbon dioxide. The treated gas stream is sent to the IR gas analyzer to measure the carbon dioxide concentration.

3.4.3. Carbon Dioxide Loading Test

This test was done for the rich amine solution with the following procedure; the Erlenmeyer flask (250 ml) was filled with a sample of a known volume of loaded amine (10 ml) then an indicator of methyl orange (2-3 drops). The Erlenmeyer flask was placed on a magnetic stirrer. It was used for mixing the titrated mixture in order to homogenize it and aid in the release of carbon dioxide. A fifty-milliliter titration burette that contained a hydrochloric acid solution was then attached to the Erlenmeyer flask and sealed. Slowly add hydrochloric acid (1 M HCl) from a 50 ml titration burette into the Erlenmeyer flask until the methyl orange indicator color changes from colorless to pink color; which is the indication of the endpoint of the titration. The released carbon dioxide gas from the Erlenmeyer flask; is connected via a delivery pipeline to the measurement cylinder. The measurement cylinder before investing in a water basin, is first filled with water. The released carbon dioxide gas is then bubbled into the graduated cylinder. At the same time, it is turned upside down and delivered through a pipeline; the water level decreases as gas bubbles up and fills the inverted graduated cylinder.

4- Results and Discussion

4.1. Effect of Total Absorbent Concentration

A set of tests was carried out under fixed conditions to examine the effect of total amine concentration on the overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η) within a range of 10 wt.%, 20 wt.%, and 30 wt.%. It can be shown from Fig. 4 and

Fig. 5 that all systems' overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η) increased as the total amine concentration increased. Enhancement in K_Ga_v and η with increasing the total concentration because a greater number of active free molecules of alkanol amine would be present per unit weight when the amine concentration was raised. It diffuses towards the gas-liquid interface and reacts with the dissolved carbon dioxide molecules, as shown in Eq.16, increasing the enhancement factor to promote rapid carbon dioxide absorption into an amine solution [16]. The change in the solution concentration impacts the concentration of the active amine. These values were based on the relationship between the carbon dioxide loading and the total concentration of the aqueous solution as follows:

$$C_{active\ amine} = \left(\frac{\alpha_{CO2.eq} - \alpha_{CO2}}{\alpha_{CO2.eq}}\right) * C_{total} \quad (15)$$

Where: $C_{active\ amine}$ = concentration of the active amine. C_{total} = concentration of the aqueous solution. α_{CO2} = carbon dioxide loading. $\alpha_{CO2.eq}$ = carbon dioxide loading at equilibrium condition.

However, if the concentration of the alkanol amine solution increased, the amine's viscosity would increase as well; because of the high viscosity, carbon dioxide has difficulty diffusing from the gas/liquid contact into the liquid bulk phase; as a result, a reduction in mass transfer. Despite how it influences overall mass transfer, equipment corrosion is also significantly affected by the concentration of the solution; these drawbacks would make it difficult to enhance carbon dioxide absorption performance and would also raise maintenance costs; therefore, many considerations are needed to find the optimal solution concentration [20].

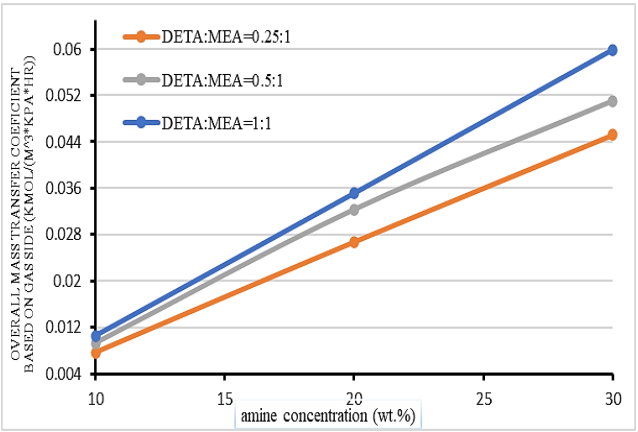

Fig. 4. Effect of Total Absorbent Concentration on K_Ga_v at T= 298.15 K, Unloaded Feed Amine, CO_2 Feed =20 v/v%, G= 3.8410 (Kmol/m^2.hr), L= 0.9549 (m^3/m^2.hr)

4.2. Effect of Liquid Flow Rate

Repeated tests were conducted under specific conditions to examine the effect of liquid flow rate on the overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η), 0.9549 (m^3/m^2.hr), 1.4324 (m^3/m^2.hr), and 1.9099 (m^3/m^2.hr) was the set flows used. Its influence on the K_Ga_v and η, as demonstrated in Fig. 6 and Fig. 7, respectively, clearly indicates an increase in both K_Ga_v and η values with the increase of liquid flow rate. This enhancement because a higher liquid flow rate led to (i) An increase in the gas-liquid interface's effective contact area; (ii) an increase in the enhancement factor (E) a larger number of free active amines molecules in the entire system; (iii) Improved physical mass transfer coefficient (k_L^o) in the liquid phase [16]. For these reasons, an enhancement in the overall mass transfer Coefficient (K_Ga_v) occurs according to Eq. 16:

$$\frac{1}{K_Ga_v} \approx \frac{1}{E*k_L^o*a_v} \quad (16)$$

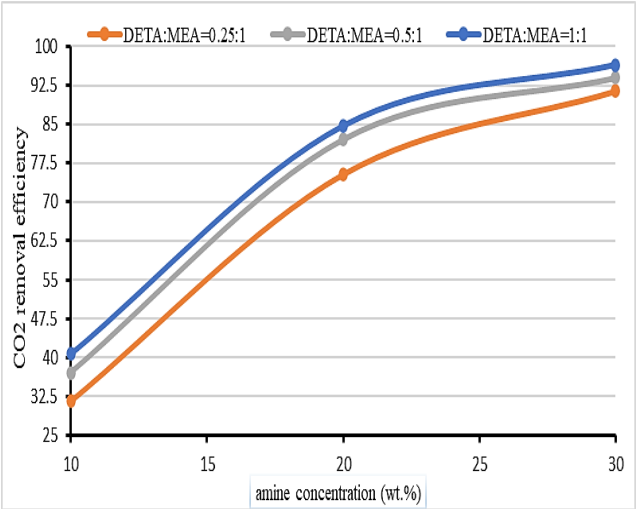

Fig. 5. Effect of Total Absorbent Concentration on Carbon Dioxide Capture Efficiency at T= 298.15 K, Unloaded Feed Amine, CO_2 Feed =20 v/v%, G= 3.8410 (Kmol/m^2.hr), L= 0.9549 (m^3/m^2.hr)

This means that higher liquid flow rates result in a reduction in the resistance of mass transfer in the liquid phase and a higher Reynolds number [16]. It is significant to consider that depending on the blending mass ratio of alkanol amine, the effect of the liquid flow varies significantly; this can be seen in Fig. 6 and Fig. 7, respectively, which give K_Ga_v and η values of three blending mass ratio of alkanol amine under a range of liquid flow rate. These values were based on the mentioned operating conditions with increasing DETA blending mass ratio to MEA, which become more sensitive to the variation in liquid flow rate. This is due to diethylentriamine's molecular structure, which has two or more amino groups with each molecule, it is a promising absorbent for absorbing carbon dioxide due to its high kinetics and capacity for absorption [21]. While a greater liquid flow rate can improve packed column mass transfer performance, the costs of both circulation and regeneration increase; as a result, it would be unreasonable to increase the liquid flow rate in the packed column without giving due consideration to a number of other factors [16].

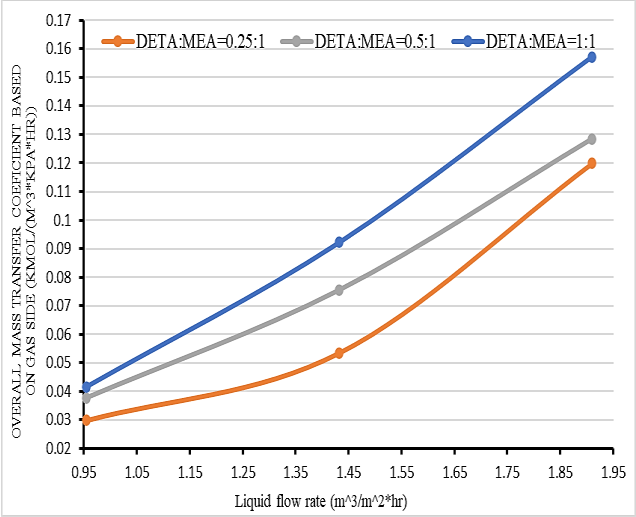

Fig. 6. Effect of Liquid Flow Rate on K_Ga_v at T= 298.15 K, Unloaded Feed Amine, CO_2 Feed =20 v/v%, G=7.6817(Kmol/m^2.hr), wt.=30%

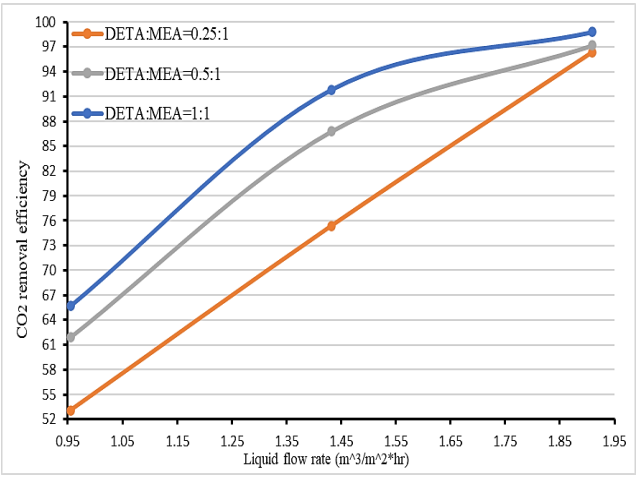

Fig. 7. Effect of Liquid Flow Rate on Carbon Dioxide Capture Efficiency at T= 298.15K, Unloaded Feed Amine, CO_2 feed =20 v/v%, G=7.6817(Kmol/m^2.hr), wt.=30%

4.3. Effect of Gas Flow Rate

Repeated tests were conducted under specific conditions to examine the effect of the total gas flow rate on the coefficient of mass transfer (K_Ga_v) and carbon dioxide capture efficiency (η). 3.8408 (Kmol/m^2.hr), 7.6817(Kmol/m^2.hr), and 11.5225 (Kmol/m^2.hr) were the set of simulated gas flows used in the study. The gas flow rate influences the gas component's detention time and; thus the solution's mixing regime. Their effect on the overall mass transfer coefficient (K_Ga_v), and carbon dioxide capture efficiency (η) are shown in Fig. 8 and Fig. 9, respectively. For all other blended amine ratios DETA: MEA, overall mass transfer coefficient, and carbon dioxide capture efficiency were decreased as the gas flow rate increased. This is due to the fact that an increase in gas flow rate may cause: (i) Carbon dioxide renewal rate increases, leading to higher bulk partial pressure at the gas/liquid interface (ii) Molecular ratios of amines to carbon dioxide have decreased; (iii) Reduction in gas phase residence time in the absorber, which has a negative impact on carbon dioxide absorption performance [22]. According to Fig. 8, illustrations of the overall mass transfer coefficient variations; thus, in order to lower the gas-side resistance, it is recommended that the gas flow rate reach a specified threshold. i.e., maintaining an appropriate gas flow rate is critical.

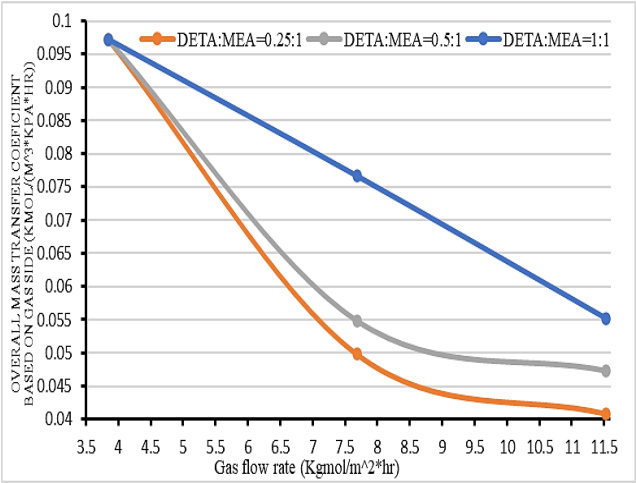

Fig. 8. Effect of Gas Flow Rate on K_Ga_v at T= 298.15 K, Unloaded Feed Amine, CO_2 Feed =20 v/v%, L=1.4324 (m^3/m^2.hr), wt.=30%

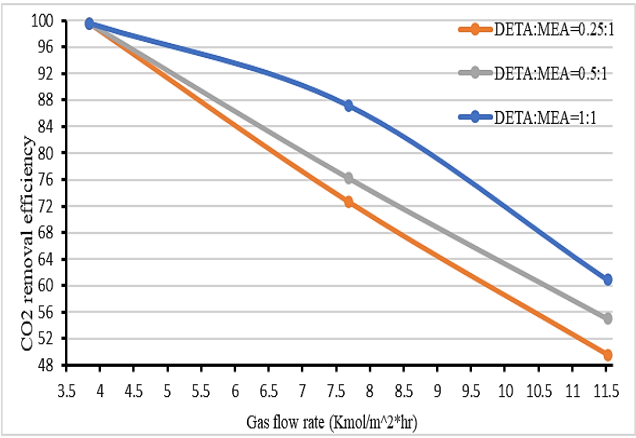

Fig. 9. Effect of Gas Flow Rate on Carbon Dioxide Capture Efficiency at T= 298.15 K, Unloaded Feed Amine, CO_2 feed =20 v/v%, L=1.4324 (m^3/m^2.hr), wt.=30%

4.4. Effect of Absorbent Temperature

Repeated tests were conducted under specific conditions to examine the effect of absorbent temperature on the overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η); 298.15 K, 313.15 K, and 323.15 K were the set temperature used. Their effect on K_Ga_v and η are shown in Fig. 10 and Fig. 11, respectively. The obtained experimental results show a gradual decrease in K_Ga_v and η value for all blended ratios of DETA: MEA. This, due to higher absorbent temperature, causes a reduction in carbon

dioxide solubility, and an increase in absorbent volatilization loss [23]. Increasing absorbent temperature causes a decrease in the absorption capacity of amine because of the exothermic carbon dioxide absorption system's thermodynamics, which could lead to reversible reactions with increasing temperature [24]. All of these factors are detrimental to carbon dioxide absorption; as a result, a reduction in absorption performance occurs.

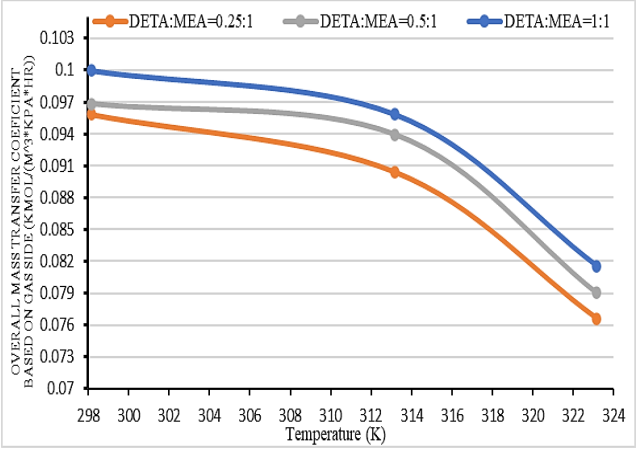

Fig. 10. Effect of Temperature on K_Ga_v at wt.=20%, CO_2 Feed =20 v/v%, G=7.6817(Kmol/m^3.hr), L=1.9099(m^3/m^2.hr), Unloaded Feed Amine

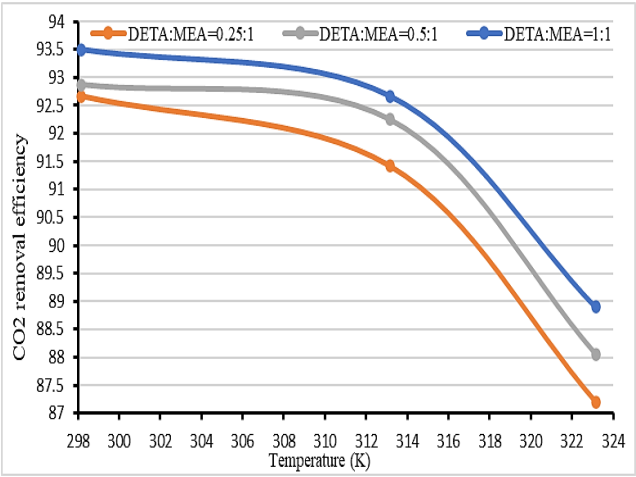

Fig. 11. Effect of Temperature on Carbon Dioxide Capture Efficiency at wt.=20%, G=7.6817(Kmol/m^3.hr), L=1.9099(m^3/m^2.hr), Unloaded Feed Amine, CO_2 feed =20 v/v%

4.5. Effect of Lean Amine Loading

Repeated tests were conducted under specific conditions to examine the effect of lean amine loading on the overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η), 0 (molCO_2/molamine), 0.15 (molCO_2/molamine), and 0.30 (molCO_2/molamine) were the set of initial loading used. Their effect on K_Ga_v and η are shown in Fig. 12 and Fig. 13, respectively. The obtained experimental results show a sharp decrease in K_Ga_v and η values for all blended ratios of DETA: MEA; this is because the carbon dioxide loading value approached the amine's absorption capacity at very high loadings, the diffusion rate of carbon dioxide simultaneously reduced [25]. Another reason is that with increased loading, there is a lower active free amine which directly decreases the driving force of mass transfer between the liquid and gas phase [26].

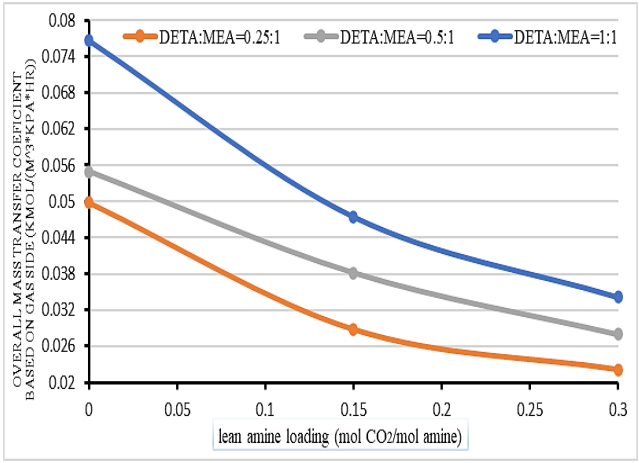

Fig. 12. Effect of Lean Loading on K_Ga_v at T= 298.15 K, CO_2 Feed =20 v/v%, G=7.6817(Kmol/m^3.hr), L=1.9099 (m^3/m^2.hr), wt.=30%

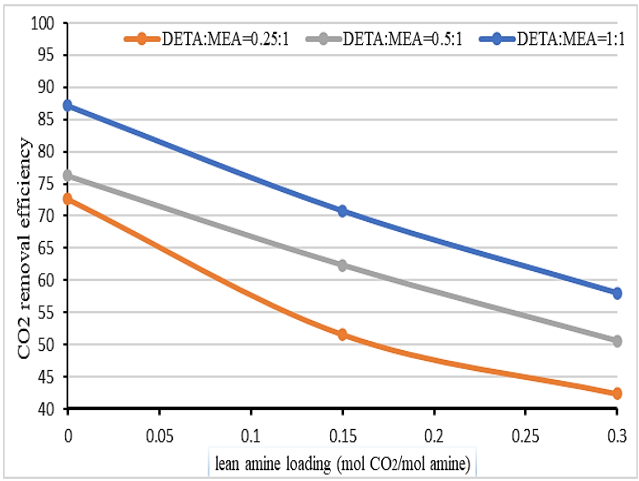

Fig. 13. Effect of Lean Loading on Carbon Dioxide Capture Efficiency at T= 298.15 K, CO_2 Feed =20 v/v%, G=7.6817(Kmol/m^3.hr), L=1.9099 (m^3/m^2.hr), wt.=30%

4.6. Effect of Feed Carbon Dioxide Concentration

Repeated tests were conducted under specific conditions to examine the effect of feed carbon dioxide concentration on the overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η); 0.2 v/v, 0.3 v/v, and 0.4 v/v were the set of inlet concentrations used. Their effect on K_Ga_v and η are shown in Fig. 14 and Fig. 15, respectively. The obtained experimental results show a sharp decrease in both K_Ga_v and η values with increasing feed carbon dioxide concentration for all blended ratios of DETA: MEA; this behavior is thought to be caused by the restriction of diffusion of the solvent molecules within the liquid phase since the amount of carbon dioxide captured remains practically constant due to the

restriction in the liquid phase diffusion. Thus higher inlet carbon dioxide concentrations lead to lower mass transfer performance [27].

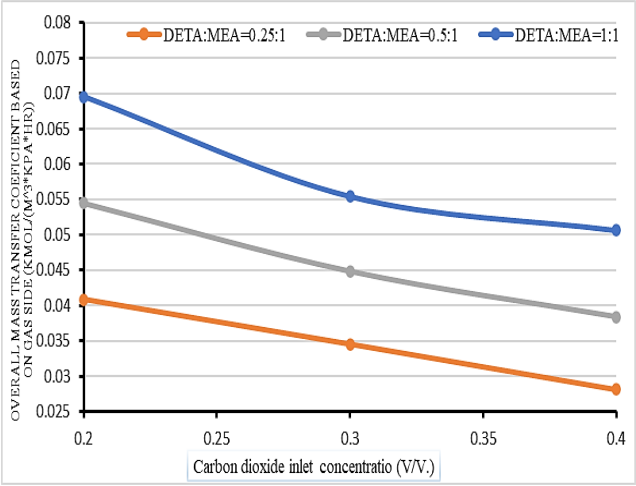

Fig. 14. Effect of Feed Carbon Dioxide Concentration on K_Ga_v at T= 298.15 K, Unloaded Feed Amine, wt. =20 %, G= 11.5225(Kmol/m^2.hr), L= 1.4324(m^3/m^2.hr)

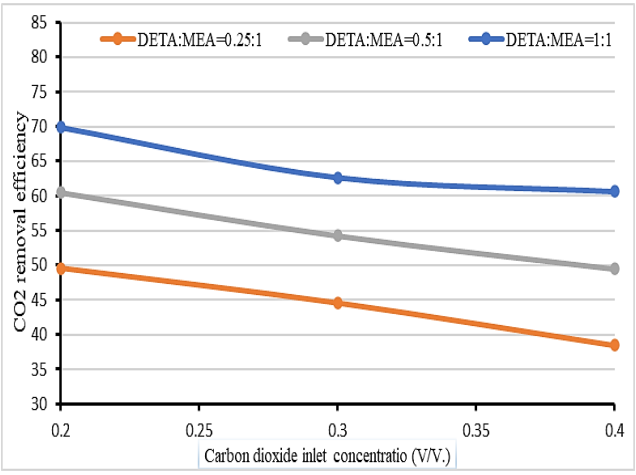

Fig. 15. Effect of Feed Carbon Dioxide Concentration on Carbon Dioxide Capture Efficiency at T= 298.15 K, Unloaded Feed Amine, wt. =20 %, G= 11.5225(Kmol/m^2.hr), L= 1.4324(m^3/m^2.hr)

4.7. Effect of Amine Blending Ratio

Based on data from experiments of carbon dioxide content in the sweet gas stream conducted with the packed-bed absorption column, carbon dioxide was absorbed with five different blending ratios of MEA with DETA to examine the effect of the absorbent blending ratio on the overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η). It can be shown from Fig. 16 and Fig. 17 that the better order ranked of the K_Ga_v and η is DETA: MEA (1:1) > DETA: MEA (0.5:1) > DETA: MEA (0.25:1) under similar operating conditions to ensure the objectivity of the comparison. There is an enhancement in K_Ga_v value by 31.2% when blending DETA with MEA in the mass ratio of 1:1 which was 0.1572(kmol/(m^3∗Kpa∗hr)) than using DETA: MEA with the mass ratio of 1:0.25 which was 0.1198(kmol/(m^3∗Kpa∗hr)). Carbon dioxide capture efficiency, there is an enhancement of 2.5% when blending DETA with MEA in the mass ratio of 1:1, which was 98.79%, then using DETA: MEA with the mass ratio of 1:0.25 which was 96.36%. These results would suggest that the overall mass transfer coefficient and carbon dioxide capture efficiency both increased as increasing of mass blending ratio of DETA to MEA. These consistent outcomes would be attributable to the variation in the capacity for absorption, which is limiting the carbon dioxide absorption rate. A comparison between DETA and MEA in terms of absorption capacity confirmed that the absorption capacity was in the following order: DETA (156 g CO_2 Kg^{-1} solution) > MEA (125 g CO_2 Kg^{-1} solution) [28-30]. Consequently, a higher capacity for absorption led to an improvement in the overall mass transfer coefficient (K_Ga_v) and carbon dioxide capture efficiency (η).

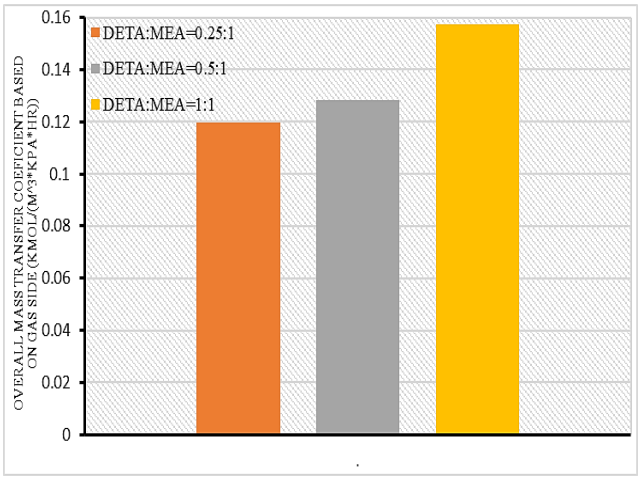

Fig. 16. Effect of Amine Blending Ratio on K_Ga_v at T= 298.15 K, Unloaded Feed Amine, CO_2 Feed =20 v/v%, wt. =30 %, G=7.6817(Kmol/m^2.hr), L=1.9099 (m^3/m^2.hr)

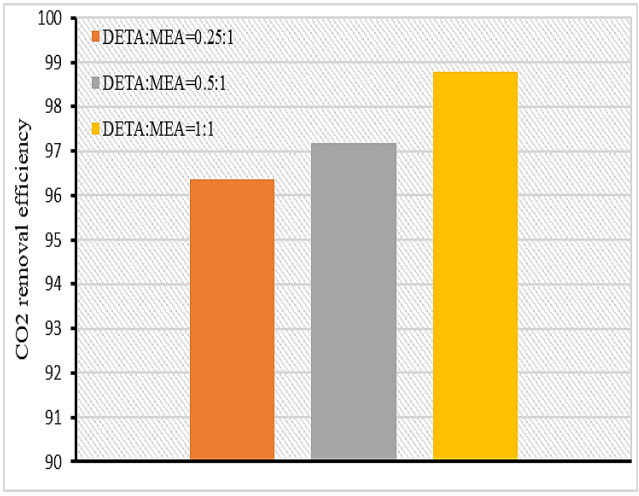

Fig. 17. Effect of Amine Blending Ratio on Carbon Dioxide Capture Efficiency at T= 298.15 K, Unloaded Feed Amine, CO_2 Feed =20 v/v%, wt. =30 %, G=7.6817(Kmol/m^2.hr), L= 1.909 (m^3/m^2.hr)

5- Conclusion

The experimental results show that (I) All alkanol amine blended solutions exhibited that K_Ga_v and η improved with higher liquid flow rates, amine concentrations, and mass ratio of DETA: MEA (II) Alkanol amine blended solutions exhibited a reduction in the K_Ga_v and η value with increasing inlet carbon dioxide concentration, lean amine loading, inlet absorbent temperature, and gas flow rate (III) All of the experimental outcomes revealed that blending the DETA into the MEA solution exhibited the best possible performance in terms of K_Ga_v and η (IV) DETA as the blender with higher mass ratio can significantly reduce the equipment cost of the carbon dioxide absorption process compared to lower mass ratio blending of DETA used in this study.

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Nomenclature

Nomenclature	Meaning
α	Amine carbon dioxide loading
CO_2	Carbon dioxide
η	Carbon dioxide capture efficiency
α_{CO2}	Carbon dioxide loading
$\alpha_{CO2.eq}$	Carbon dioxide loading at equilibrium condition
C_{amine}	Concentration of amine
y_{CO2}	Concentration of carbon dioxide in the bulk gas side
C_{HCl}	Concentration of hydrochloric acid
$C_{\text{active amine}}$	Concentration of the active amine
DETA	Diethylenetriamine
dZ	Differential height section of the packing
E	Enhancement factor
y^*_{CO2}	Equilibrium concentration of carbon dioxide
$y_{CO2,in,}$	Feed gas stream molar concentration of carbon dioxide
HCl	Hydrochloric acid
$a_{v,}$	Interfacial area
Y_{CO2}	Molar ratio of carbon dioxide in the bulk gas side
MEA	Monoethanolamine
N_2	Nitrogen
AOAC	Official Analytical Chemists Association
p	Operating pressure (kpa)
T	Operating temperature
N_{CO2}	Overall carbon dioxide molar flux
K_Ga_v	Overall coefficient of mass transfer
Z	Packed bed height
k_L^O	Physical liquid phase mass transfer coefficient
G	Total inert gas molar flow rate
C_{total}	Total concentration of the aqueous solution
$y_{CO2,out}$	Treated gas stream molar concentration of carbon dioxide
V_{amine}	Volume of amine sample titratant
V_{gas}	Volume of gas released
V_{HCl}	Volume of hydrochloric acid titrated

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التخلص من ثاني أكسيد الكربون باستخدام مخاليط المحاليل الامينية في برج محشو بصورة عشوائية

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الخلاصة

العديد من الباحثين يقومون حالياً بالبحث في التقاط وتخزين ثنائي أكسيد الكربون نظراً إلى أن هناك توجهات لوضع حد لظاهرة الاحتباس الحراري العالمية. تعد عملية الامتصاص الكيميائي لثاني أكسيد الكربون هي أكثر الطرق فعالية. تتضمن هذه الدراسة إمكانية تطبيق واختبار أداء خليط من المحاليل الأمينية لاحادي ايثانول امين(MEA) مع ثنائي اثيلين ثلاثي امين (DETA) كخليط كيميائي ممتص. تم التحقق من الخليط في برج امتصاص محشو عشوائياً بحشوات حلقية. تقدم نتائج اداء عملية الامتصاص من حيث الثابت العام الانتقال الكتلة (K_Ga_v) وكذلك كفاءة التقاط ثاني أكسيد الكربون (η). DETA: MEA مع نسبة خلط وزنية ١:١ وتركيز وزني كلي ٣٠٪ يمكن أن تعطي أعلى K_Ga_v بقيمة ٠,١٥٧٢(kmol/(m^3*Kpa*hr)) و كفاءة التقاط ثاني أكسيد الكربون بنسبة ٩٨,٧٩ في المائة. بينما في نفس الظروف من حيث معدل تدفق السائل والغاز، لكن بخلط DETA: MEA بنسبة خلط وزنية ٠,٢٥:١ حيث ان قيمتا K_Ga_v وη تساويان: ٠,١١٩٨ (kmol/(m^3*Kpa*hr)) و٩٦,٣٧ في المائة على التوالي. استناداً إلى هذه النتائج فمن المنطقي افتراض أن المحلول الاميني لثنائي اثيلين ثلاثي امين (DETA) سيكون بمثابة خليط واعد وفعال لازالة ثاني أكسيد الكربون.

الكلمات الدالة: الامتصاص الكيميائي، ازالة ثاني اكسيد الكربون، البرج المحشو، خليط الكانول أمين، احادي ايثانول امين، ثنائي اثيلين ثلاثي امين.