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ABSORPTION OF CARBON DIOXIDE VIA SINGLE AND BLENDS OF AQUEOUS AMINE SOLUTIONS AND NANOFLUIDS IN GAS-LIQUID HOLLOW FIBER MEMBRANE CONTACTOR

Zia Ur Rehman Said Rehman

This thesis is submitted in partial fulfilment of the requirements for the degree of
Master of Science in Chemical Engineering

Under the Supervision of Professor Nayef Mohamed Ghasem

April 2018

Declaration of Original Work

I, Zia Ur Rehman Said Rehman, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Absorption of Carbon Dioxide via Single and Blends of Aqueous Amine Solutions and Nanofluids in Gas-Liquid Hollow Fiber Membrane Contactor*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Professor Nayef Mohamed Ghasem, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

In this work, CO_2 gas was absorbed from a gas mixture (20 vol.% CO_2 + 80 vol.% N_2) in a custom made Polyvinylidene fluoride (PVDF) hollow fiber membrane contactors by using a variety of single and blends of aqueous amine solutions and nanofluids. An ultrasonic dispersion method was used to prepare nanofluids where SiO_2 nanoparticles and carbon nanotubes (CNTs) were dispersed in deionized (DI) water without adding any surfactant. The prepared solvents were fed into the tube side of the membrane module, whereas the gas mixture was passed through the shell side. CO_2 absorption experiments were carried out using four different liquid flow rates: 10, 20, 30 & 40 ml/min. All experiments were conducted at ambient temperature and atmospheric pressure. CO_2 absorption process carried out by using pure deionized water in the same module was used as a reference. The effects of different parameters on the removal efficiency of CO_2 were investigated and analyzed with a focus on concentrations and types of amines and nanoparticles and liquid flow rates.

Keywords: Carbon dioxide, absorption, hollow fiber membrane contactors, amines, nanofluids.

Title and Abstract (in Arabic)

امتصاص ثاني أكسيد الكربون عن طريق استخدام محاليل أمينية مائية و موائع نانوية و مخاليطهم في قواطع من الألياف الغشائية الجوفاء المختصة في السماح بالاحتكاك الغير المباشر بين الغاز و السائل

الملخص

في هذا العمل، تم امتصاص و استخلاص ثاني أكسيد الكربون من النيتروجين في قواطع من الألياف الغشائية الجوفاء المصنوعة من مادة بولي فينيلدين فلورايد (PVDF) عن طريق استخدام تشكيلة متنوعة من محاليل أمينية مائية و موائع نانوية و مخاليطهم. لقد تمت استخدام طريقة التشتيت بالموجات فوق الصوتية لاستحضار موائع نانوية من الجسيمات النانوية لثاني أكسيد السيليكا و الأنابيب النانوية الكربونية حيث أنه تم تشتيت و تعليق هذه الجسيمات في ماء منزوع الأيونات بدون إضافة أية مادة خافضة للتوتر السطحي. المذيبات المستحضرة تم تمريرها في الإطار الداخلي للألياف الغشائية بينما سمح لخليط الغاز من النيتروجين و ثاني أكسيد الكربون بالتدفق عبر الأسطح الخارجية لتلك الأغشية. أجريت تجارب امتصاص ثاني أكسيد الكربون في هذا البحث على أربعة قيم مختلفة لمعدل تدفق السائل و هي: ١٠ و ٢٠ و ٣٠ و ٤٠ مليلتر/دقيقة. تم تثبيت تركيز ثاني أكسيد الكربون في خليطه مع النيتروجين على مستوى عشرون في المئة من الحجم الكلي لخليط الغاز. لقد تم إجراء كل التجارب تحت الضغط الجوي و كذلك عند درجة حرارة المحيط و تم اختيار عملية الامتصاص بماء نقي منزوع الأيونات في نفس الوحدة ليتم استعمال نتائجها كمرجع. شمل هذا البحث دراسة و تحليل تأثير مختلف العوامل على كفاءة إزالة ثاني أكسيد الكربون مع التركيز على أنواع و تراكيز الأمينات و الجسيمات النانوية و معدلات تدفق السائل.

مفاهيم البحث الرئيسية: ثاني أكسيد الكربون، امتصاص، قواطع من الألياف الغشائية الجوفاء، أمينات، موائع نانوية.

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I would like also to use this opportunity to extend my special thanks to my siblings, especially my brother Abdulrahman Said Rehman, and my lovely parents for being very supportive and making me such productive along the way. I am pretty sure they suspected it was endless. I believe my thank and gratitude words cannot meet their favor.

Dedication

To my beloved parents and family

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List of Abbreviations

AMP	2-Amino-2-Methyl-1-Propanol
CCP	Carbon Capture Project
CLC	Chemical Looping Combustion
CNT	Carbon Nanotube
CO_2	Carbon Dioxide
DEA	Diethanolamine
DETA	Diethylenetriamine
DI	Deionized
EDA	Ethylenediamine
GLMC	Gas Liquid Membrane Contactor
H_2S	Hydrogen Sulfide
HFMC	Hollow Fiber Membrane Contactor
HIULP	High Intensity Ultrasonic Liquid Processor
LPM	Liter Per Minute
MDEA	N-methyldiethanolamine
MEA	Monoethanolamine
N_2	Nitrogen
PE	Polyethylene
PFA	Perfluoroalkoxy Alkane
PIP	Piperidine
PP	Polypropylene
PTFE	polytetrafluoroethylene

PVDF	Polyvinylidenefluoride
PZ	Piperazine
PZEA	Piperazinyl-1,2-ethylamine
SiO_2	Silicon Dioxide
TIPS	Thermal Induced Phase Separation

Chapter 1: Introduction

1.1 Overview

Carbon dioxide (Greenhouse gas) has been well-known to contribute considerably to global warming. It has thusly brought serious global environmental issues [1]. Eighty percent of greenhouse gases are represented by CO_2 and it is the major gaseous contaminant in the atmosphere [2]. Undoubtedly human activities speed up this process despite a part of this increase in CO_2 concentration is because of some natural factors. Therefore, significant attention has been given to CO_2 capture and separation and achieving efficient technologies for CO_2 removal from gas mixtures should be taken in consideration.

1.2 Statement of the Problem

Absorption, adsorption, cryogenic process and membrane technology are the basic physical and chemical processes for CO_2 separation. There are several drawbacks regarding the conventional processes like flooding, foaming, entraining, channeling, high capital and operating costs. As a result, many researchers attempt to enhance the efficiency of these processes or figure out alternative technologies [3]. Over the past few decades, the usage of hollow fibers membrane contactor for CO_2 separation has been studied extensively [4]. A combination between hallow fiber membrane (HFM) contactor and nanofluids as new gas separation processes has attracted the attention of many researchers in recent years. The characteristics of nanoparticles make the nanofluids with special interest. Carbon nanotubes, as an example, can be considered as one of the most interesting materials for gas separation processes under extreme condition due to its unique structures and transport, chemical and mechanical properties. Silica nanoparticles, as another example, could improve the behavior of the fluid used for gas separation processes because of its stability and high mechanical resistance and surface area [5]–[12]. This research focuses on investigating CO_2 absorption in gas-liquid membrane contactor by using single and blends of amine solutions and nanofluids.

1.3 Relevant Literature

1.3.1 Carbon Dioxide Capture Modes

Carbon dioxide capture process can be broadly classified as pre-combustion, oxy-fuel combustion and post combustion types where this process of removal of CO_2 depends on the type of combustion process employed. Additional infrastructure requirement and energy penalty [13] is involved as well. As a consequence, it is a choice only when it comes in large scale plants where the process could be economically applicable. The fuel in pre-combustion method goes through a process which makes carbon dioxide separation much easier later. Gasification process, as an example, is applied to fuels like natural gas in order to directly convert it to syn-gas using reforming [14]. In the oxy-fuel combustion method, pure oxygen is used instead of air in order to minimize NO_x concentration that is formed. For this reason, and in this case, water vapor, CO_2, SO_2 and particulate matter are the major components of the flue gases [15]. However, the necessity of extraction of oxygen from atmosphere to generate pure O_2 is a main drawback of this method [16]. In contrast, carbon dioxide is separated from the flue gases, in post combustion method, after the fuel combustion. Very slight modifications are required since it is compatible with the existing power plants. The energy penalty, however, included in this type of CO_2 capture is high, as CO_2 concentration in the flue gases is excessively low [17]–[19]. Moreover, the gas approximately always exists with a considerable amount of SO_2, NO_2 and some other constituents, although carbon dioxide concentration varies in these flue gases owing to factors like fuel and process employed. The energy penalty, consequently, is always present with the process [20].

1.3.2 Techniques for CO_2 Capture

Absorption, adsorption, chemical looping combustion (CLC), cryogenic distillation and membrane technology are the most prominent techniques available for the carbon dioxide separation from flue gases [20].

1.3.2.1 Absorption

Absorption process (which could be both physical and chemical) is the most common process used for CO_2 capture and separation and it has been commercialized. It is a technically proper option which could be utilized in pre- or post-combustion modes. Carbon dioxide solubility in the solvent is the main factor which physical absorption depends on; hence, it is preferred at high pressure [21]. Rectisol, selexol and purisol are some of the most popular physical absorbents that have been reported [22]. Chemical absorption usually offers higher capacity at low pressure [23], thus, it is preferable in coal fired power plants where it has been reported that CO_2 concentration in flue gases from such plants could reach up to 15 % at low pressure conditions [24], [25]. Any chemical absorption system typically comprises three fundamental components: solvent, absorber and stripper. In the absorber, a direct contact between the lean solution and flue gases from power plants which contain carbon dioxide ordinarily takes place in a counter-current manner. The used solvents then absorb CO_2 from the flue gases to reduce its concentration to a desired level. The task of the stripper after this is to regenerate the solvent rich carbon dioxide. CO_2 in the next step is collected at the top of the stripper and compressed in order to be prepared for storage and transportation, while the regenerated lean solution is returned back to the absorber. Figure 1 [26] shows a typical solvent-based absorption process for CO_2 separation from flue gas streams. So far, chemical absorption has been considered as the most beneficial technology for CO_2 capture where it could be fitted easily within power plants. However, there are several drawbacks related to this type of absorption processes such as less loading capacity regarding CO_2, high corrosion rate, energies penalties during solvents regeneration, requirement of elevated equipment size and the degradation of the solvents, specifically when amines are used where degraded volatile compounds could be produced. Improving the employed solvents properties and procedures included in the process itself could resolve such issues [3], [27], [28].

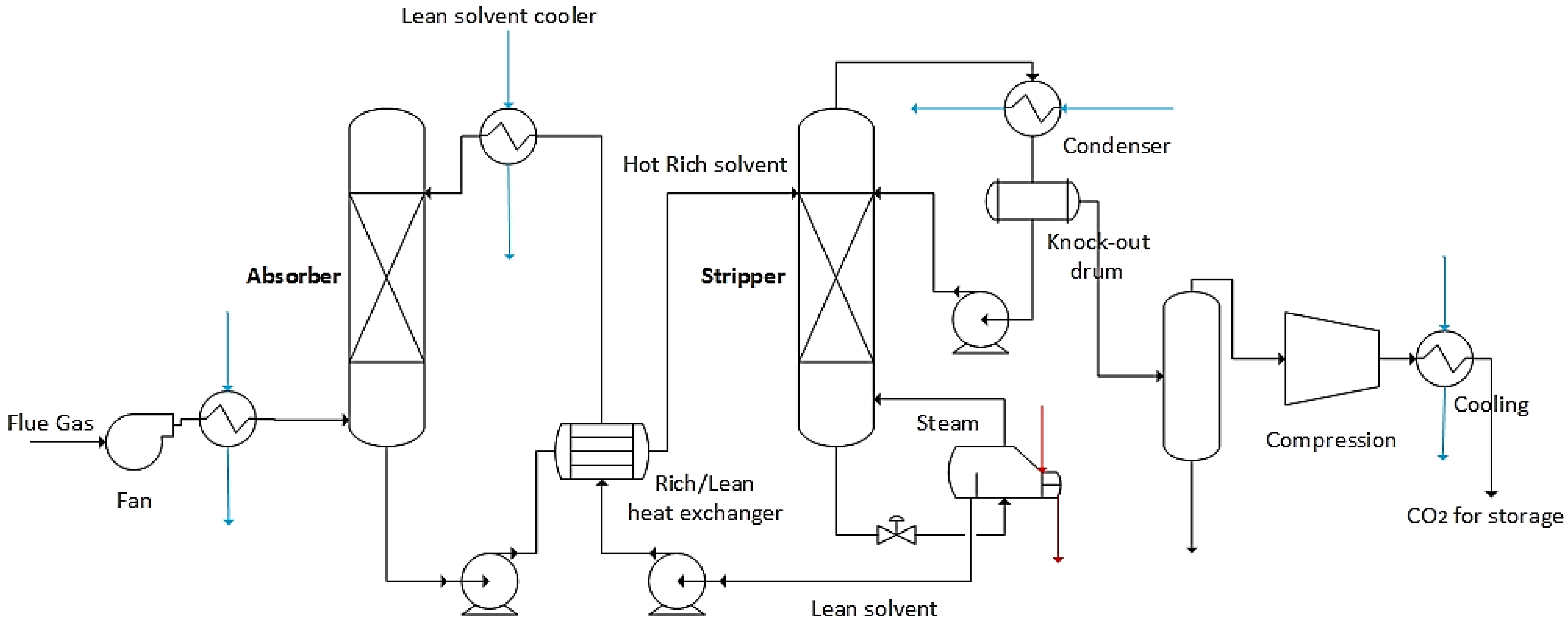

Figure 1: Solvent-based absorption process for CO_2 separation from flue gas streams

1.3.2.2 Adsorption

Adsorption process depends on using solid sorbent for the separation of CO_2 which makes it a viable alternative method. Selectivity, surface area and regeneration ability are the major parameters which the sorbent selection is based on. The recovery of carbon dioxide from the sorbent can be achieved by changing the pressure (PSA) [29]–[31] or temperature [32], [33]. An efficiency of around 85 % at commercial scale recovery has been shown by PSA [34]. Researchers worldwide have recently shown interests in this area in general and particularly searching for appropriate sorbents for certain applications [35]–[38].

1.3.2.3 Chemical Looping Combustion (CLC)

CLC method, regarding cost reduction, was reported to be one of the best alternatives in the phase I of the Carbon Capture Project (CCP). CCP is a group of main energy companies work together to develop techniques for CO_2 capture and storage over several phases (periods). In CLC process, O_2 is transferred from air to fuel by carrier like metals oxides which makes it similar to oxy-fuel combustion [39]. Oxidation and reduction are the main two stages that CLC process involves. During the fuel combustion, metal oxide gets reduced and then by oxidation in the presence of air it is regenerated again. There are various metal oxides containing Mg, Fe, Cu & Ni are being examined because of their effectiveness in transferring O_2 in addition to other parameters related to the process. A blend of CO_2 and H_2O is produced in CLC where by using condensing water after that, CO_2 can easily be separated. This is considered as one of the most important advantages of CLC method [40]–[44].

1.3.2.4 Cryogenic Distillation

Cryogenic distillation is a relevant choice in the case for which the energy input is a significant parameter and high efficiency is needed. This process is carried out at very high pressure and low temperature which allows a mixture of gases to be separated. By applying a pressure of almost 200 atm, carbon dioxide could be separated by de-sublimating it from a blend of gases. The efficiency of this process could reach up to 95%, however, due to the required high pressure and low temperature, it is highly energy intensive [20], [45].

1.3.2.5 Conventional Methods Disadvantages

Flooding, foaming, entraining, channeling, and high capital and operating costs are the main drawbacks related to the conventional processes. Furthermore, in the post combustion mode, large re-engineering and scale-up is required since amine processes are commercially available at relatively small scale. Moreover, in order to reduce the use of sorbent and cost, very pure flue gas is needed. Researchers, consequently, try to enhance the efficiency of these conventional techniques in addition to search for alternatives [3]. Many researchers has found the usage of membrane contactor for CO_2 separation as a promising technology which could overcome a lot of the drawbacks related to the conventional methods [5]–[10].

1.3.2.6 Membrane Technology

Membrane contactor is a device which allows direct contact between two different fluids without dispersion of one phase into the other in order for a mass transfer of specific species to take place. The gas mixture flows on one side of a hydrophobic microporous membrane (usually shell side) whereas the liquid absorbent flows on the other side [46]. Acidic gases like CO_2 and H_2S diffuse from the gas phase to the gas-liquid interface and then will be absorbed by the liquid phase [47], [48]. Figure 2 below shows the cross section of hollow fiber membrane and how it works as Gas-Liquid Membrane Contactor.

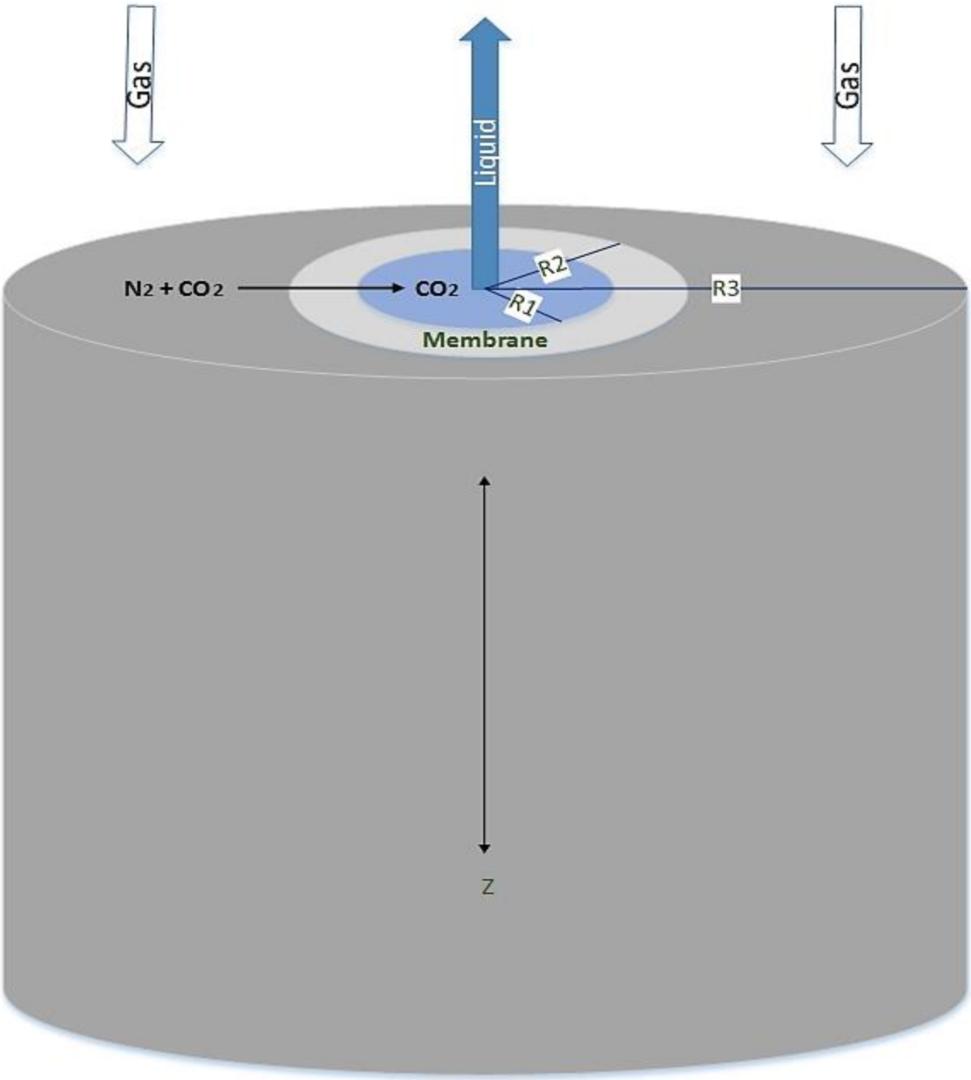

Figure 2: Schematic of cross section and CO_2 transfer in GLMC

This technology has several advantages over columns and other conventional mass transfer equipment. That includes the independency of the two fluids, emulsion formation will not occur, straightforwardness of the scale-up with membrane contactor, constant and known interfacial area (makes performance prediction easy), virtually higher efficiency (as measured by HTU) will be achieved compared to dispersive contactors, existence of low solvent holdup and no moving parts [49]. In addition, in the industrial applications, it is flexible in the extreme, where it could be employed both in pre-combustion & post-combustion modes. However, to absorb comparatively low concentration of CO_2 from flue gases, high selectivity is required [20]. This is considered one of the main limitations of membrane contactor technology and thus, an appropriate membrane separation design is quite critical.

1.3.2.6.1 Solvents used in Gas-Liquid Membrane System

Solvents used in gas-liquid membrane system mostly provide selectivity. The most widely used absorbent for CO_2 capture are alkanolmines because of their high CO_2 loading capacity and absorption and regeneration rates [26]. Their various structures comprise primary, secondary and ternary amines which contains at least one OH and amine group such as monoethanolamine (MEA), diethanolamine (DEA) and N-Methyldiethnolamine (MDEA). Beside these amines, there are others which could be convenient to be used in gas liquid membranes and show better performance such as sterically hindered amine (2-amino-2-methyl-1-propanol (AMP)) and cyclical amines which are usually employed as activators, namely (piperidine (PIP)), a cyclical monoamine, (piperazine (PZ)), a cyclical diamine, and (piperazinyl-1,2-ethylamine (PZEA)), a cyclical triamine where these types of amines contain three amine functions (primary, secondary, and tertiary) [3], [50]. Figure 3 illustrates the chemical structures of some of the amines that have been mentioned so far.

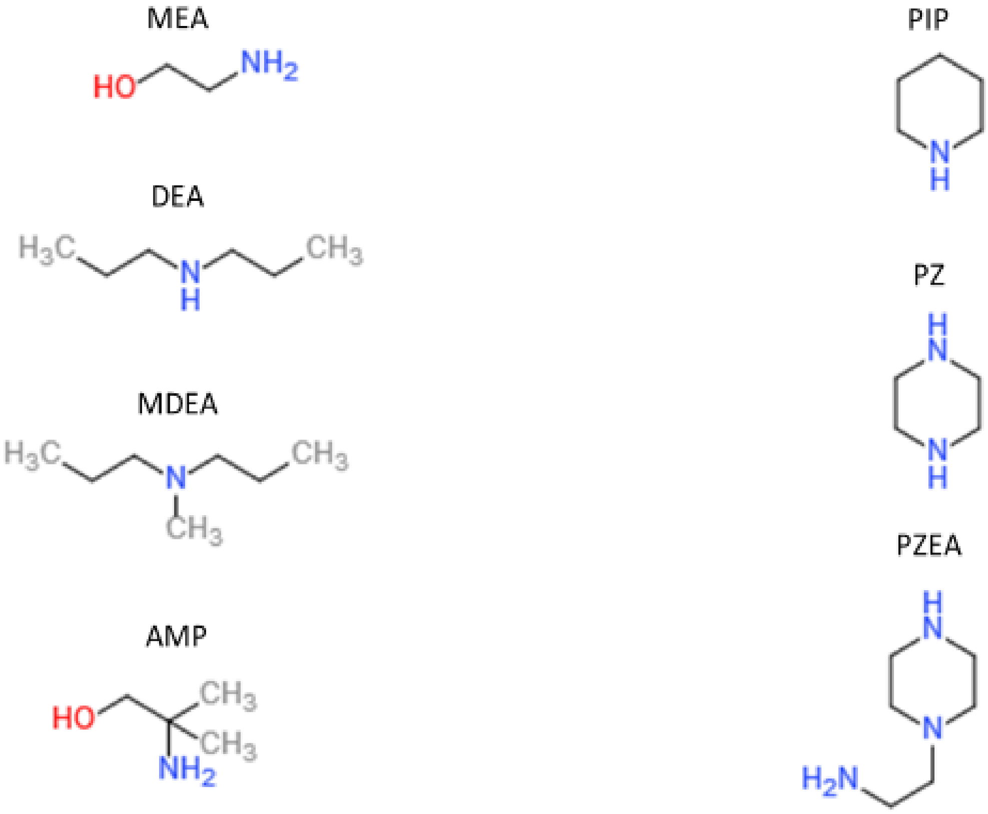

Figure 3: Chemical structures of some studied amines

1.3.2.6.2 CO_2 Absorption-Reaction Mechanisms

The knowledge of carbon dioxide absorption-reaction mechanisms occurring for the various types of amines are extremely important for modeling of the absorption process using aqueous amine solutions and deduction of characteristic solvent parameters. Data on reaction kinetics of individual amine systems and their mixtures or innovative amine-based solvents beside the different reaction mechanisms such as zwitterion, termolecular, and base-catalyzed hydration have been studied extensively [51], [52]. It has been overall considered the formation of a zwitterion intermediate leading to carbamate formation for reaction mechanisms of the absorption of CO_2 with primary amines (R_1–NH_2 with R_1 = $(CH_2)_2$–OH for MEA) or secondary amines (R_1R_2–NH) [53], [54].

$$CO_2 + R_1R_2{-}NH \leftrightarrow R_1R_2{-}NH^{+}COO^{-} \quad (1)$$

$$R_1R_2{-}NH^{+}COO^{-} + B \leftrightarrow R_1R_2{-}NCOO^{-} + BH^{+} \quad (2)$$

B here is a basic compound (OH-, H_2O or amine).

The regeneration costs are considerable of such amines because of the strong heat of absorption produced with carbamate formation [55], [56].

The hydrogen atom which is attached to the nitrogen atom is absent in tertiary alkanolamines ($R_1R_2R_3$–N with R_1 = CH_3 and R_2, R_3 = $(CH_2)_2$–OH for MDEA), thence, it drives to the production of bicarbonate [52]. The reactions equations are as shown below:

$$CO_2 + H_2O \leftrightarrow H^{+} + HCO_3^{-} \quad (3)$$

$$R_1R_2R_3{-}N + H^{+} \leftrightarrow R_1R_2R_3{-}NH^{+} \quad (4)$$

$$CO_2 + R_1R_2R_3{-}N + H_2O \leftrightarrow R_1R_2R_3{-}NH^{+} + HCO_3^{-} \quad (5)$$

Tertiary amines ordinarily release low reaction heat when bicarbonate is formed and accordingly it reduces the solvent regeneration costs. However, since the reaction which leads to the formation of carbamate is not taking place, the reactivity of carbon dioxide with such amine is indeed weak [55].

In the case of AMP as sterically hindered amine, hydrolytic reaction happens where the formed carbamate is not stable since the hindrance of the bulky group adjacent to the amino group. This leads to bicarbonate formation as a final product of the reaction. As a result, lower regeneration costs are associated with this class of amines compared to the costs associated with the regeneration of classical primary and secondary amines. Sterically hindered amine provides advantages such as high selectivity, absorption capacity and degradation resistance. It is thus preferable over conventional amine for separation of carbon dioxide from flue gases [57], [58].

1.3.2.6.3 Materials for Synthesizing Gas-Liquid Membrane

High contact angles between solvent and membrane are usually preferred and therefore, hydrophobic materials such as polypropylene (PP), polyethylene (PE), polytetrafluoroethylene (PTFE), poly(tetrafluoroethylene-co-perfluorovinylether) (PFA), and polyvinylidene fluoride (PVDF) are usually used for synthesizing gas-liquid membrane contactors. Membranes made out of polypropylene (PP) are inexpensive and commercially available but are not as hydrophobic as the fluorine containing polymeric membranes (PTFE and PVDF). Low hydrophobicity of a membrane leads to pore wetting and so the membrane will exhibit poorer performance. Table 1 [26] presents a variety of investigations including the utilization of these membranes in association with alternate solvents.

Table 1: Performance of different membranes and solvents for CO_2 absorption

Membrane material (abbreviation)	Reference	Gases separated	Solvent(s) trialed	Comments
Polypropylene (PP)	[59]	N_2/CO_2	MEA, DEA, MDEA, MEA/MDEA, DEA/2-amino-2-methyl-1-propanol (AMP), and MDEA/PZ	
	[60]	CO_2, CO, H_2, N_2, CH_4	Monoethanolamine, potassium carbonate	Pore wetting observed with MEA, but not potassium carbonate

Table1: Performance of different membranes and solvents for CO_2 absorption (continued)

Membrane material (abbreviation)	Reference	Gases separated	Solvent(s) trialed	Comments
Polypropylene (PP)	[61]	N_2/CO_2	Water, 10 wt% MEA, 10 wt% DEA	
	[62]	CO_2	MEA	
	[63]	N_2/CO_2	Water	Rate controlled by absorbent flow rate
	[64]	N_2/CO_2	Monoethanolamine (MEA), [3 M]	
	[63]	N_2/CO_2	Diethanolamine (DEA) [2 M]	
	[46]	$N_2/CO_2/O_2$	Potassium Glycinate (PG)	Limited wetting observed
	[46]	$N_2/CO_2/O_2$	Monoethanolamine (MEA) [0.5–3 M]	
	[46]	$N_2/CO_2/O_2$	Methyldiethanolamine (MDEA) [0.5–3 M]	
Polyvinylidene fluoride (PVDF)	[63]	N_2/CO_2	Water	Rate controlled by absorbent flow rate
	[63]	N_2/CO_2	Diethanolamine (DEA) [2 M]	Membrane wetting
	[65]	N_2/CO_2	Diethanolamine (DEA)	
Polytetrafuloroethylene (PTFE)	[60]	CO_2, CO, H_2, N_2, CH_4	Monoethanolamine [30 wt%], potassium carbonate [30 wt%]	Pore wetting observed with MEA, but not potassium carbonate

Table1: Performance of different membranes and solvents for CO_2 absorption (continued)

Membrane material (abbreviation)	Reference	Gases separated	Solvent(s) trialed	Comments
Polytetrafuloroethylene (PTFE)	[66]	CO_2, N_2	2-Amino-2-methyl-1-propanol (AMP)	

1.3.2.6.4 Researches on Single and Blended Amines Solutions

Researchers started with using single amines as solvents in HFMC. For example, Yeon et al. [9] studied the behavior of mass transfer of carbon dioxide through a membrane contactor system containing PTFE and PVDF hollow fiber membrane with monoethanolamine (MEA). PVDF was found in their investigation to be more resistance to pore wetting phenomena and so it displayed superior CO_2 mass transfer performance. Wang et al. [67] used three different types of absorbent (2-amino-2-methyl-1-propanol (AMP), DEA and MDEA) to investigate CO_2 absorption in HFMC. They figured out that MDEA is less efficient than AMP and DEA.

Moreover, blended amine solutions can be considered as good alternatives to the traditional single one to be employed in gas-liquid membrane contactors [68]–[70]. Blended amines like primary-tertiary amines (MEA-MDEA) and secondary-tertiary amines (DEA-MDEA) gain the properties of both amines such as high reaction rate of primary or secondary amines with the high equilibrium capacity and lower enthalpy of tertiary amines [22]. The absorption and regeneration efficiency of MEA and AMP in packed bed columns was explored experimentally by Khan et al. [71]. Borhani et al. [72] examined in industrial DEA promoted potassium carbonate absorption unit the behavior of different promoters (MEA, MDEA, diglycolamine (DGA) and diisopropanolamine (DIPA)) for the capture of CO_2. By using blends of AMP and DEA aqueous solutions, absorption experiments were conducted by Mandal & Bandyopadhyay [73] in a wetted wall column to check the effect of contact time, temperature and concentration on the rate of absorption and the selectivity.

Furthermore, researchers employed activator amines like piperazine (PZ) or (piperazinyl-1)-2-ethylamine (PZEA) mixed with primary, secondary, tertiary and sterically hindered amines such as MEA, DEA, MDEA and AMP to promote the absorption of carbon dioxide process [22], [74]–[76]. For different mixtures of AMP and PZ, the specific rate of absorption, CO_2 loading capacity after absorption performance and percentage of CO_2 absorbed have been examined by Khan et al. [77]. Yan et al. [70] investigated the carbon dioxide absorption performance of blended solutions of MDEA/PZEA in HFMC. A comparison of absorbents performance of MEA, PZ and their mixture for CO_2 capture was made by Dugas and Rochelle [78]. Bishnoi and Rochelle [79] used blends of MDEA and PZ to carry out CO_2 absorption experiments where their performance was compared with other promoted MDEA systems. An outstanding performance has been exhibited by the blended amine solutions in those researches mentioned above.

1.3.2.6.5 Nanofluids as Absorbents

All those solvents mentioned above are acting as appropriate chemical absorbents in CO_2 capture system. However, nanoparticles dispersed in carried fluid (becomes nanofluid) could work as proper absorbents as well and improve carbon dioxide absorption performance [80].

1.2.3.6.5.1 Mechanism of Mass Transfer

Based on some theories, three mechanisms have been proposed so far where the exact one which could interpret such mass transfer enhancement is still not well-known or assured. Alper et al. [81], for instance, presented grazing effect of nanoparticles as a base for mass transfer enhancement by nanofluids. The grazing effect is related to the adsorption performance of nanoparticles. Gas molecules interact with the gas-liquid interface and get adsorbed, where a small diffusion layer and high concentration of gas molecules exists [11], [82].

The second suggested theory relates the impacts of nanoparticles to the liquid velocity distribution in the fibers. The liquid flow rate is usually laminar inside the fibers where it delays the mass transfer. Due to the Brownian motion of nanoparticles, micro-conventions can take place when nanoparticles are added to the liquid phase. This can enhance carbon dioxide mass diffusion avoiding its accumulation close to the fibers [83]–[85].

The third theory discusses formed bubbles as in tray towers and bubble columns where they have significant influence on the mass transfer. The diffusion area increases as the motion of nanoparticles breaks the bubbles into smaller [82], [86], [87]. In spite of that, in gas-liquid membrane contactors, such theory cannot be adequate since there are no bubbles formation in the liquid phase.

1.2.3.6.5.2 Researches on Nanofluids

By dispersing nanoparticles of SiO_2 and Al_2O_3 in methanol, Lee et al. [88] studied CO_2 capture process in a bubble type absorber. They figured out from their study that the carbon dioxide absorption rate increases by 4.5% and 5.6% when using Al_2O_3/methanol and SiO_2/methanol nanofluids at 20°C, respectively. Rahmatmand et al. [89] investigated CO_2 absorption improvement when SiO_2, Al_2O_3, carbon nanotubes (CNTs), and Fe_3O_4 nanoparticles were dispersed in amine aqueous solutions. The outcomes of their investigation showed that Fe_3O_4 and CNT are more efficient at low nanoparticles concentrations, while Al_2O_3 and SiO_2 could be more effective at larger ones. In addition to all that has been introduced so far, proposing a combination between membrane contactors and nanofluids and employing them in CO_2 capture system was reported in some recent works. An experimental study has been conducted by Gokhar et al. [11] to test the absorption of carbon dioxide in HFMCs by using SiO_2 and CNT nanofluids. They found that the removal efficiency was enhanced up to 9% for silica nanoparticles and 20% for CNTs at high liquid flow rates, whereas it increased up to 20% for silica nanoparticles and 40% for CNTs at low liquid flow rates. Peyravi et al. [12] examined CO_2 physical absorption in constructed pilot-scaled hollow fiber membrane contactor by using aqueous nanofluids of Al_2O_3, CNT, Fe_3O_4, and SiO_2. The maximum improvement in mass-transfer rate they concluded was 3%, 25%, 38% and 44% for Al_2O_3, SiO_2, CNT and Fe_3O_4, respectively. The results of these previous mentioned works illustrate that adding nanoparticles to a liquid phase decreases the mass transfer resistance of this phase and therefore, enhances CO_2 absorption rate [90]. Beside that, absorbent nanofluids could promote the performance of hollow fiber membrane contactors [91]–[93]. In general, works on the investigation of mass transfer using nanofluids are much less than on the usage of them in the field of heat transfer [90], [94]–[97].

1.4 Purpose of This Work

To the best of our knowledge, no researcher used aqueous amine solutions enhanced by silica nanoparticles or CNTs in HFMC. The major objective of this work was to visualize the CO_2 separation process in PVDF hollow fiber membrane contactors by employing various aqueous amine solutions and nanofluids. Aqueous amine solutions were prepared by magnetic stirrer while SiO_2 and CNTs nanofluids were prepared by ultrasonic dispersion method without adding any surfactant. The prepared amine solutions and nanofluids were used in the tube side of the membrane module, whilst the gas mixture of nitrogen and carbon dioxide (N_2/CO_2) was flown through the shell side. CO_2 absorption process was also conducted for pure deionized water in the same module in order to be used as a reference. The effects of different parameters on the removal efficiency of CO_2 were examined and analyzed with a focus on concentrations and types of amines and nanoparticles and liquid flow rates.

Chapter 2: Experimental Work and Set-up

2.1 Hollow Fiber Membrane Contactors Construction

The only type of fibers utilized in this study were Polyvinylidene difluoride (PVDF) and data from this work were compared with data from literature where polypropylene fibers were used.

2.1.1 Fabrication of PVDF Fibers

The used polymer material (PVDF (solef®6020/1001)) for fibers preparation was purchased from Solvay (France) company. Thermal Induced Phase Separation (TIPS) Method has been employed to fabricate PVDF hollow fiber membrane in the lab. TIPS could be defined as a method of preparing a polymer membrane by mixing the polymer with a substance (solvent) at high temperature and casting the solution into a film. Solidification will occur When the solution is cooled. All the other chemicals used for the fabrication process were purchased from Sigma-Aldrich with purity more than 99%. Figure 4 shows the cross section and surface of a prepared fiber sample where the pictures were taken by SEM.

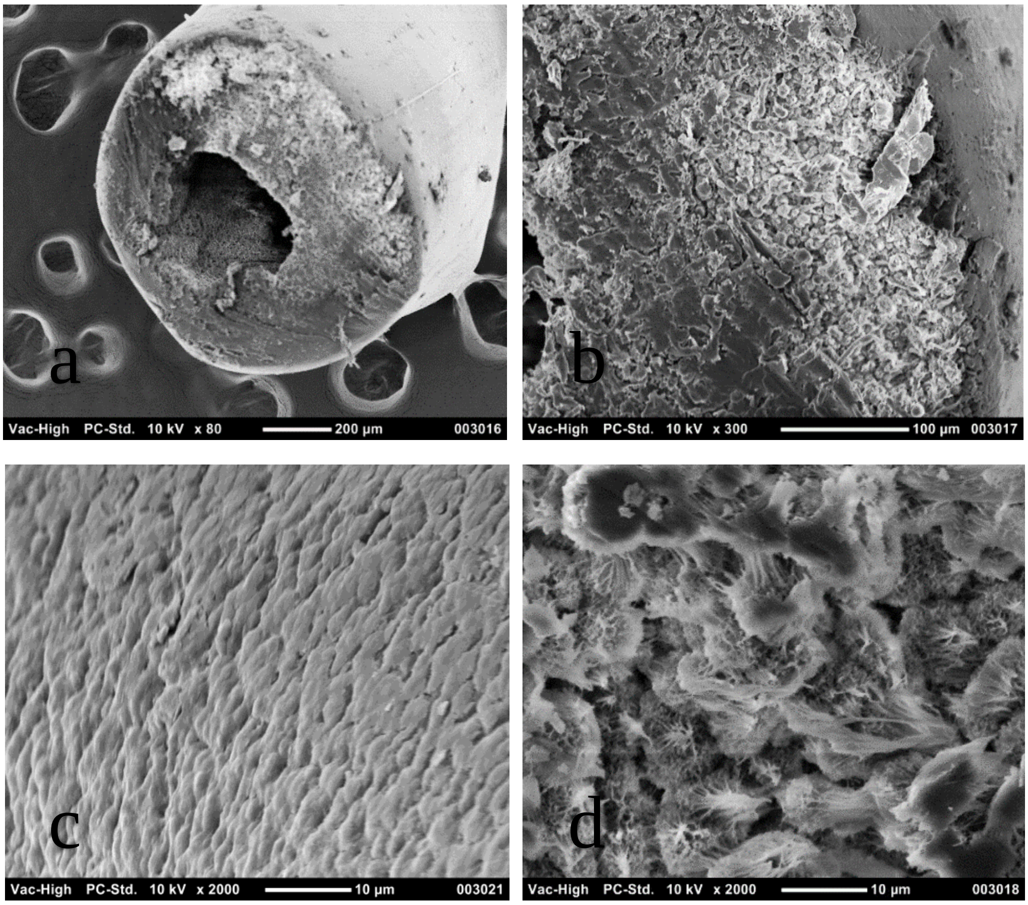

Figure 4: Different parts of a prepared PVDF hollow fiber: a) Cross section b) Between inner and outer surface c) Outer surface d) Inner surface

2.1.2 Module Preparation of Gas-liquid Membrane Contactor (GLMC)

Perspex glass was used as a shell of the module, whilst the prepared PVDF fibers were packed inside the shell to be used as tube side in the same module of GLMC. Perspex glass was purchased from Sign Trade L.L.C (United Arab Emirates). Equal lengths of shells were prepared and two holes were drilled in each shell before the edges by a distance (3 cm) in order to act as inlet and outlet for the gas in the shell side. The prepared PVDF fibers were kept in water and dried whenever there was a demand to be utilized. Before inserting the prepared fibers in the module, they were tested by passing DI water through the lumen side of each fiber to check blockings and leaks. After packing the fibers inside the Perspex glass, each side of the module was filled with 5 minutes epoxy FEVICOl® Brand bought in a local market. For connection purposes, electrode caps were fixed at the entry and exit points of the module. The whole prepared PVDF hollow fibers membrane contactor modules were checked for any gas or liquid leakages before employing them in the experiments. Figure 5 displays a schematic diagram of the shell and tube sides of the GLMC, whereas Figure 6 presents a real PVDF hollow fibers membrane contactor module constructed in the lab. The detailed specifications of the gas liquid membrane contactor module is listed in Table 2.

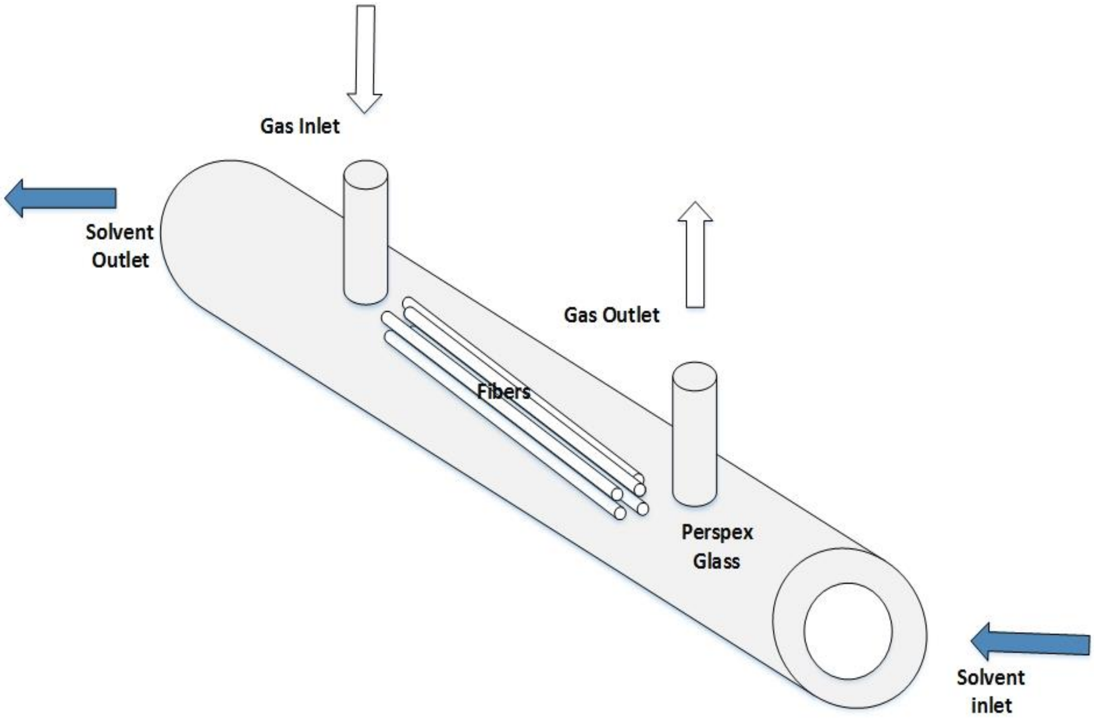

Figure 5: Schematic diagram of the GLMC module

Figure 6: A real PVDF hollow fibers membrane contactor module constructed in the lab

Table 2: PVDF GLMC module characteristics

Length of Active Fiber, cm	21
Number of Fibers	11
Inner Diameter, mm	0.42
Outer Diameter, mm	1.1
Thickness, mm	0.34
Porosity, %	45.85
Contact Area, m^2	0.003046
Module Inner Diameter, cm	0.8
Module Outer Diameter, cm	1.2

The contact area (A) was calculated as following:

$$A = 2\,\pi\, r\, h\, n \tag{6}$$

Here A represents the contact area, r is the inner diameter of the fiber, h is the length of the active fiber or length of active module and n is the number of fibers in the modules.

So, the area = (2 * 3.14 * 0.00042 m * 0.21 m * 11) / 2 = 0.003046 m^2.

2.2 Absorbents and Methods of Preparation

2.2.1 Amine Solutions as Absorbents

The main chemicals used in this work were Monoethanolamine (MEA), Diethanolamine (DEA), N-methyldiethanolamine (MDEA), 2-Amino-2-Methyl-1-Propanol (AMP), Ethylenediamine (EDA) and Diethylenetriamine (DETA), in addition to Piperazine (PZ) and Piperazinyl-1,2-ethylamine (PZEA) as activator amines where all of them were purchased from Sigma Aldrich Company (Germany). The purity of these chemicals was more than 99 % except for AMP where its purity was just above 90 %. Aqueous solutions as solvents based on such chemicals were prepared by adding certain amount (based on weight percentage) of these amines to deionized water and dissolving it. A magnetic stirrer was used to agitate the solution and make it homogeneous. The chosen weight percentages for the major amines were 5, 10 and 20 with and without fixed 5 wt% of any of the activator amines.

2.2.2 Nanofluids as Absorbents

Silica (SiO_2) nanoparticles and short multi-wall carbon nanotubes-COOH were used to prepare nanofluids in order to be used as adsorbents. SiO_2 nanoparticles were purchased from Sigma Aldrich Company, while CNTs were purchased from Cheap Tubes Ins. Company (USA). The characteristics of nanosilca and CNTs are listed in Tables 3 & 4, respectively. In addition to that, Figure 7 shows some SEM images of aggregates of silica nanoparticles and bundles of nanotubes.

Table 3: Silica nanoparticles specifications

Assay	99.5% trace metals basis
Form	Nanopowder (spherical, porous)
Particles Size	5-15 nm (TEM)
Surface Area	590-690 m^2/g (TEM)
Density	2.2-2.6 g/mL at 25 °C
Bulk Density	0.068 g/mL

Table 4: Multi wall carbon nanotubes specifications

Outer Diameter	<8 nm
Inside Diameter	2-5 nm
Ash	<1.5 wt%
Purity	>95 wt%
Length	0.5-2.0 um
Specific Surface Area	500 m^2/g
Bulk Density	0.27 g/cm^3
True Density	~2.1 g/cm^3

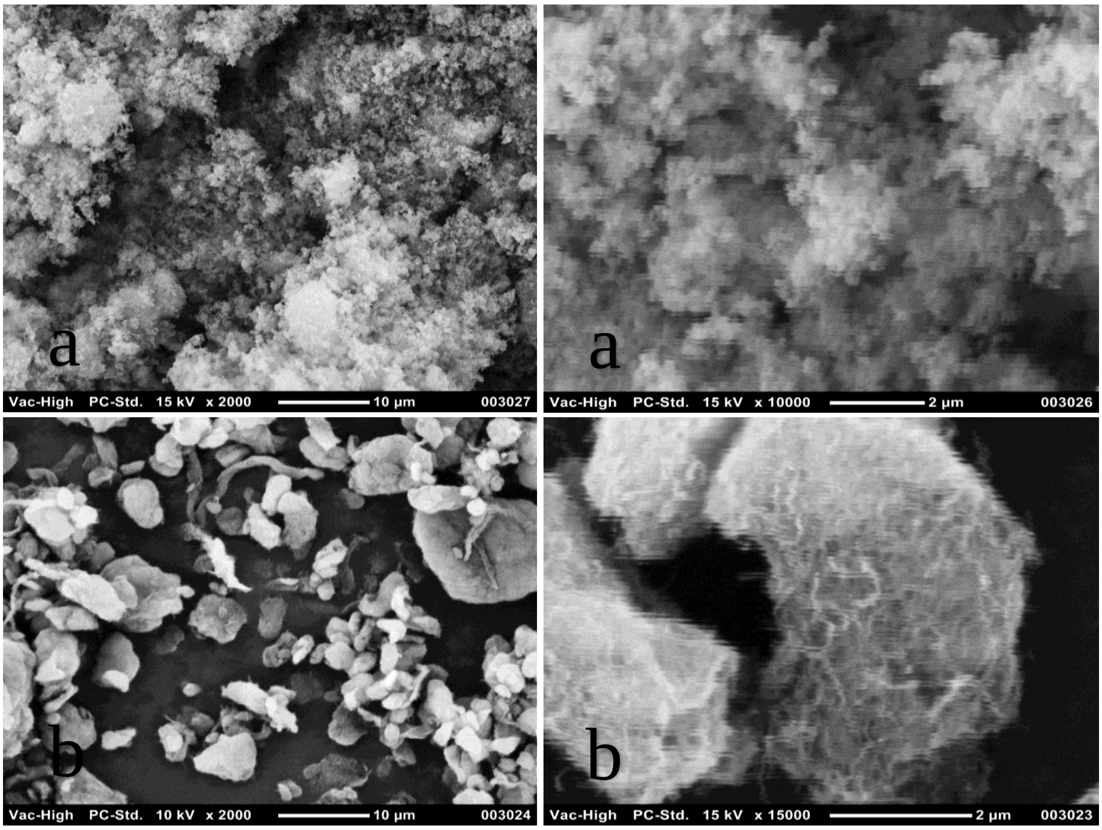

Figure 7: SEM images of: a) SiO_2 nanoparticles. b) Carbon nanotubes

High intensity ultrasonic liquid processor (HIULP) (Purchased from Sonics & Materials, Inc. (USA)) was utilized to disperse the specified quantity of the nanoparticles with weight percentages of 0.5 % and 1 % for nanosilica and 0.05 %, 0.1 %, 0.2 % and 0.5 % for carbon nanotubes in a base deionized water. An image of the HIULP is shown in Figure 8 and its specifications are listed in Table 5. Each of these amounts of nanoparticles suspended in the DI water by sonication for 1 hour. The usage of surfactants was avoided in order to prevent their negative effects on the surface tension (decrease) of the base fluid which may cause membrane wetting [84]. Since ultrasonic dispersion method usually produces heat in the base fluid [98], especially when it is done for long period of time like in this experimental work, a cooling water bath was used in order to remove the generated heat from the fluid. Figure 9 shows two samples of 0.5 wt% of silica nanoparticles and 0.05 wt% of CNTs dispersed in DI water.

Figure 8: High intensity ultrasonic liquid processor

Table 5: Specifications of HIULP

Model	VC 505
Power	500 watts
Frequency	20 kHz
Volts	230 VAC~50/60Hz NOM
Fuse Size	8 AMPS SLO-BLO

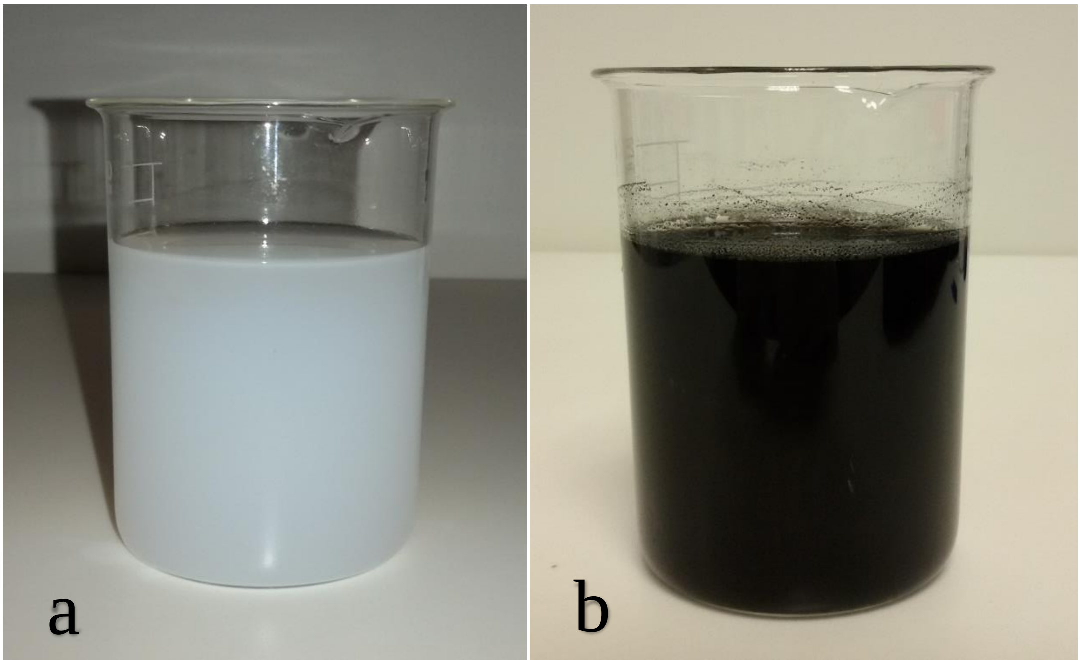

Figure 9: a) 0.5 wt% SiO_2 nanoparticles dispersed in DI water b) 0.05 wt% CNTs dispersed in DI water

2.2.3 Mixture of Amine Solutions and Nanofluids as Absorbents

MDEA solution was first prepared at three basic concentrations of 5 wt%, 10 wt% and 20 wt%. Next, 0.5 wt% of CNT was added to each of the prepared aqueous amine solutions and was sonicated by the high intensity ultrasonic liquid processor for one hour. The mixture was then ready to be used in the tube side of the module as a solvent where no surfactant was required to preserve its suspension.

2.2.4 Mixture of the Two Types of Nanofluids as Absorbents

At the beginning, equal amounts of SiO_2 nanoparticles and CNTs were added to DI water (0.05 wt%, 0.1 wt% & 0.2 wt% for each) and were sonicated together at once for 1 hour. In the following stage, the concentration of CNTs in the solution was kept constant at 0.5 wt% while varying SiO_2 nanoparticles concentration (0.05 wt%, 0.1 wt% & 0.2 wt%). These blends were checked for their absorption behavior in the module.

2.3 Construction of the Experimental Set-up for the Absorption Process

The fundamental goal of this project was to visualize and study carbon dioxide absorption behavior from a gas mixture of 20 vol.% CO_2 and 80 vol.% N_2 (available in a gas cylinder purchased from Sharjah Oxygen Company in UAE) by employing amine solutions and nanofluids as absorbents in a PVDF gas-liquid membrane contactor. In the experimental runs, the gas stream flew through the shell-side and the liquid passed through the lumen side in a counter-current manner in the module. The volumetric flow rate of the gas stream was controlled by a mass flow controller provided by Alicat scientific (USA), while for liquid, it was controlled by using Masterflex L/S Digital Pump purchased from Cole Parmer Industrial Company (USA). Five different gas flow rates ((10, 100, 200, 300 & 400) ml/min) were chosen for specific experimental runs and four liquid flow rates ((10, 20, 30 & 40) ml/min) for each one of them. At the very end where the exit gas stream was coming out, CO_2 Analyzer (CAI – 600 Seri) (purchased from Gas Analyzers (U.S.A)) was utilized for measuring carbon dioxide concentration. This CO_2 Analyzer was connected to Data Logger or Oscilloscope (purchased from Pico Technology (UK)) to generate signal and analyze the concentration. A trap was used between the GLMC module and CO_2 Analyzer in order to remove any liquid drops that have skipped from the tube side to the shell side of the module (probably through membrane wetting) and carried by the gas to the CO_2 Analyzer. In every run of the experiments, at particular gas and liquid flow rates and concentrations, the data were collected after 5 minutes (the values on the CO_2 Analyzer were becoming steady within this period). The schematic of the described absorption process setup above are shown in Figure 10. The flux of the carbon dioxide absorption can be calculated by the following equation:

$$J_{\mathrm{CO_2}}(CO_2\,Flux) = V(C_i - C_o)/A_i \qquad (7)$$

The unit of the flux (J_{CO_2}) is mol m^{-2} min^{-1}. C_i and C_o are the inlet and outlet concentrations (mol/l) of carbon dioxide in the gas mixture stream, while V is the volumetric gas flow rate (l/min) which is assumed as constant over the inlet and outlet of the process since the concentration of CO_2 is very low in N_2 and its removal will not affect the flow rate considerably. The inner surface of hollow fiber membrane is represented by A_i (m^2).

The inlet and outlet concentrations of carbon dioxide can be calculated as:

$$C_{CO_2} = \frac{y_{CO_2}P}{R\,T} \qquad (8)$$

C is a concentration (inlet or outlet) in mol/l, y_{CO_2} is a mole fraction of CO_2 where it is the same here as vol. fraction, P is atmospheric pressure (1atm), R is a gas constant equals to 0.08206 L atm K^{-1} mol^{-1} and T is temperature which is constant at 298 K.

The whole experimental and computed results are presented in tables in the appendix. Graphs were developed and drawn based on these results and exhibited and discussed in the next chapter which is concerned with results and discussion part of this report.

Note: The mole fraction of carbon dioxide in the inlet gas stream (y_{CO_2}, in) was kept at 0.2 continuously and so carbon dioxide inlet concentration in mol/l was always as it is calculated below:

$$C_i = \frac{0.2 * 1\,atm}{0.08206\ \mathrm{L\ atm\ K^{-1}\ mol^{-1}} *\ 298\ \mathrm{K}} = 0.00817866\,mol/l$$

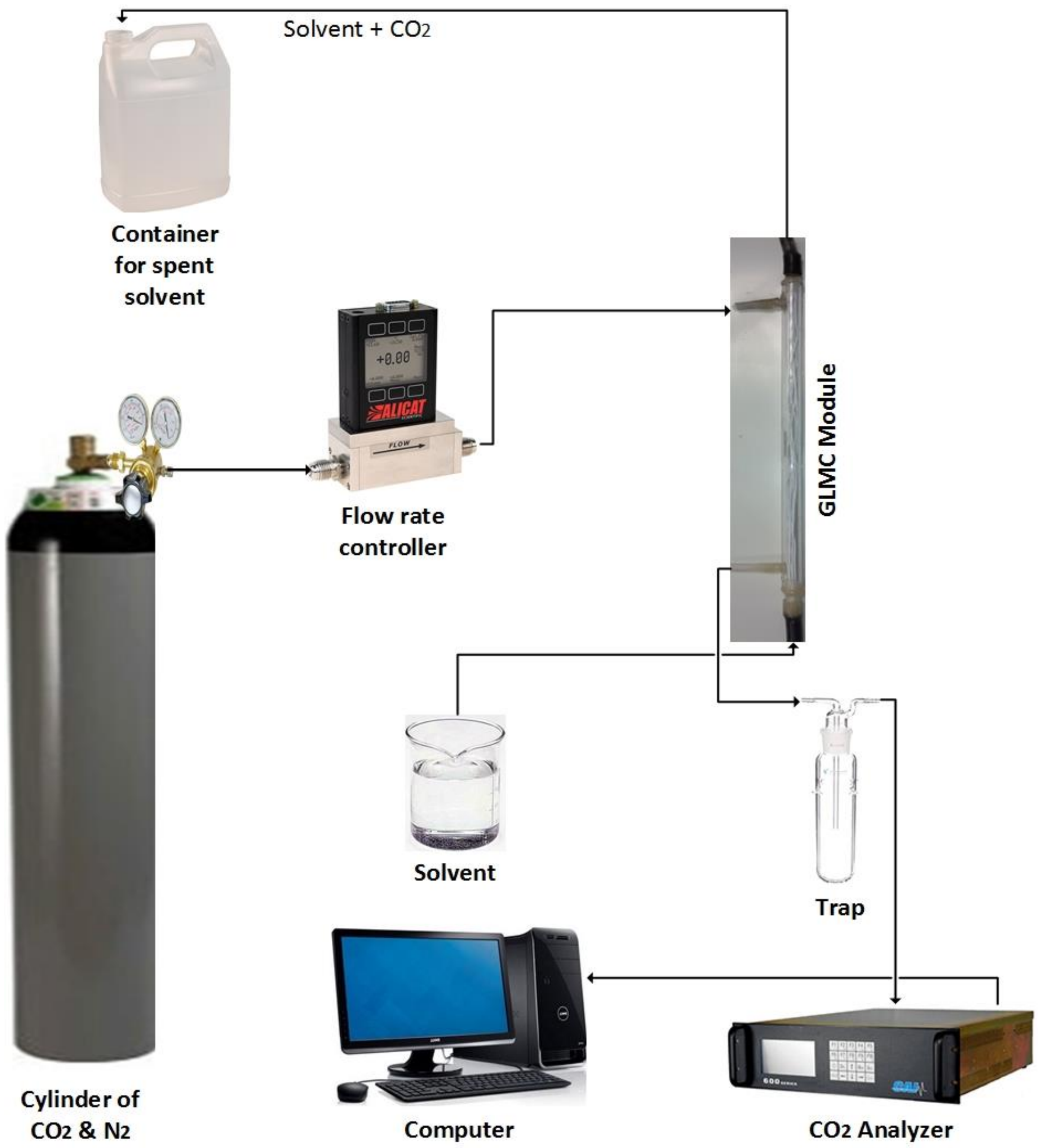

Figure 10: Schematic of the absorption process setup

To sum up, the gas mixture was transferred at predetermined concentrations (20 vol.% CO_2 & 80 vol.% N_2) using a mass flow controller and then pumped at a certain flow rate to the membrane absorber. The pressure and flow rates of gas and liquid phases were controlled by the control valves. In the membrane module, the liquid pressure should be higher than gas phase pressure to avoid bubbling. In addition, the liquid pressure should be low enough to avoid wetting. The gas pressure needed to be above the atmospheric pressure to flow from the cylinder through the membrane so it was controlled around 25.25 psia. The solvent was pumped to the membrane absorber in a counter-flow arrangement with a gas. The exit gas stream was analyzed using CO_2 analyzer to determine the concentration of CO_2.

Chapter 3: Results & Discussion

Each run of the experimental work was carried out using four different solvent flow rates: 10, 20, 30 & 40 ml/min. CO_2 concentration was fixed at 20 vol.% in the CO_2/N_2 gas mixture. All of the experiments were conducted at ambient temperature and atmospheric pressure.

3.1 Effect of Gas Flow Rate at Different Amine Concentrations

Four different gas flow rates (100, 200, 300 & 400 ml/min) were used to conduct CO_2 absorption at three different concentrations of DEA (5, 10 & 20 wt%) in DI water. Figures 11, 12 & 13 show the experimental results of CO_2 removal percentage versus solvent flow rate at specific DEA weight percentage and different gas flow rates.

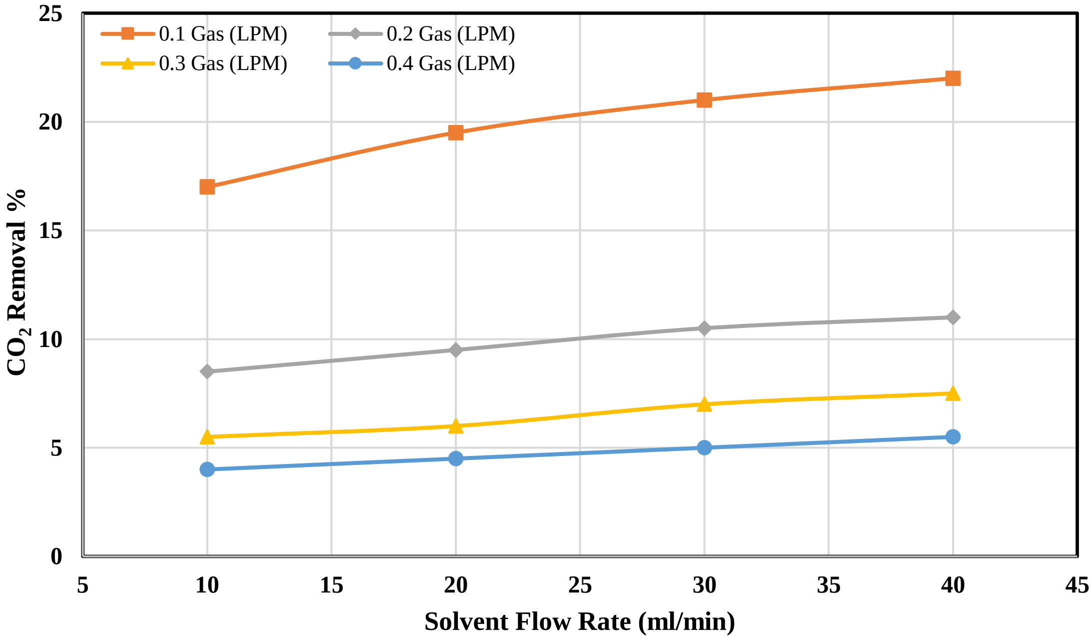

Figure 11: CO_2 removal % versus solvent flow rate for 5 wt% DEA at different gas flow rate

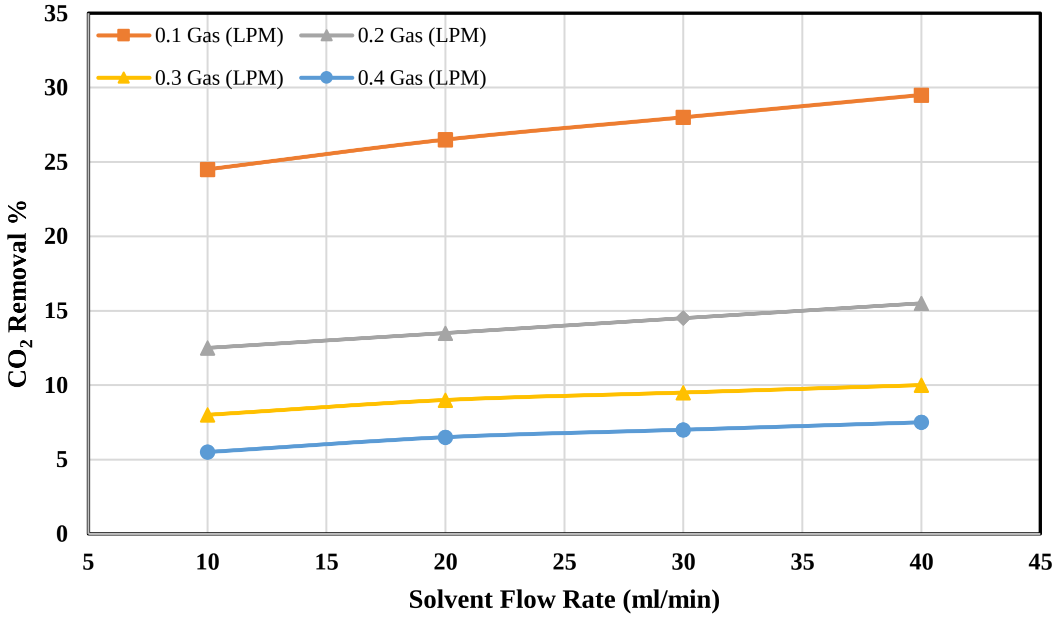

Figure 12: CO_2 removal % versus solvent flow rate for 10 wt% DEA at different gas flow rate

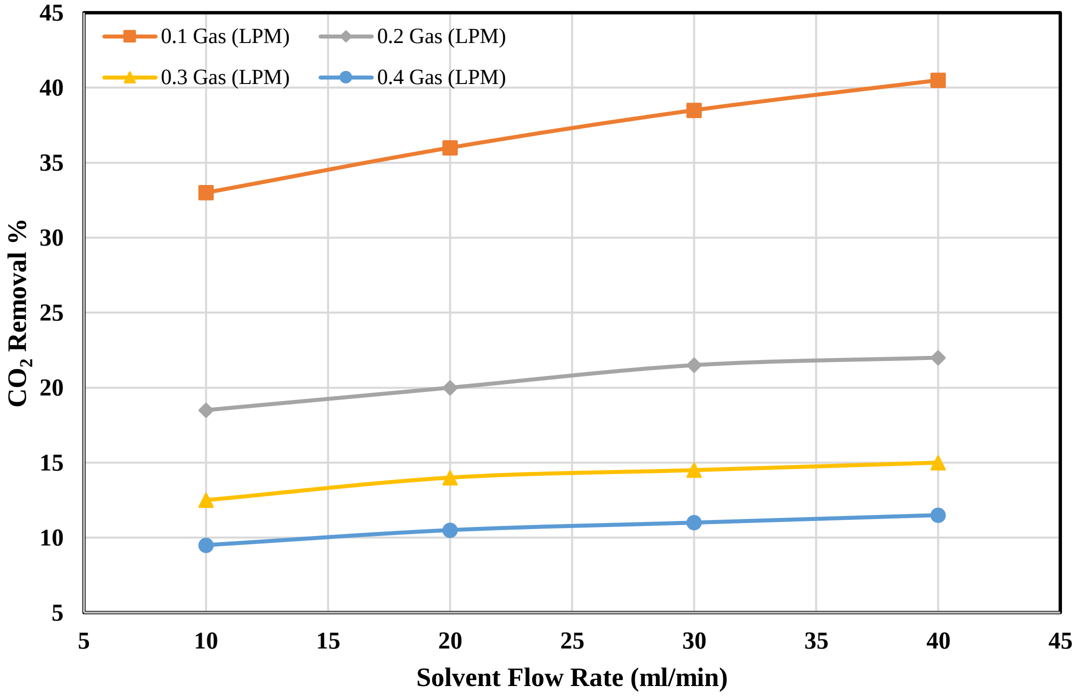

Figure 13: CO_2 removal % versus solvent flow rate for 20 wt% DEA at different gas flow rate

It can be observed that CO_2 removal % decreases as the gas flow rate increases. This can be interpreted as shorter gas residence time within the module and as a result it lowers the absorption rate of CO_2 [49].

3.2 Effect of Different Types of Amines with & without PZ or PZEA

A comparison has been done first of all between six different types of amines (MEA, DEA, MDEA, AMP, EDA & DETA) at a certain concentration (5 wt%) and over a range of solvent flow rate (10-40 ml/min). As revealed by Figure 14, the highest CO_2 removal % was achieved by EDA and DETA with a small difference between their results. EDA has two amino groups as its primary diamine. On the other hand, DETA contains two primary and one secondary amino groups. These two amines exhibits higher reactivity and mass transfer rate [76], [99]–[104]. MDEA showed very poor performance where its absorption rate was close to pure DI water. Despite the high equilibrium capacity of MDEA as a tertiary amine, it has lower reaction rate when compared with the other amines which leads to low absorption rate [22], [51], [105], [106].

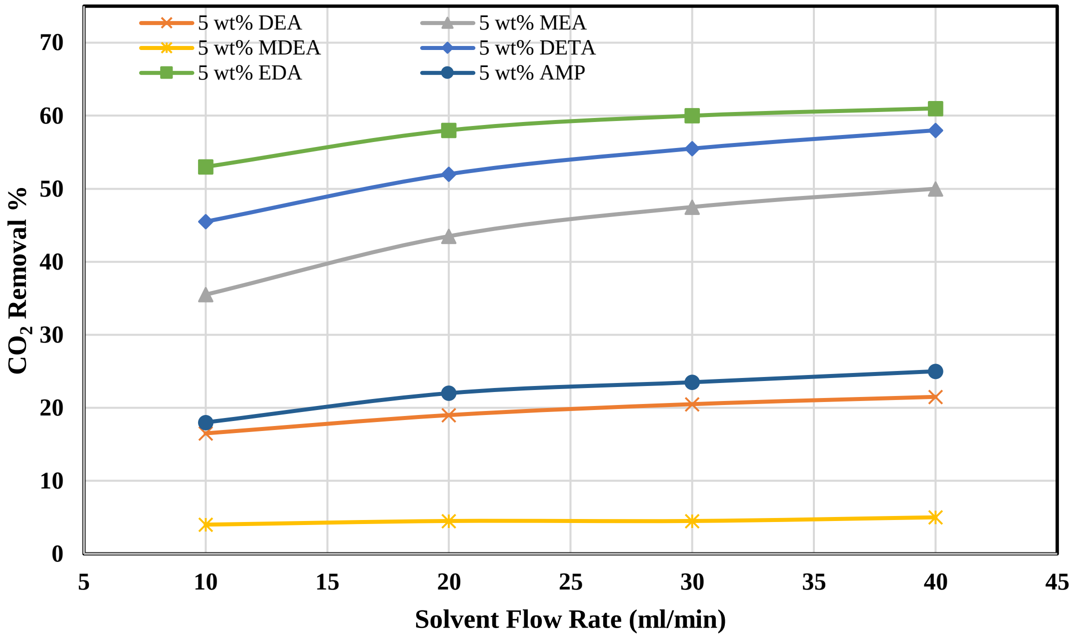

Figure 14: CO_2 removal % versus solvent flow rate for different amines at 5 wt% & 0.1 gas LPM

In addition to these six amines, the two activator amines (PZ and PZEA) were tested for their CO_2 capture behavior at 5 wt% and over the same range of solvent flow rate. Figure 15 illustrates that PZ gave moderately larger CO_2 absorption compared to PZEA. PZ is a cyclic diamine, whereas PZEA is a cyclic triamine. PZ has very high reaction constant when it reacts with carbon dioxide, and therefore, it shows a fairly good performance on CO_2 capture [76]. In addition, it provides high absorption capacity, resistance to corrosion and degradation and low regeneration costs [22]. On the other hand, several works proved that PZEA can be an efficient absorption activator in alkanolamine solutions and advantageous solvent [74], [107], [108]. However, few studies seemingly have been done examining CO2 absorption behavior in a HFMC using a blended solution consisting of PZEA and any other amine solvent.

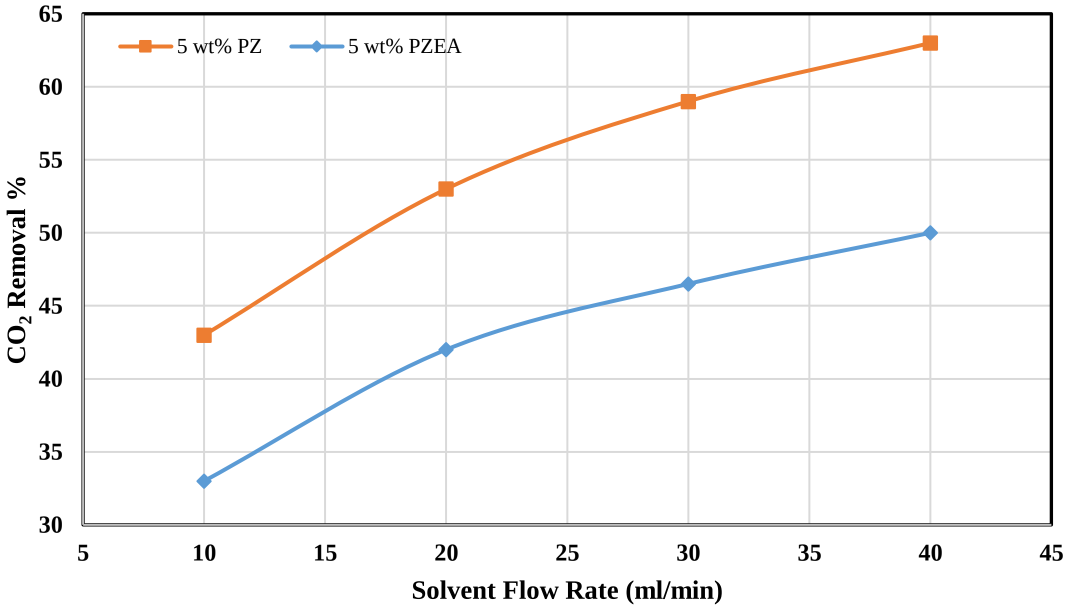

Figure 15: CO_2 removal % versus solvent flow rate for PZ and PZEA at 5 wt% & 0.1 gas LPM

Carbon dioxide absorption rate was also checked for the mixtures of the six amines (MEA, DEA, MDEA, AMP, EDA & DETA) and activator amines (PZ & PZEA). Figure 16 presents the CO_2 removal accomplished by blends of amines with PZ solutions at 5 wt% for each. Figure 17, on the other hand, displays the performance of mixtures of amines with PZEA solutions at the same weight percentage for CO_2 absorption process in the module. It was obvious that blends of DETA and PZ or PZEA solutions were achieving much better removal than the rest mixtures of amines and one of the activator amines. However, solutions of MDEA with PZ or PZEA were always showing the lowest CO_2 removal %.

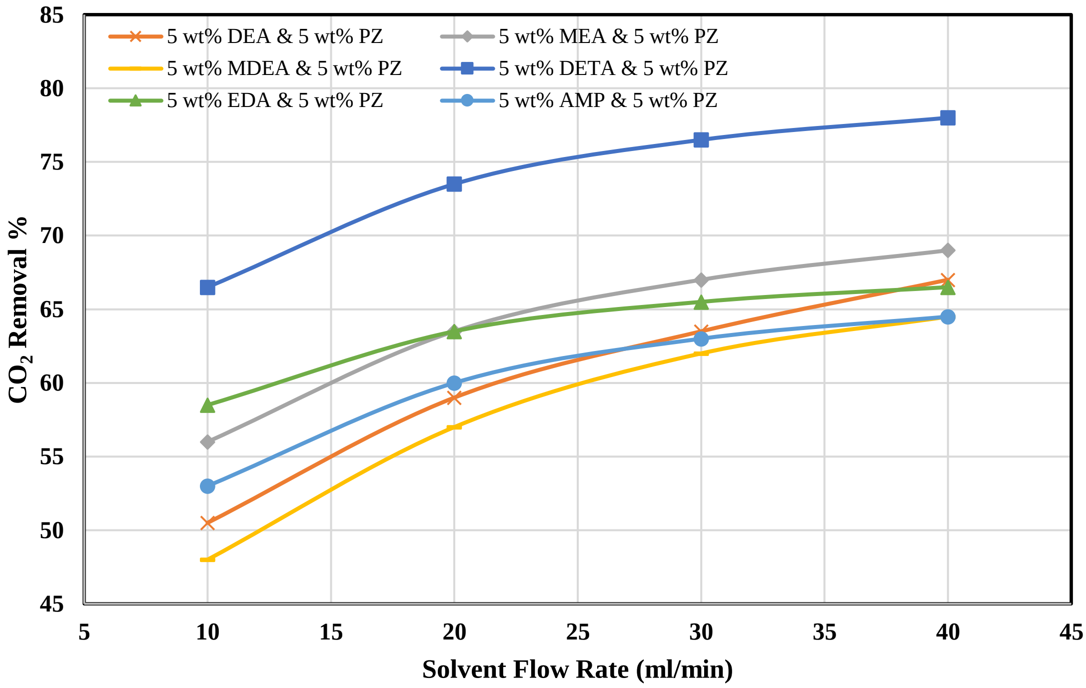

Figure 16: CO_2 removal % versus solvent flow rate for different amines at 5 wt% + 5 wt% PZ & 0.1 gas LPM

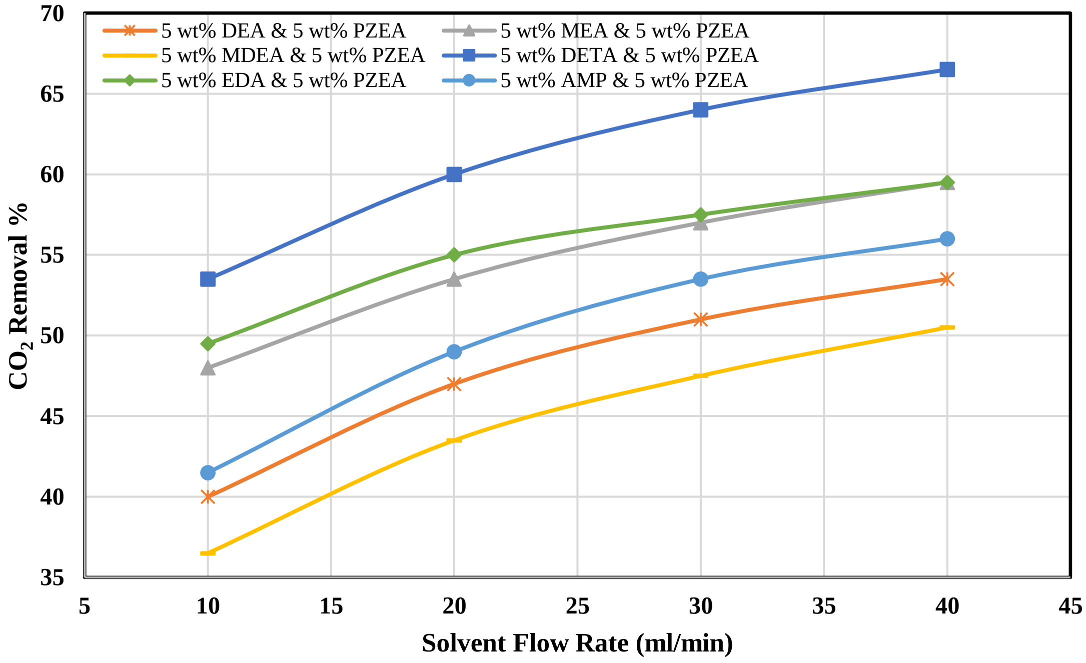

Figure 17: CO_2 removal % versus solvent flow rate for different amines at 5 wt% + 5 wt% PZEA & 0.1 gas LPM

3.3 Effect of Amine Concentrations with and without PZ or PZEA

In general, a higher efficiency of CO_2 removal was observed as increasing the concentration of amine and adding an activator amine specifically at low amine concentration (5 wt%). CO_2 reaction with the amine solution and solubility are the main factors that control the removal rate [49]. Several researchers observed the same behavior in their works regarding the effect of alkali concentration on the efficiency of CO_2 removal [66], [67], [109]. Furthermore, due to the activation phenomenon of adding cyclic amines like PZ and PZEA to the solutions, the absorption rate of CO_2 can be increased substantially as many researchers reported [22], [26], [50], [76]. In most of the cases, when increasing the amine concentration in the aqueous blended solution with activator amine (at constant 5 wt%) from 5 wt% to 20 wt%, there was an inverse effect on the CO_2 removal %. These phenomena probably appeared due to the increase in the viscosity of the blends and membrane wettability, which leads to an increase in the resistance to mass transfer and thus minimizes the separation of CO_2 [110]–[113].

In this work, three different concentrations (5, 10 & 20 wt%) were chosen for each amine and one specific concentration (5 wt%) for both of the two types of the activator amines. Figures 18 & 19 show the outcomes of using MEA for CO_2 absorption process in the membrane contactor. The plotted results in the two graphs showed that the concentration of single amine MEA in DI water has observable effect on CO_2 removal. It shows a dramatic increase in CO_2 removal percentage as the concentration of MEA increased from 5 wt% to 10 wt% and moderate increase as moving from 10 wt% to 20 wt%. By adding PZ, CO_2 removal enhanced considerably for 5 wt% of MEA, whereas it gave less removal with 10 and 20 wt% of the same amine.

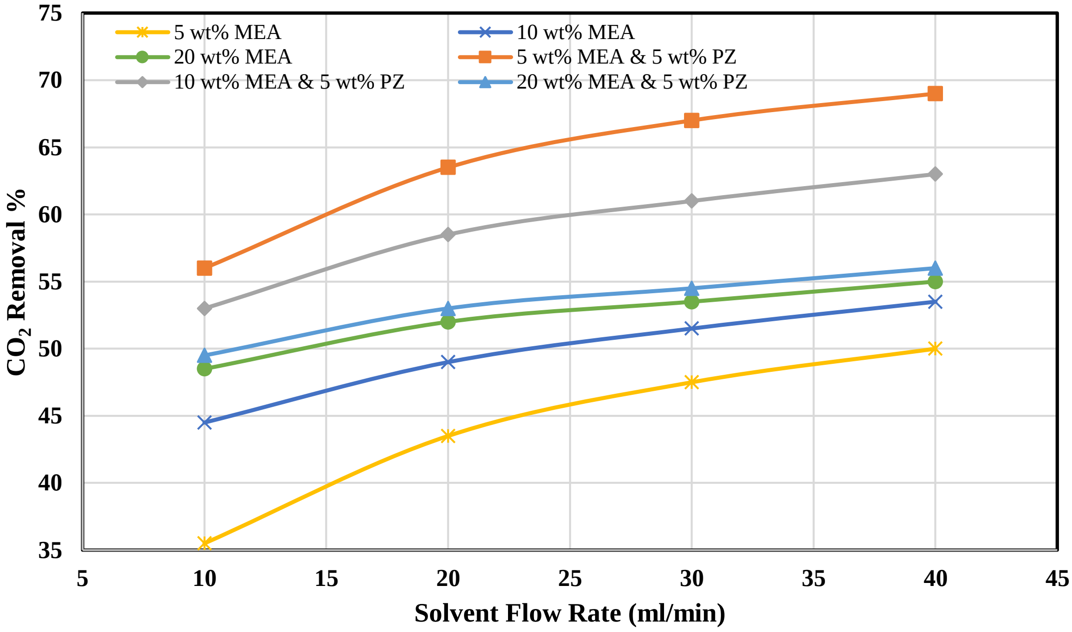

Figure 18: CO_2 removal % versus solvent flow rate for different MEA concentration with & without 5 wt% PZ at 0.1 gas LPM

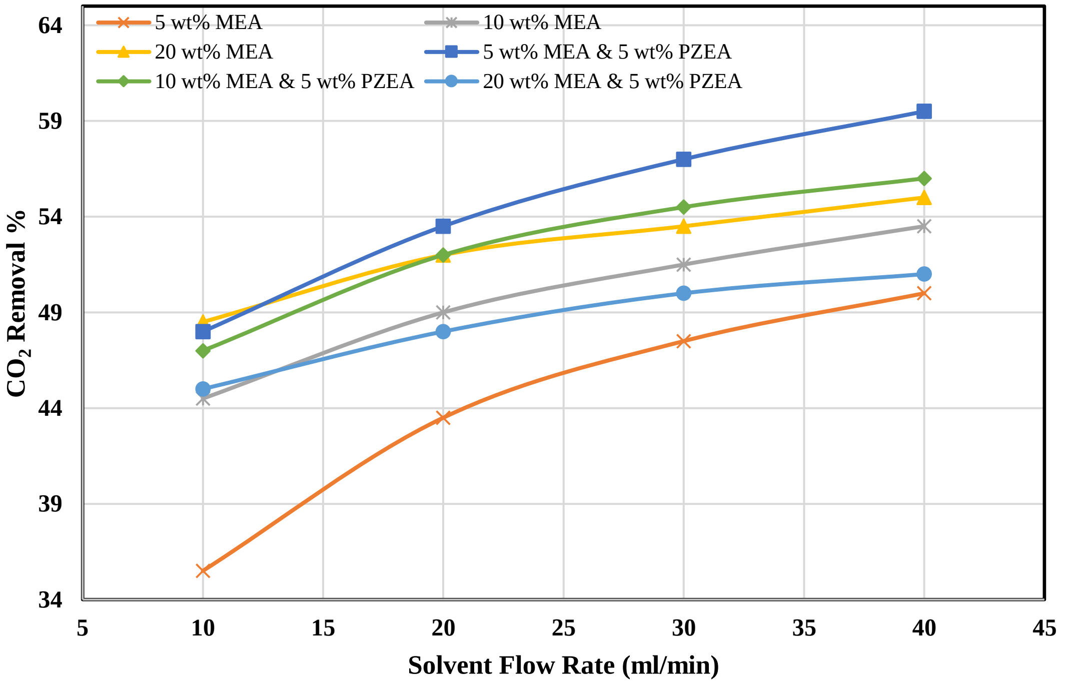

Figure 19: CO_2 removal % versus solvent flow rate for different MEA concentration with & without 5 wt% PZEA at 0.1 gas LPM

The experimental results of the effect of DEA concentration (5, 10 & 20 wt%) and the addition of an activator amine (5 wt%) are illustrated in Figures 20 & 21. The two figures obviously showed that increasing DEA weight percentage in DI water solution enhanced CO_2 removal normally. The addition of an activator amine like PZ and PZEA improved CO_2 absorption. Addition of PZ to the solution seemed to enhance the absorption process more than PZEA. A slight difference was observed when increasing DEA concentration while keeping the concentration of an activator amine constant.

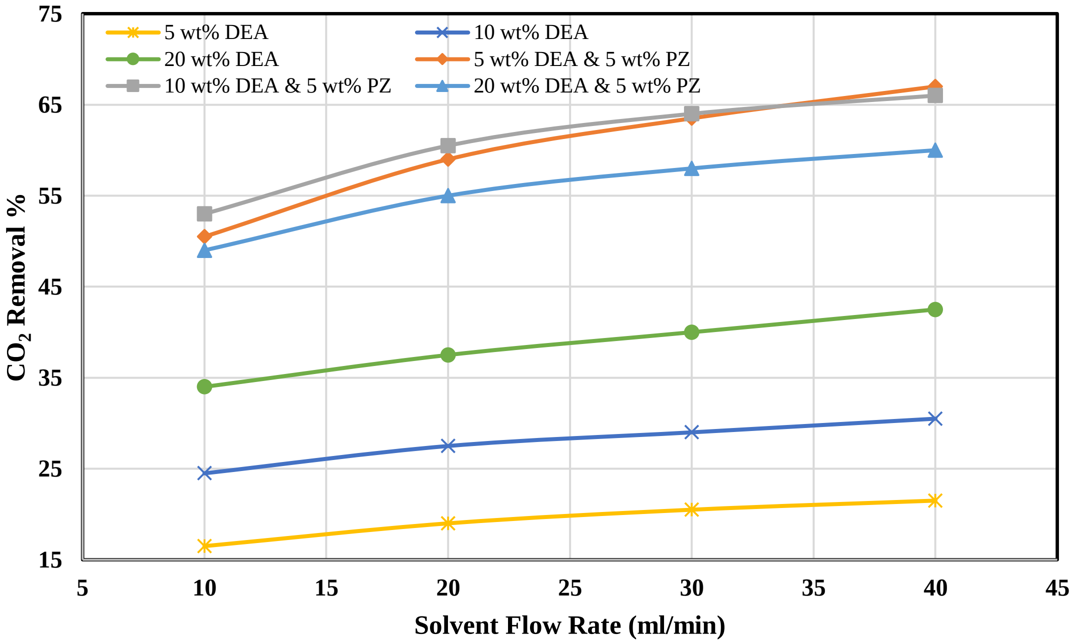

Figure 20: CO_2 removal % versus solvent flow rate for different DEA concentration with & without 5 wt% PZ at 0.1 gas LPM

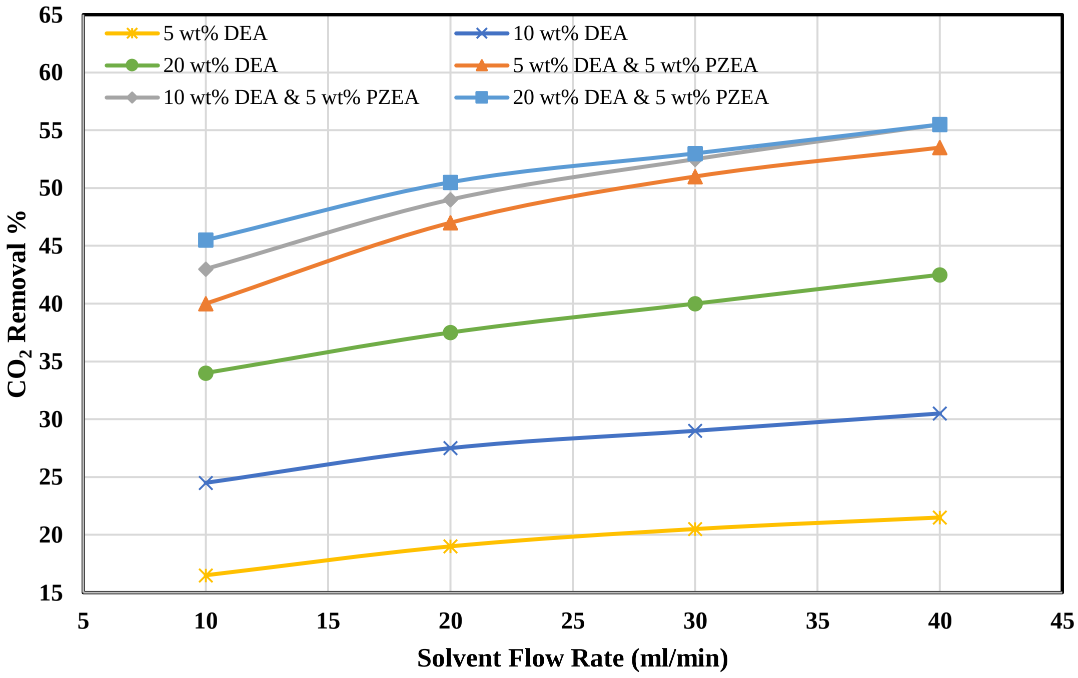

Figure 21: CO_2 removal % versus solvent flow rate for different DEA concentration with & without 5 wt% PZEA at 0.1 gas LPM

In the case of using different concentrations of MDEA dissolved in DI water as absorbent, the CO_2 removal % were very close to each other and to the removal % achieved by pure DI water as well. Figures 22 & 23 reveal the trends for the removal percentage of CO_2 by single MDEA solutions and their mixtures with PZ and PZEA, respectively, at different solvent flow rates. Adding an activator amine, specifically PZ, to 5 wt% MDEA promoted the removal of CO_2 significantly, whilst almost the same trends scenarios was noted with MEA before when the MDEA concentration was increased from 5 wt% to 20 wt% in the blended aqueous amine solution.

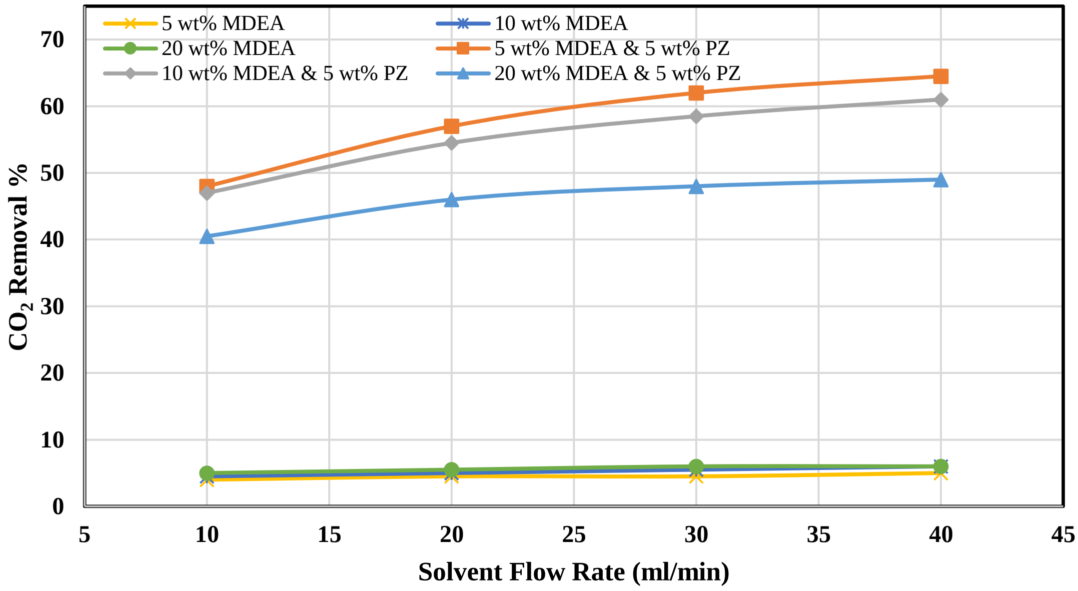

Figure 22: CO_2 removal % versus solvent flow rate for different MDEA concentration with & without 5 wt% PZ at 0.1 gas LPM

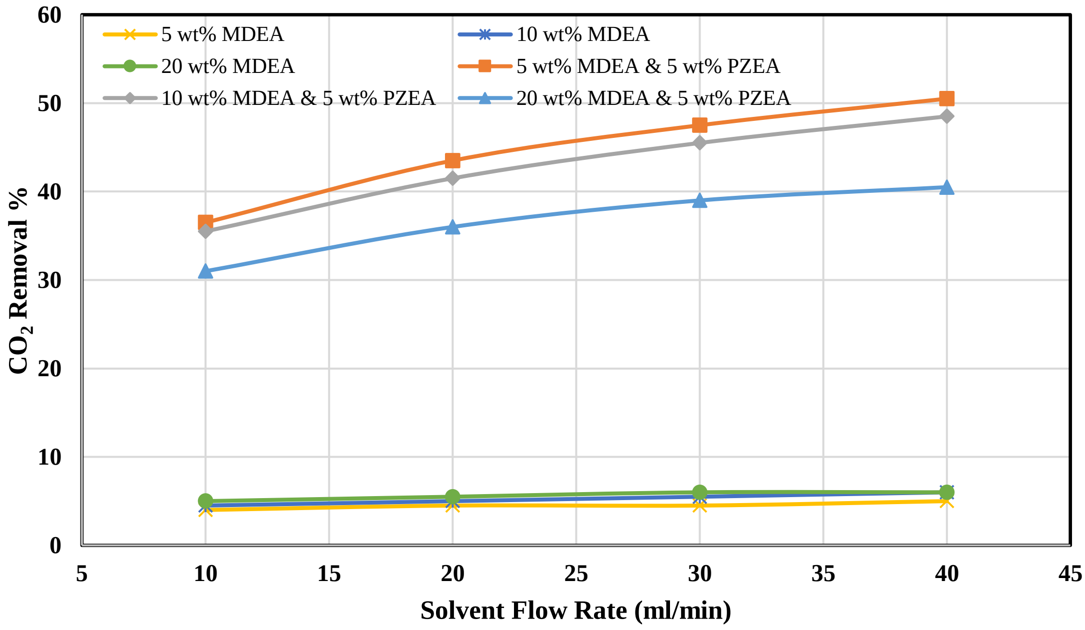

Figure 23: CO_2 removal % versus solvent flow rate for different MDEA concentration with & without 5 wt% PZEA at 0.1 gas LPM

Increasing the concentration of AMP from 5 wt% to 10 wt% enhanced CO_2 absorption in the module, while 20 wt% of the same amine hindered the absorption process as it is shown in Figures 24 & 25. A mixture of 5 wt% of AMP and 5 wt% of PZ or PZEA promoted CO_2 removal % sharply compared to a 5 wt% of AMP alone in DI water. The removal efficiency of CO_2 was reduced as the concentration of AMP in the solution with particular activator amine concentration increased.

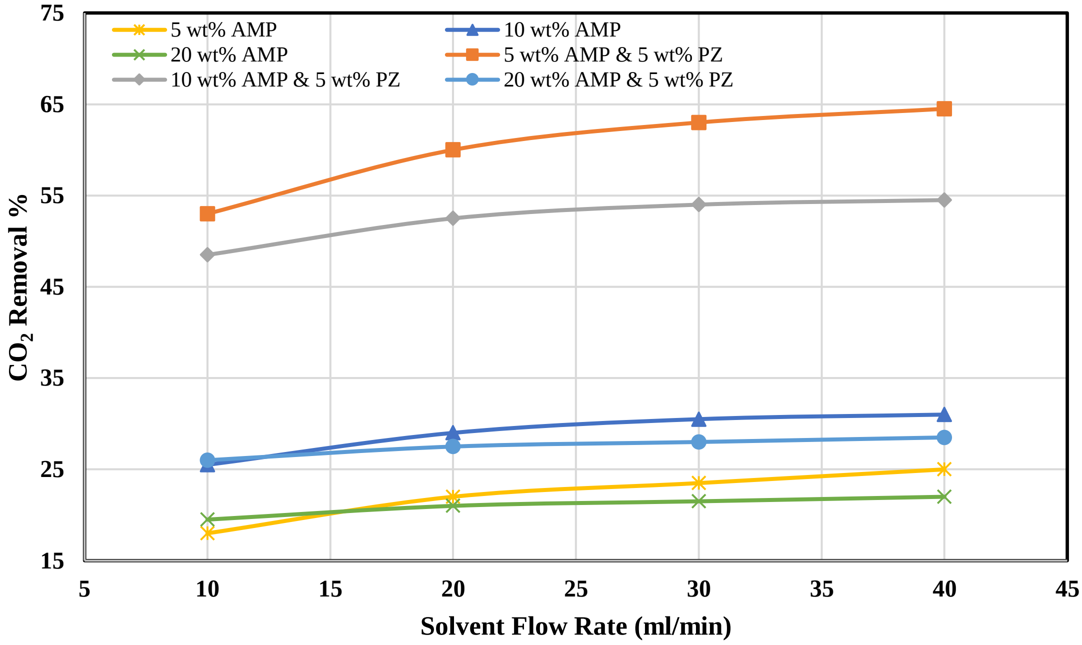

Figure 24: CO_2 removal % versus solvent flow rate for different AMP concentration with & without 5 wt% PZ at 0.1 gas LPM

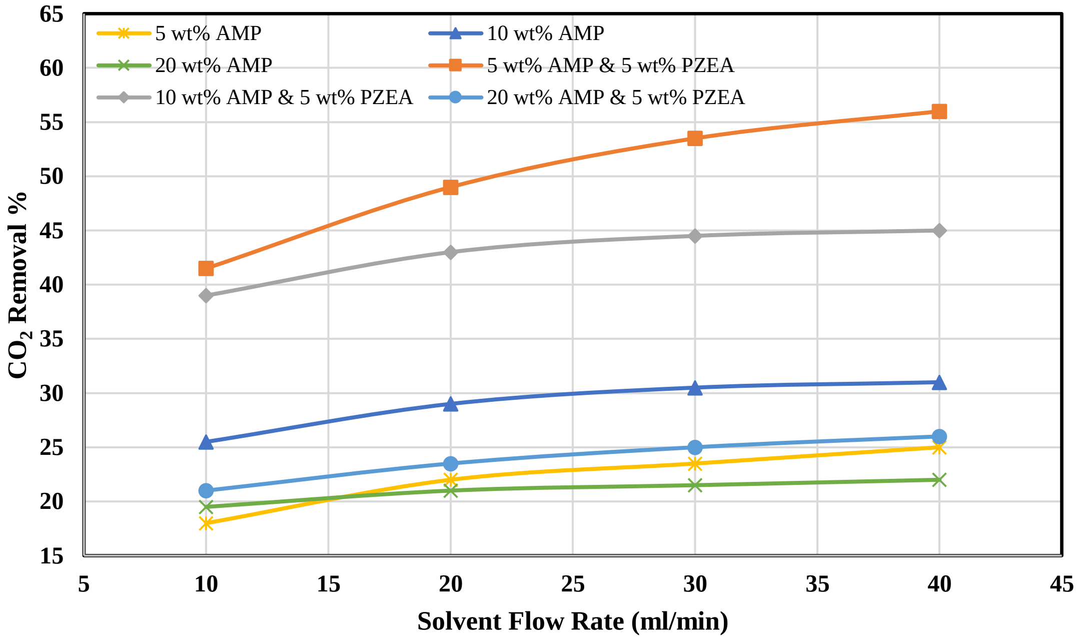

Figure 25: CO_2 removal % versus solvent flow rate for different AMP concentration with & without 5 wt% PZEA at 0.1 gas LPM

Figures 26 and 27 present the removal percentage of CO_2 in the hollow fiber membrane contactor using EDA and its blends with activator amines in DI water as absorbents. When compared to 5 wt% of single EDA solution, 10 wt% of the same amine enhanced the absorption of CO_2 dramatically, while on the other hand, 20 wt% of EDA showed an inconsiderable increase in CO_2 removal after that. A mixture of 5 wt% for each of EDA and PZ in DI water promoted CO_2 separation process. Otherwise, a decrease was observed in CO_2 removal for a concentration of EDA higher than 5 wt% in a blend with 5 wt% of PZ and DI water. However, the removal of carbon dioxide using mixtures of EDA and PZEA was always lower than using single EDA aqueous solution.

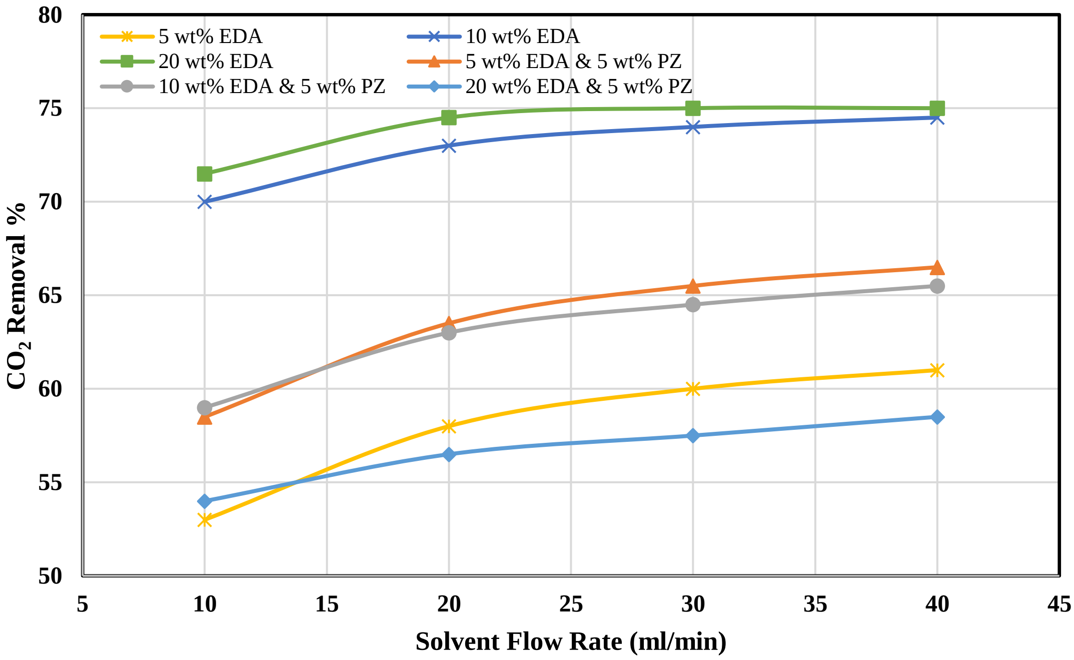

Figure 26: CO_2 removal % versus solvent flow rate for different EDA concentration with & without 5 wt% PZ at 0.1 gas LPM

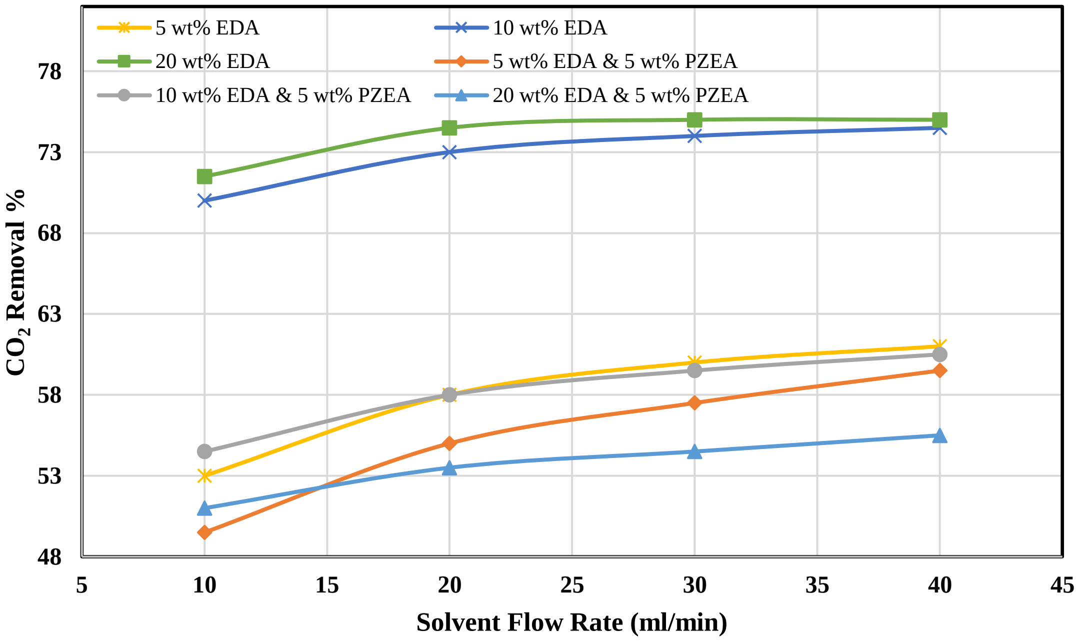

Figure 27: CO_2 removal % versus solvent flow rate for different EDA concentration with & without 5 wt% PZEA at 0.1 gas LPM

The behavior of single DETA as a solvent at different weight percentages in DI water was similar to that noted when using EDA. Figures 28 & 29 display a great enhancement in CO_2 removal% when a 10 wt% of DETA was used compared to 5 wt% and a medium improvement with 20 wt% in contrast with 10 wt% of the same amine solution. On the other hand, solution consists of 5 wt% of DETA and 5 wt% of PZ in DI water appeared to promote CO_2 removal much better than single 5 wt% DETA in DI water. A blend of 10 wt% of DETA and 5 wt% of PZ in DI water gave almost the same results as the blend of 5 wt% of DETA and 5 wt% of PZ solution. A mixture of 20 wt% DETA and 5 wt% of PZ solution seemed to hinder the absorption of carbon dioxide in the membrane when compared to the findings of single DETA at 20 wt%. In contrast to the addition of PZ, adding 5 wt% of PZEA to 5 wt% and 10 wt% of DETA solutions increased the removal of CO_2 normally and slightly, respectively, whereas it lowered the removal in the case of 20 wt% DETA aqueous solution.

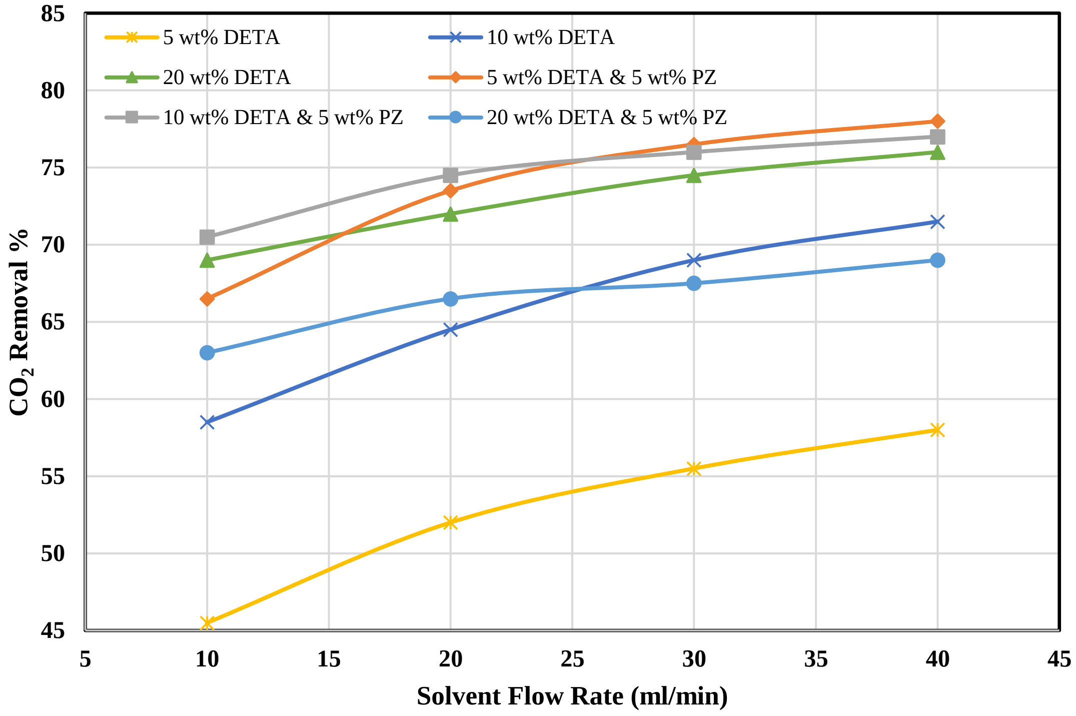

Figure 28: CO_2 removal % versus solvent flow rate for different DETA concentration with & without 5 wt% PZ at 0.1 gas LPM

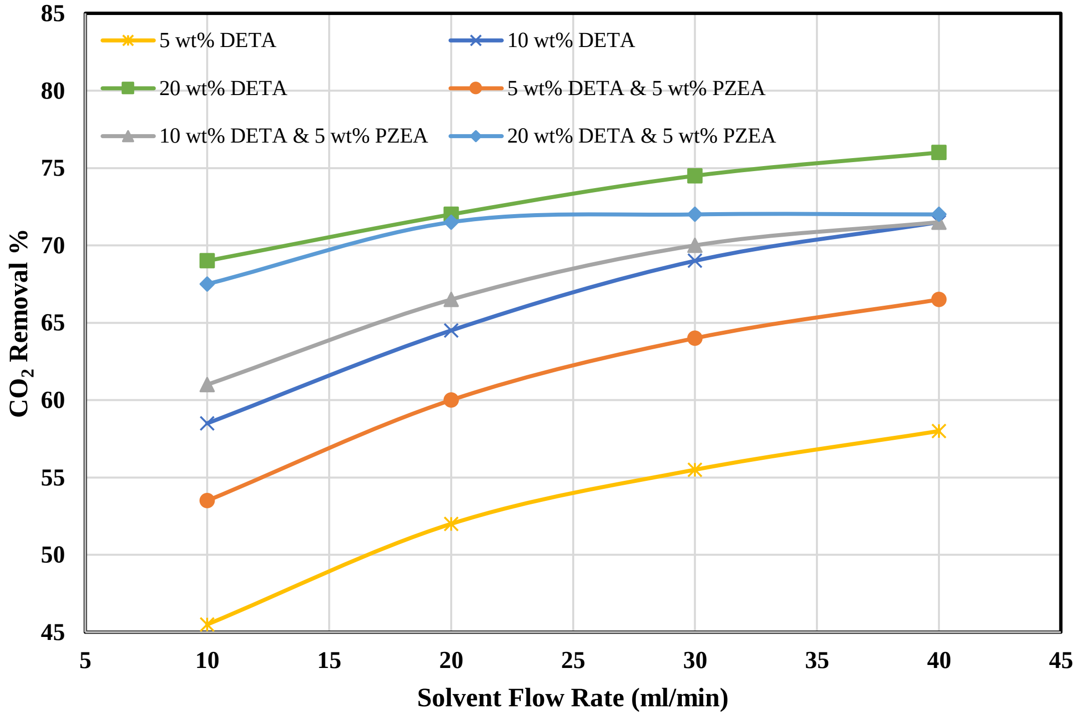

Figure 29: CO_2 removal % versus solvent flow rate for different DETA concentration with & without 5 wt% PZEA at 0.1 gas LPM

3.4 Effect of Different Types of Amines at Very Low Gas Flow Rate

Figures 30 and 31 showed that all types of amines give removal % of CO_2 between 95 and 100 at 5 wt% except for MDEA where the removal is much less (between 33.5% and 44.5%) compared to the rest of amine solutions but higher than removal achieved by DI water. Carbon dioxide removal in the module was increased steadily as the concentration of MDEA increased from 5 wt% to 20 wt%. The results are shown in Figure 32.

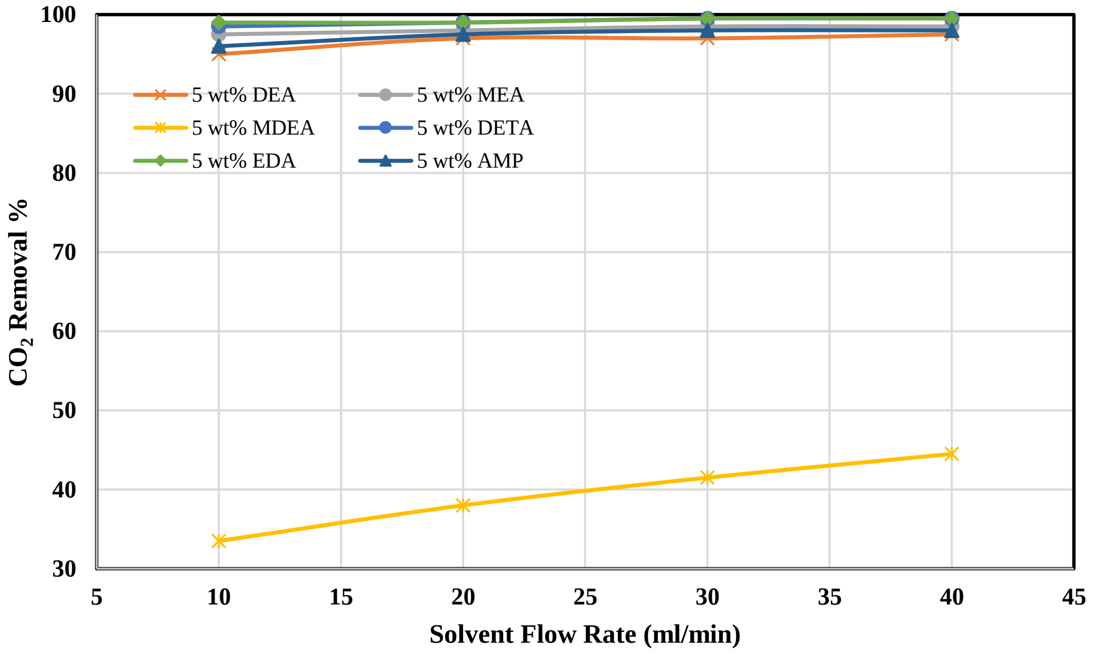

Figure 30: CO_2 removal % versus solvent flow rate for different amines at 5 wt% & 0.01 gas LPM

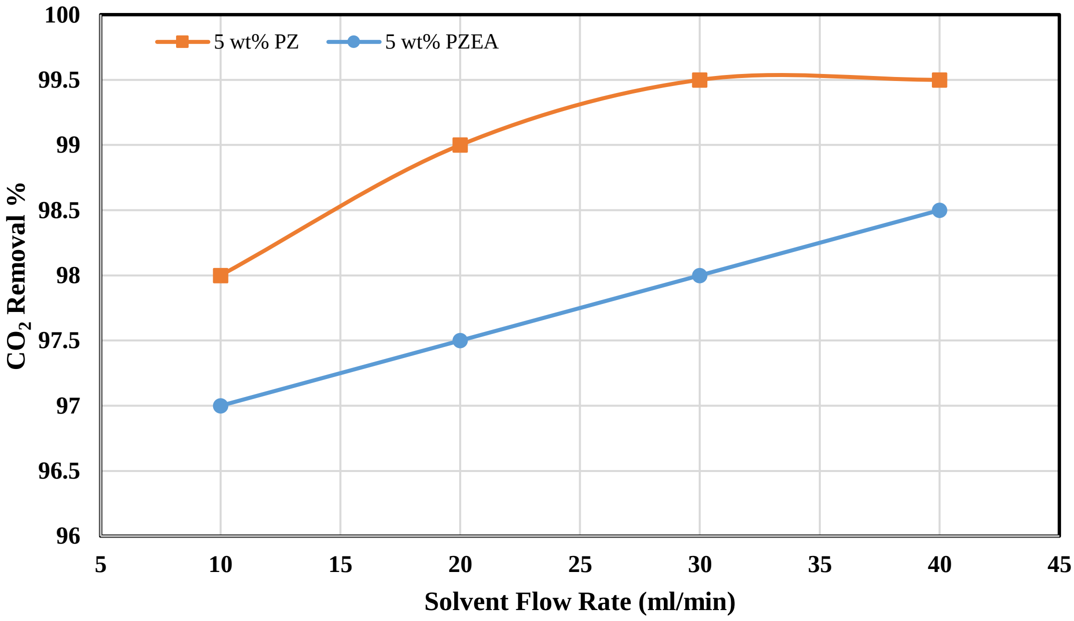

Figure 31: CO_2 removal % versus solvent flow rate for PZ and PZEA at 5 wt% & 0.01 gas LPM

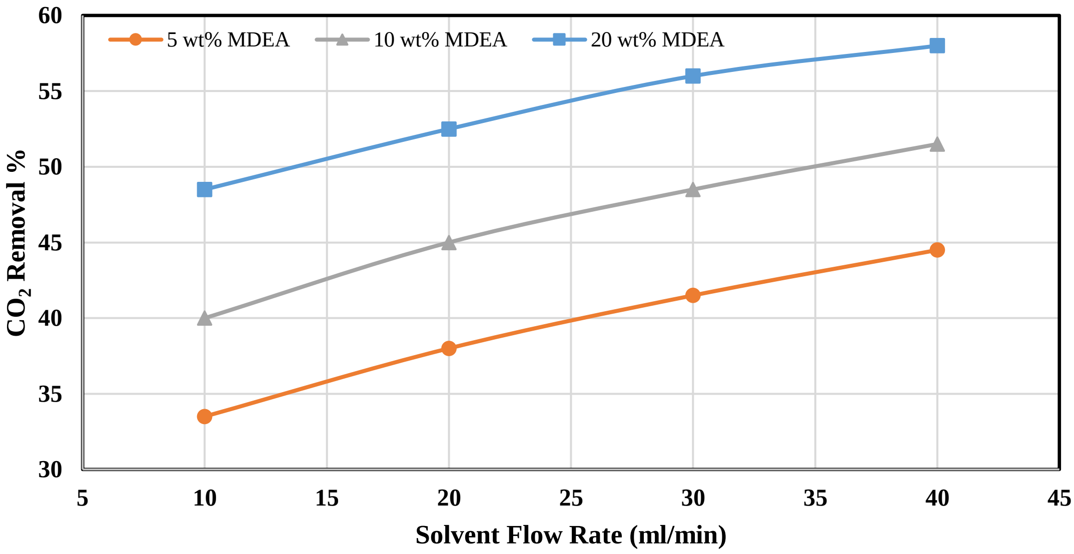

Figure 32: CO_2 removal % versus solvent flow rate for different MDEA concentration at 0.01 gas LPM

3.5 Effect of Nanofluids at Different Concentrations

Gokhar et al. [11] reported steps of carbon dioxide absorption mechanism in nanofluids used in HFMC. After the diffusion of CO_2 in the flue gas and membrane pores, it dissolves in the liquid phase of nanofluid. Carbon dioxide then diffuses in the liquid and gets adsorbed at the exposure surface of the solid (nanoparticles) phase of the nanofluid.

In this section, when liquid flow rates for absorbents were increased, CO_2 removal % increased. While increasing the liquid flow rate, a decrease in the liquid phase boundary layer could happen and it helps in growing of carbon dioxide diffusion into the nanofluids. This improves the efficiency of CO_2 removal as the gas-liquid interface could be persistently kept at a fresh absorbent [12].

The effect of SiO_2 nanoparticles on CO_2 removal in the PVDF hollow fiber membrane was insignificant. Figure 33 shows CO_2 removal % for pure DI water and SiO_2 nanofluids at 0.5 wt% and 1 wt%. It is obvious from the figure that the difference in the removal percentage is very small. The impact of silica nanoparticles on the gas-liquid mass transfer is usually weak and, in some cases, it hindered the removal of CO_2. Because of the strong hydrophilia of silica nanoparticles, it adds more viscous resistance to the solution and so restrains mass transfer. Another factor which could intensify such resistance and diminish the removal of CO_2 is that due to the easy dehydration of the surface of these nanoparticles because of the hydroxyl they contain, they are more presumably to agglomerate and reduce the exposed area [114].

In Figure 34, on the other hand, it has been figured out that CNTs dispersed in DI water at different concentration had important impact on CO_2 removal in the module used in this work. There was a slight promotion in the removal of CO_2 when 0.05 wt% and 0.1 wt% CNTs nanofluids used and a medium promotion at 2 wt%. A significant enhancement in CO_2 removal% was carried out by using 0.5 wt% of CNT nanofluid. This is due to its absorption property and performance and adsorption capacity which promotes the driving force between the two phases [11], [12], [89], [115].

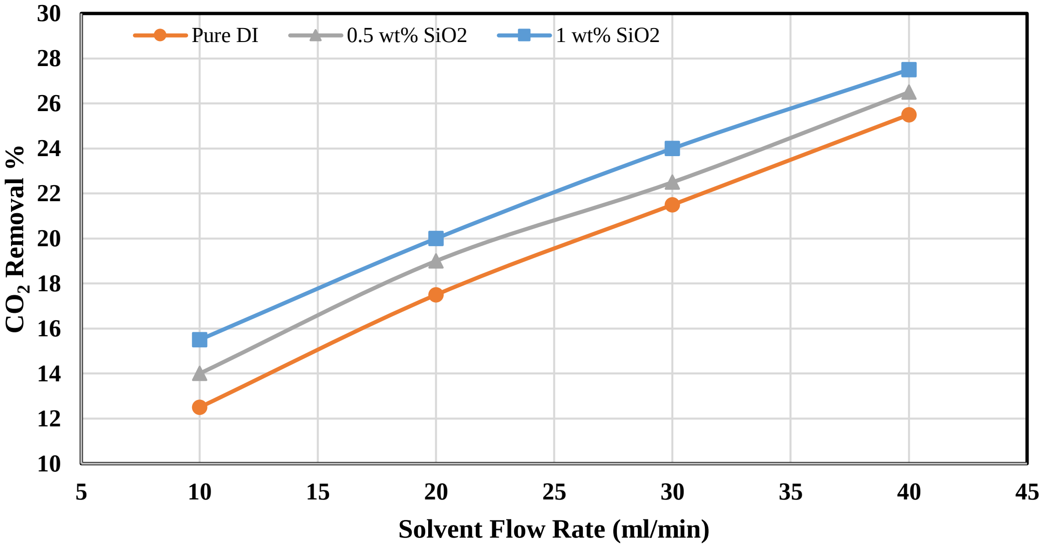

Figure 33: CO_2 removal % versus solvent flow rate for different SiO_2 nanofluids concentration at 0.01 gas LPM

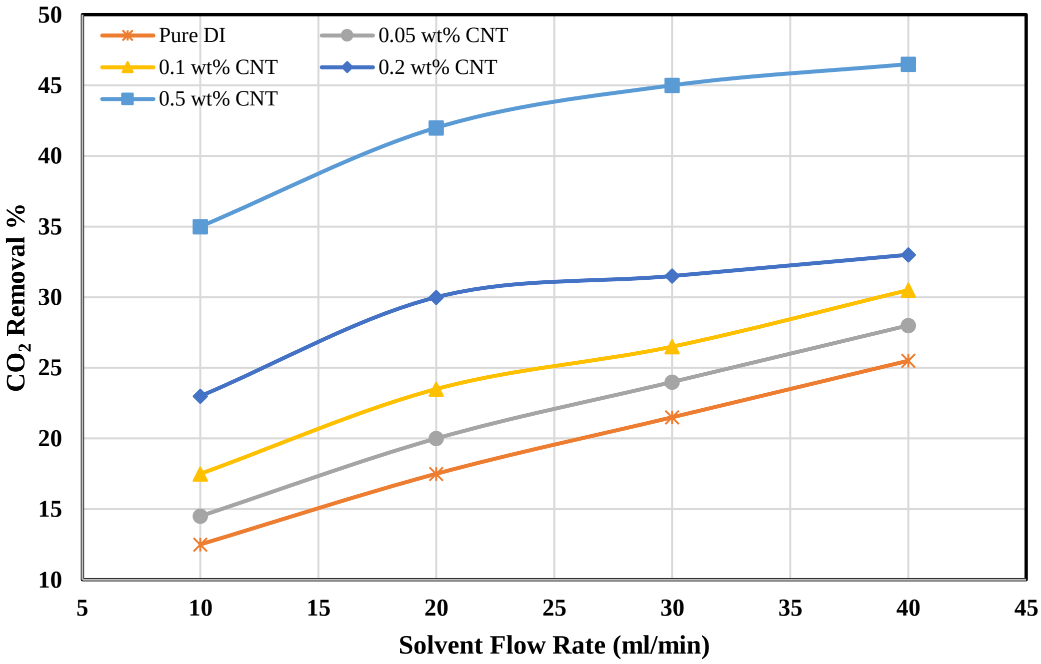

Figure 34: CO_2 removal % versus solvent flow rate for different CNTs nanofluids concentration at 0.01 gas LPM

3.5 Effect of Mixtures of MDEA Solutions + CNTs Nanofluids

The addition of nanoparticles to amine solutions can increase the diffusion coefficient in the liquid phase and so the mass transfer coefficient [116]. Because of the significance of diffusion coefficients and low Reynolds number in the hollow fibers membrane contactors, adding nanoparticles to chemical solvents could be efficient [11]. It has been shown in several researches that the capacity and mass transfer for carbon dioxide absorption were enhanced when nanoparticles were added to the amine solution [82], [85], [89], [117].

The purpose of this work was to disperse 0.5 wt% of CNT (which gave the highest carbon dioxide removal percentage in the previous work when it was dispersed in DI water) in MDEA solution at different concentrations and check its behavior in the synthesized PVDF hollow fiber membrane contactor module for the capture of carbon dioxide. The experimental results of CNTs dispersed in MDEA solvent are presented in Figure 35 and compared with single MDEA solvents as well. Apparently when adding CNTs to MDEA solution, the removal % of CO_2, was higher than CO_2 removal% by single MDEA solutions. The difference between the CO_2 removal % by single MDEA solution at specific concentration and CO_2 removal % by mixture of MDEA solution and dispersed CNTs was minimizing as the concentration of MDEA increased in the blend. It seems that the probability of CO_2 removal by chemical absorption (represented by MDEA), as it was getting into the absorbent in the tube side of HFMC, was growing up as the concentration of such tertiary amine was increasing in the mixture.

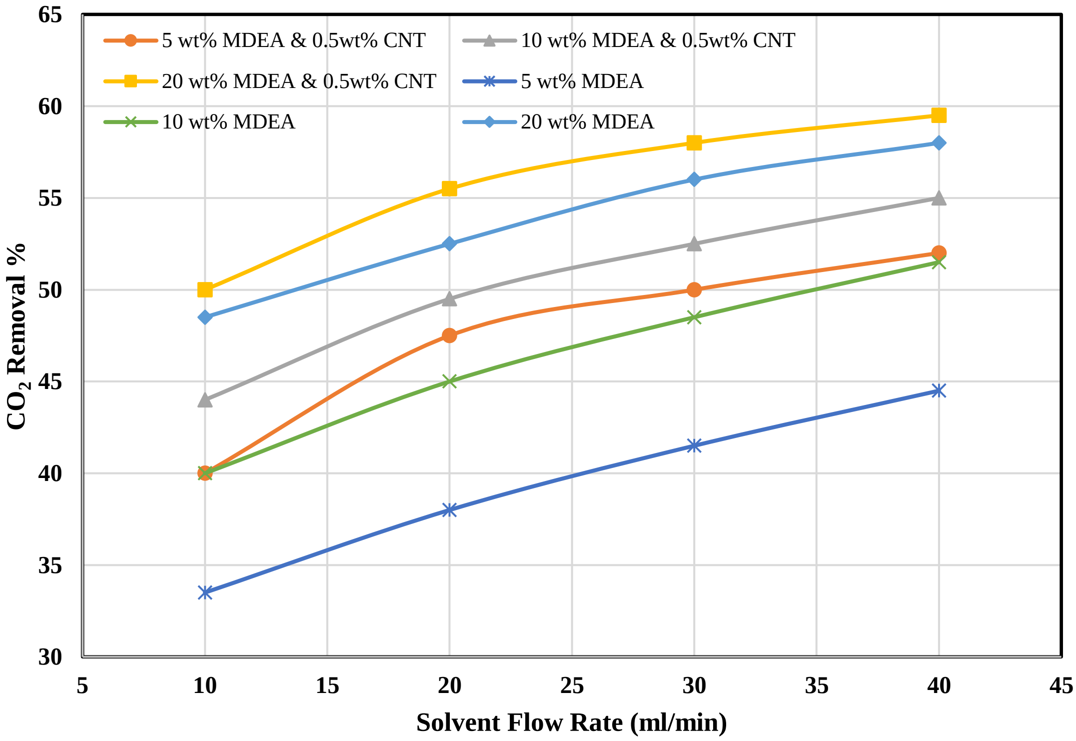

Figure 35: CO_2 removal % versus solvent flow rate for different MDEA concentration with & without 0.5 wt% of dispersed CNTs at 0.01 gas LPM

3.6 Effect of Mixtures of SiO_2 & CNTs Nanofluids

In this section, both silica nanoparticles & CNTs has been added to DI water at different concentrations and dispersed in order to examine their performance in the hollow fibers for carbon dioxide separation. Figure 36 illustrates a comparison between CO_2 removal conducted by CNT nanofluid and its mixtures with silica nanoparticles at the same concentrations for both. The mixture offered less removal and the difference in CO_2 removal by the mixture and the original CNT nanofluid was increased with increasing the concentration. It was clear that silica nanoparticle added more viscous resistance to the mixture and hence decreased the removal % of CO_2. The behavior of such a mixture was also studied by fixing the concentration of CNT at 0.5 wt% and varying SiO_2 nanoparticles concentration. As it can be seen in Figure 37, when the concentration of silica nanoparticles increased, the removal percentage of carbon dioxide decreased. Some previous studies demonstrated that viscosity of distillated water is usually less than nanofluids [118], [119]. Mass transfer resistance in the liquid phase can increase when the viscosity increases and it subsequently effects the absorption negatively [11]. In addition, an increase in the nanoparticles concentration might impact the stability of the nanofluid and agglomeration of nanoparticles could take place. Accordingly, the mass transfer surface on the nanoparticles will be diminished. Furthermore, the movement of nanoparticles will be hindered in the nanofluid by adjacent nanoparticles. As a result, nanofluid absorption capacity and rate will decrease [12], [82], [85], [89]. However, beside all that, removing mixtures of SiO_2 and CNT nanolfuids from the liquid path in the experimental set-up was much easier than single CNT nanofluid where less amount of DI water was required and with much lower flow rate.

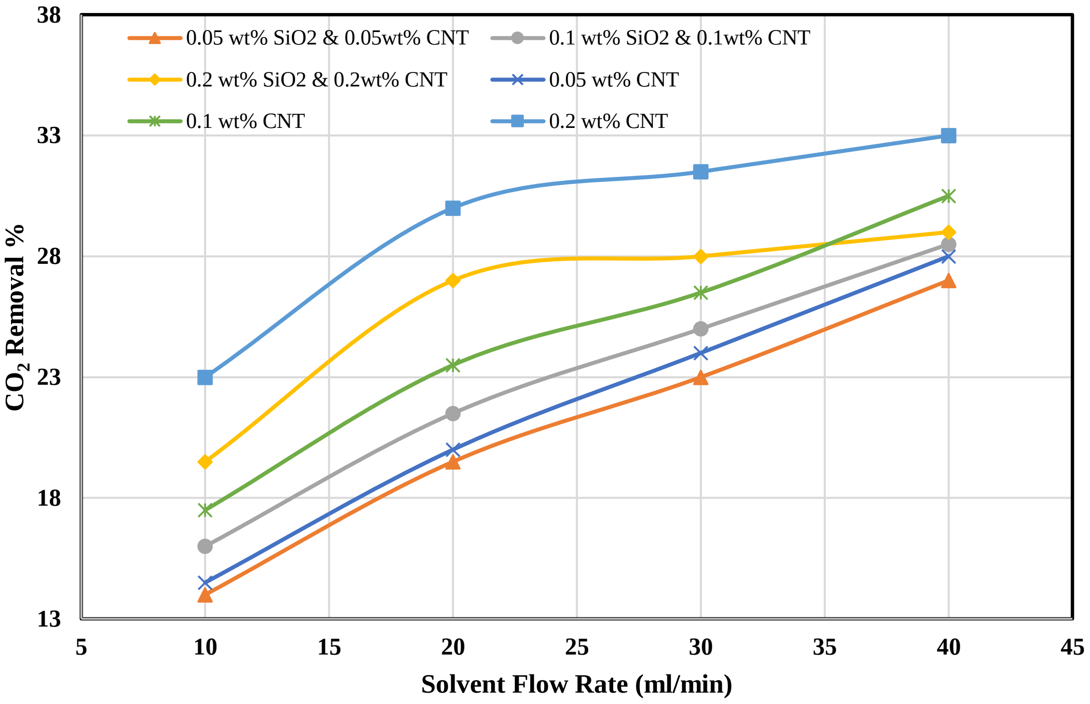

Figure 36: CO_2 removal % versus solvent flow rate for different concentrations of nanosilica + CNTs nanofluids at 0.01 gas LPM

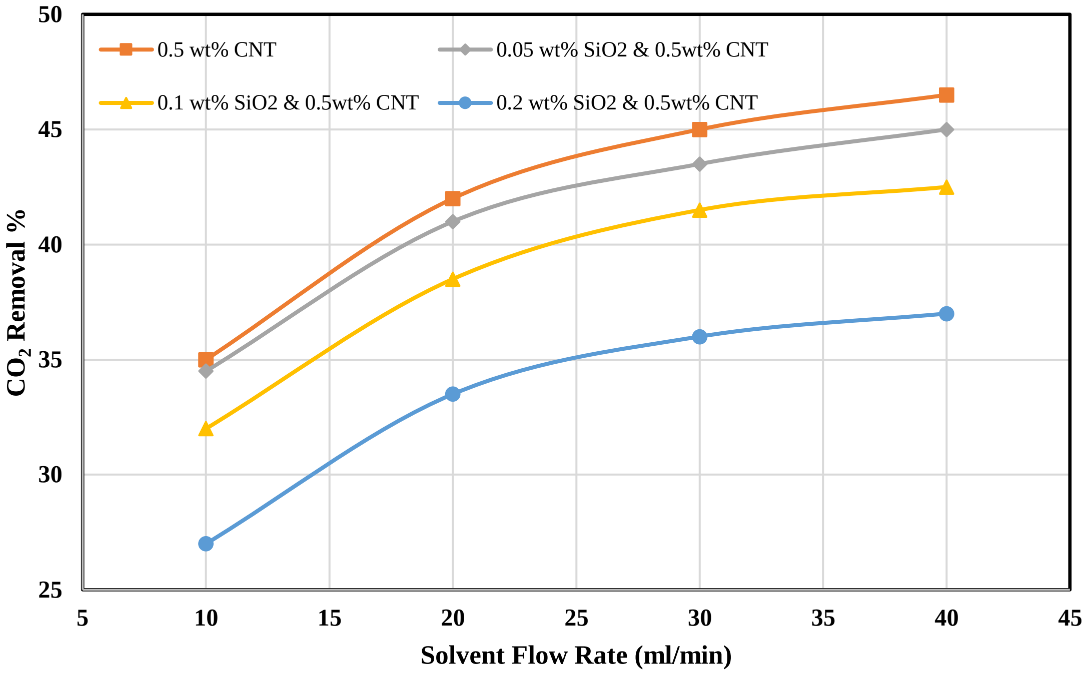

Figure 37: CO_2 removal % versus solvent flow rate for 0.5 wt% CNTs & different nanosilica concentration dispersed in DI water at 0.01 gas LPM

At the end, it is worth mentioning here that absorption flux and/or removal % for all amine solutions and nanofluids increased at low liquid flow rate whereas moved toward stationary as the liquid flow rate went up (values of CO_2 removal % and absorption flux are listed in tables in the appendix). At low liquid flow rate conditions, the driving force is reduced as the solution loading rapidly rises. However, in the case of high liquid flow rate, the solution loading will not increase considerably which consequently leads later to fixed driving force and hence stable CO_2 removal % and absorption flux [5], [120].

3.7 Comparison with Literature

In Gokhar et al. [11] work, nanofluids of nanosilica and carbon nanotube were applied in a gas-liquid hollow fiber membrane contactor where the fibers were made of polypropylene (Purchased from Parsian Pooya Polymer Company (Iran)). The gas was passed through the shell-side and the liquid flowed co-currently through the lumen side of the hollow fibers. The operation pressure was atmospheric, the temperature was 303 K, gas flow rate was 16 l/hr, CO_2 inlet concentration was 40 wt% in nitrogen and the liquid flow rate was varied between around 5 l/hr and before 40 l/hr. The characteristics of the membrane module, SiO_2 nanoparticles and CNTs are listed in Tables 6, 7 & 8, respectively.

Table 6: Characteristics of PP hollow fiber membrane contactor

Length of Fiber, cm	40
Number of Fibers	400
Inner Diameter, mm	0.32
Outer Diameter, mm	0.45
Average Pore Size, nm	150
Membrane Contact Area, m^2	0.16
Module Inner Diameter, cm	2

Table 7: Silica nanoparticles specifications

Morphology	Spherical
Average Particles Size	10-15 nm
Specific Surface Area	180–270 m^2/g
Pore Volume	0.549 cm/g
Average Pore Size	110.13 A°
True Density	2.2 g/cm^3

Table 8: Multi wall carbon nanotubes specifications

Outer Diameter	8 nm
Inside Diameter	2-5 nm
Purity	>95 wt%
Length	10 um
Specific Surface Area	500 m^2/g
True density	~2.1 g/cm^3

The outcomes of their work showed that, when it compared to distillated water, 0.5 wt% of CNT nanofluid enhanced the removal efficiency up to 20% at high liquid flow rate while it increased to 40% at low one. On the other hand, SiO_2 nanofluid improved the efficiency by 9% and 20% at high and low liquid flow rates respectively. In contrast, in this current work, injection of 0.5 wt% CNT nanofluid increased the CO_2 removal efficiency (compared to DI water) by an average value around 22.86% over the four specified liquid flow rates. Unfortunately, almost no enhancement has been observed in the case where silica nanofluid was used as absorbent at its two particular concentrations 0.5 wt% and 1 wt%.

Chapter 4: Conclusion

The serious matter of carbon dioxide contribution to global warming, requires the need of accomplishing an effective technology for CO_2 separation. Here the issue has been introduced and discussed. Brief explanation of carbon dioxide capture modes and some main physical and chemical processes for CO_2 separation with a focus on membrane technology and the absorbents which could be efficient were presented as well.

In the present work, various types of single and blends of aqueous amine solutions and nanofluids were applied in PVDF hollow fiber membrane contactors to investigate carbon dioxide separation from nitrogen. The PVDF hollow fibers were fabricated first and then a whole gas-liquid membrane contactor module and experimental set-up for the absorption process were constructed and prepared in the lab. Aqueous amine solutions were prepared simply by magnetic stirrer while nanopowders of SiO_2 and CNTs were dispersed in DI water by utilizing high intensity ultrasonic liquid processor for one hour for each sample to prepare nanofluids. The gas mixture of carbon dioxide 20 vol.% and nitrogen 80 vol.% and the prepared liquid solvents flew through the shell and tube sides of the gas-liquid membrane module, respectively. There were always four different liquid flow rates (10, 20, 30 & 40 ml/min) used for each experimental run. CO_2 absorption process by DI water was conducted at the beginning in order to be used as a reference. The experiments were carried out under atmospheric pressure and at ambient temperature. The effects of different parameters on CO_2 removal such as amine concentration, types of amines and nanoparticles and gas and liquid flow rates were visualized and studied in the prepared module.

In general, the results revealed that CO_2 removal % was increasing as the solvent flow rate increased and decreased as the gas flow rate increased. Amines solutions of MEA, DEA, MDEA, AMP, EDA & DETA at 5 wt% in DI water were compared with each other for their CO_2 absorption performance and EDA and DETA were found to achieve the highest removal %. In addition, fixed 5 wt% of activator amines (PZ or PZEA) was added to 5, 10 & 20 wt% of each of the six specified amine solutions and their absorption behaviors were investigated. As an overall trend, adding 5 wt% of PZ or PZEA to 5 wt% of any of the amines solutions was increased CO_2 removal efficiency. However, increasing the amine concentration in the same blend to 10 or 20 wt% was decreasing the efficiency of the removal with some exceptions. It was observed that blends of DETA and activator amine aqueous solutions offered the best results especially at low amine concentration. Besides that, the effect of SiO_2 nanoparticles and carbon nanotubes dispersed in DI water at different concentrations and their mixtures together and with MDEA solution was examined at very low gas flow rate. The effect of silica nanofluid was negligible while a considerable enhancement in CO_2 absorption was carried out by using 0.5 wt% of CNT nanofluid. Furthermore, dispersing CNTs in MDEA aqueous solution improved the mass transfer for carbon dioxide absorption in contrast to single MDEA aqueous solution. Nanofluids prepared by dispersing a mixture of CNTs and silica nanoparticles in DI water were offering less removal % of CO_2 than pure CNT nanofluid and the removal percentage was decreased when increasing SiO_2 nanoparticles concentration in the mixture. Anyway, a lower volume of DI water with a slow flow rate was required to eliminate a mixture of SiO_2 and CNT nanofluids from the liquid path in the experimental set-up.

Eventually, here are some suggested ideas which are recommended for future researches based on employing nanofluids in HFMC.

1) Application of PTFE and PFA hollow fibers membranes.
2) Usage of other types of nanoparticles like A_2O_3, Fe_3O_4, TiO_2 and MgO with different particles size.
3) Working on a more variety of amine solutions + nanofluids blends as absorbents.
4) Investigating the effects of pressure, temperature and gas flow rates and concentrations.
5) Conducting the absorption process for longer periods of time in order to examine membrane wetting and fouling.
6) Addition of a stripping unit to the experimental set-up and studying regeneration of the nanofluids.

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Appendix

Table 9: Results based on using DI water and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	19.7	0.008056	0.00403	1.5
20	19.6	0.008015	0.00537	2
30	19.5	0.007974	0.00671	2.5
40	19.4	0.007933	0.00806	3

Table 10: Results based on using 5 wt% DEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	16.6	0.0067882	0.04565	17
20	16.1	0.0065838	0.05236	19.5
30	15.8	0.0064611	0.05639	21
40	15.6	0.0063793	0.05907	22

Table 11: Results based on using 5 wt% DEA and 0.2 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	18.3	0.0074834	0.04565	8.5
20	18.1	0.0074016	0.05102	9.5
30	17.9	0.0073199	0.05639	10.5
40	17.8	0.0072790	0.05907	11

Table 12: Results based on using 5 wt% DEA and 0.3 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	18.9	0.0077288	0.04430	5.5
20	18.8	0.0076879	0.04833	6
30	18.6	0.0076061	0.05639	7
40	18.5	0.0075652	0.06041	7.5

Table 13: Results based on using 5 wt% DEA and 0.4 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	19.2	0.0078515	0.04296	4
20	19.1	0.0078106	0.04833	4.5
30	19	0.0077697	0.05370	5
40	18.9	0.0077288	0.05907	5.5

Table 14: Results based on using 10 wt% DEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	15.1	0.0061748	0.06578	24.5
20	14.7	0.0060113	0.07115	26.5
30	14.4	0.0058886	0.07518	28
40	14.1	0.0057659	0.07921	29.5

Table 15: Results based on using 10 wt% DEA and 0.2 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	17.5	0.0071563	0.06713	12.5
20	17.3	0.0070745	0.07250	13.5
30	17.1	0.0069927	0.07787	14.5
40	16.9	0.0069109	0.08324	15.5

Table 16: Results based on using 10 wt% DEA and 0.3 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	18.4	0.0075243	0.06444	8
20	18.2	0.0074425	0.07250	9
30	18.1	0.0074016	0.07652	9.5
40	18	0.0073607	0.08055	10

Table 17: Results based on using 10 wt% DEA and 0.4 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	18.9	0.0077288	0.05907	5.5
20	18.7	0.0076470	0.06981	6.5
30	18.6	0.0076061	0.07518	7
40	18.5	0.0075652	0.08055	7.5

Table 18: Results based on using 20 wt% DEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	13.4	0.00548	0.08861	33
20	12.8	0.005234	0.09666	36
30	12.3	0.00503	0.10337	38.5
40	11.9	0.004866	0.10874	40.5

Table 19: Results based on using 20 wt% DEA and 0.2 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	16.3	0.0066656	0.09935	18.5
20	16	0.0065429	0.10740	20
30	15.7	0.0064202	0.11546	21.5
40	15.6	0.0063793	0.11814	22

Table 20: Results based on using 20 wt% DEA and 0.3 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	17.5	0.007156	0.10069	12.5
20	17.2	0.007034	0.11277	14
30	17.1	0.006993	0.11680	14.5
40	17	0.006952	0.12083	15

Table 21: Results based on using 20 wt% DEA and 0.4 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	18.1	0.007402	0.10203	9.5
20	17.9	0.00732	0.11277	10.5
30	17.8	0.007279	0.11814	11
40	17.7	0.007238	0.12351	11.5

Table 22: Results based on using 5 wt% DEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	9.9	0.0040484	0.13560	50.5
20	8.2	0.0033532	0.15842	59
30	7.3	0.0029852	0.17050	63.5
40	6.6	0.0026989	0.17990	67

Table 23: Results based on using 10 wt% DEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	9.4	0.003844	0.14231	53
20	7.9	0.003231	0.16245	60.5
30	7.2	0.002944	0.17184	64
40	6.8	0.002781	0.17721	66

Table 24: Results based on using 20 wt% DEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	10.2	0.0041711	0.13157	49
20	9	0.0036803	0.14768	55
30	8.4	0.0034350	0.15573	58
40	8	0.0032714	0.16110	60

Table 25: Results based on using 5 wt% DEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	12	0.004907	0.10740	40
20	10.6	0.004335	0.12620	47
30	9.8	0.004008	0.13694	51
40	9.3	0.003803	0.14365	53.5

Table 26: Results based on using 10 wt% DEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	11.4	0.004662	0.11546	43
20	10.2	0.004171	0.13157	49
30	9.5	0.003885	0.14097	52.5
40	8.9	0.00364	0.14902	55.5

Table 27: Results based on using 20 wt% DEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	10.9	0.004457	0.12217	45.5
20	9.9	0.004048	0.13560	50.5
30	9.4	0.003844	0.14231	53
40	8.9	0.00364	0.14902	55.5

Table 28: Results based on using 5 wt% MEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	12.9	0.005275	0.09532	35.5
20	11.3	0.004621	0.11680	43.5
30	10.5	0.004294	0.12754	47.5
40	10	0.004089	0.13425	50

Table 29: Results based on using 10 wt% MEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	11.1	0.004539	0.11948	44.5
20	10.2	0.004171	0.13157	49
30	9.7	0.003967	0.13828	51.5
40	9.3	0.003803	0.14365	53.5

Table 30: Results based on using 20 wt% MEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.3	0.0042120	0.13022	48.5
20	9.6	0.0039257	0.13962	52
30	9.3	0.0038030	0.14365	53.5
40	9	0.0036803	0.14768	55

Table 31: Results based on using 5 wt% MEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	8.8	0.003599	0.15036	56
20	7.3	0.002985	0.17050	63.5
30	6.6	0.002699	0.17990	67
40	6.2	0.002535	0.18527	69

Table 32: Results based on using 10 wt% MEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	9.4	0.003844	0.14231	53
20	8.3	0.003394	0.15708	58.5
30	7.8	0.00319	0.16379	61
40	7.4	0.003026	0.16916	63

Table 33: Results based on using 20 wt% MEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.1	0.0041302	0.13291	49.5
20	9.4	0.0038439	0.14231	53
30	9.1	0.0037212	0.14634	54.5
40	8.8	0.0035986	0.15036	56

Table 34: Results based on using 5 wt% MEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.4	0.004253	0.12888	48
20	9.3	0.003803	0.14365	53.5
30	8.6	0.003517	0.15305	57
40	8.1	0.003312	0.15976	59.5

Table 35: Results based on using 10 wt% MEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.6	0.004335	0.12620	47
20	9.6	0.003926	0.13962	52
30	9.1	0.003721	0.14634	54.5
40	8.8	0.003599	0.15036	56

Table 36: Results based on using 20 wt% MEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	11	0.004498	0.12083	45
20	10.4	0.004253	0.12888	48
30	10	0.004089	0.13425	50
40	9.8	0.004008	0.13694	51

Table 37: Results based on using 5 wt% MDEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	19.2	0.007852	0.01074	4
20	19.1	0.007811	0.01208	4.5
30	19.1	0.007811	0.01208	4.5
40	19	0.00777	0.01343	5

Table 38: Results based on using 10 wt% MDEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	19.1	0.007811	0.01208	4.5
20	19	0.00777	0.01343	5
30	18.9	0.007729	0.01477	5.5
40	18.8	0.007688	0.01611	6

Table 39: Results based on using 20 wt% MDEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	19	0.0077697	0.01343	5
20	18.9	0.0077288	0.01477	5.5
30	18.8	0.0076879	0.01611	6
40	18.8	0.0076879	0.01611	6

Table 40: Results based on using 5 wt% MDEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.4	0.004253	0.12888	48
20	8.6	0.003517	0.15305	57
30	7.6	0.003108	0.16647	62
40	7.1	0.002903	0.17319	64.5

Table 41: Results based on using 10 wt% MDEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.6	0.004335	0.12620	47
20	9.1	0.003721	0.14634	54.5
30	8.3	0.003394	0.15708	58.5
40	7.8	0.00319	0.16379	61

Table 42: Results based on using 20 wt% MDEA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	11.9	0.004866	0.10874	40.5
20	10.8	0.004416	0.12351	46
30	10.4	0.004253	0.12888	48
40	10.2	0.004171	0.13157	49

Table 43: Results based on using 5 wt% MDEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	12.7	0.005193	0.09800	36.5
20	11.3	0.004621	0.11680	43.5
30	10.5	0.004294	0.12754	47.5
40	9.9	0.004048	0.13560	50.5

Table 44: Results based on using 10 wt% MDEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	12.9	0.005275	0.09532	35.5
20	11.7	0.004785	0.11143	41.5
30	10.9	0.004457	0.12217	45.5
40	10.3	0.004212	0.13022	48.5

Table 45: Results based on using 20 wt% MDEA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	13.8	0.005643	0.08324	31
20	12.8	0.005234	0.09666	36
30	12.2	0.004989	0.10472	39
40	11.9	0.004866	0.10874	40.5

Table 46: Results based on using 5 wt% DETA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.9	0.004457	0.12217	45.5
20	9.6	0.003926	0.13962	52
30	8.9	0.00364	0.14902	55.5
40	8.4	0.003435	0.15573	58

Table 47: Results based on using 10 wt% DETA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	8.3	0.003394	0.15708	58.5
20	7.1	0.002903	0.17319	64.5
30	6.2	0.002535	0.18527	69
40	5.7	0.002331	0.19198	71.5

Table 48: Results based on using 20 wt% DETA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	6.2	0.0025353	0.18527	69
20	5.6	0.0022900	0.19332	72
30	5.1	0.0020855	0.20004	74.5
40	4.8	0.0019628	0.20406	76

Table 49: Results based on using 5 wt% DETA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	6.7	0.00274	0.17856	66.5
20	5.3	0.002167	0.19735	73.5
30	4.7	0.001922	0.20541	76.5
40	4.4	0.001799	0.20943	78

Table 50: Results based on using 10 wt% DETA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	5.9	0.002413	0.18930	70.5
20	5.1	0.002086	0.20004	74.5
30	4.8	0.001963	0.20406	76
40	4.6	0.001881	0.20675	77

Table 51: Results based on using 20 wt% DETA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	7.4	0.003026	0.16916	63
20	6.7	0.00274	0.17856	66.5
30	6.5	0.002658	0.18124	67.5
40	6.2	0.002535	0.18527	69

Table 52: Results based on using 5 wt% DETA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	9.3	0.003803	0.14365	53.5
20	8	0.003271	0.16110	60
30	7.2	0.002944	0.17184	64
40	6.7	0.00274	0.17856	66.5

Table 53: Results based on using 10 wt% DETA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	7.8	0.00319	0.16379	61
20	6.7	0.00274	0.17856	66.5
30	6	0.002454	0.18795	70
40	5.7	0.002331	0.19198	71.5

Table 54: Results based on using 20 wt% DETA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	6.5	0.002658	0.18124	67.5
20	5.7	0.002331	0.19198	71.5
30	5.6	0.00229	0.19332	72
40	5.6	0.00229	0.19332	72

Table 55: Results based on using 5 wt% EDA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	9.4	0.003844	0.14231	53
20	8.4	0.003435	0.15573	58
30	8	0.003271	0.16110	60
40	7.8	0.00319	0.16379	61

Table 56: Results based on using 10 wt% EDA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	6	0.002454	0.18795	70
20	5.4	0.002208	0.19601	73
30	5.2	0.002126	0.19869	74
40	5.1	0.002086	0.20004	74.5

Table 57: Results based on using 20 wt% EDA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	5.7	0.0023309	0.19198	71.5
20	5.1	0.0020855	0.20004	74.5
30	5	0.0020446	0.20138	75
40	5	0.0020446	0.20138	75

Table 58: Results based on using 5 wt% EDA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	8.3	0.003394	0.15708	58.5
20	7.3	0.002985	0.17050	63.5
30	6.9	0.002822	0.17587	65.5
40	6.7	0.00274	0.17856	66.5

Table 59: Results based on using 10 wt% EDA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	8.2	0.003353	0.15842	59
20	7.4	0.003026	0.16916	63
30	7.1	0.002903	0.17319	64.5
40	6.9	0.002822	0.17587	65.5

Table 60: Results based on using 20 wt% EDA & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	9.2	0.003762	0.14499	54
20	8.7	0.003558	0.15171	56.5
30	8.5	0.003476	0.15439	57.5
40	8.3	0.003394	0.15708	58.5

Table 61: Results based on using 5 wt% EDA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	10.1	0.00413	0.13291	49.5
20	9	0.00368	0.14768	55
30	8.5	0.003476	0.15439	57.5
40	8.1	0.003312	0.15976	59.5

Table 62: Results based on using 10 wt% EDA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	9.1	0.003721	0.14634	54.5
20	8.4	0.003435	0.15573	58
30	8.1	0.003312	0.15976	59.5
40	7.9	0.003231	0.16245	60.5

Table 63: Results based on using 20 wt% EDA & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	9.8	0.004008	0.13694	51
20	9.3	0.003803	0.14365	53.5
30	9.1	0.003721	0.14634	54.5
40	8.9	0.00364	0.14902	55.5

Table 64: Results based on using 5 wt% AMP and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	16.4	0.006707	0.04833	18
20	15.6	0.006379	0.05907	22
30	15.3	0.006257	0.06310	23.5
40	15	0.006134	0.06713	25

Table 65: Results based on using 10 wt% AMP and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	14.9	0.006093	0.06847	25.5
20	14.2	0.005807	0.07787	29
30	13.9	0.005684	0.08189	30.5
40	13.8	0.005643	0.08324	31

Table 66: Results based on using 20 wt% AMP and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	16.1	0.0065838	0.05236	19.5
20	15.8	0.0064611	0.05639	21
30	15.7	0.0064202	0.05773	21.5
40	15.6	0.0063793	0.05907	22

Table 67: Results based on using 5 wt% AMP & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	9.4	0.003844	0.14231	53
20	8	0.003271	0.16110	60
30	7.4	0.003026	0.16916	63
40	7.1	0.002903	0.17319	64.5

Table 68: Results based on using 10 wt% AMP & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.3	0.004212	0.13022	48.5
20	9.5	0.003885	0.14097	52.5
30	9.2	0.003762	0.14499	54
40	9.1	0.003721	0.14634	54.5

Table 69: Results based on using 20 wt% AMP & 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	14.8	0.006052	0.06981	26
20	14.5	0.005930	0.07384	27.5
30	14.4	0.005889	0.07518	28
40	14.3	0.005848	0.07652	28.5

Table 70: Results based on using 5 wt% AMP & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	11.7	0.004785	0.11143	41.5
20	10.2	0.004171	0.13157	49
30	9.3	0.003803	0.14365	53.5
40	8.8	0.003599	0.15036	56

Table 71: Results based on using 10 wt% AMP & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	12.2	0.004989	0.10472	39
20	11.4	0.004662	0.11546	43
30	11.1	0.004539	0.11948	44.5
40	11	0.004498	0.12083	45

Table 72: Results based on using 20 wt% AMP & 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	15.8	0.006461	0.05639	21
20	15.3	0.006257	0.06310	23.5
30	15	0.006134	0.06713	25
40	14.8	0.006052	0.06981	26

Table 73: Results based on using 5 wt% PZ and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	11.4	0.004662	0.11546	43
20	9.4	0.003844	0.14231	53
30	8.2	0.003353	0.15842	59
40	7.4	0.003026	0.16916	63

Table 74: Results based on using 5 wt% PZEA and 0.1 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	13.4	0.0054797	0.08861	33
20	11.6	0.0047436	0.11277	42
30	10.7	0.0043755	0.12485	46.5
40	10	0.0040893	0.13425	50

Table 75: Results based on using DI water and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	17.5	0.007156	0.00336	12.5
20	16.5	0.006747	0.00470	17.5
30	15.7	0.00642	0.00577	21.5
40	14.9	0.006093	0.00685	25.5

Table 76: Results based on using 5 wt% DEA and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	1	0.000409	0.02551	95
20	0.6	0.000245	0.02604	97
30	0.6	0.000245	0.02604	97
40	0.5	0.000204	0.02618	97.5

Table 77: Results based on using 5 wt% MEA and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	0.5	0.000204	0.02618	97.5
20	0.4	0.000164	0.02631	98
30	0.3	0.000123	0.02645	98.5
40	0.3	0.000123	0.02645	98.5

Table 78: Results based on using 5 wt% DETA and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	0.3	0.000123	0.02645	98.5
20	0.2	8.18E-05	0.02658	99
30	0.1	4.09E-05	0.02672	99.5
40	0.1	4.09E-05	0.02672	99.5

Table 79: Results based on using 5 wt% EDA and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	0.2	8.18E-05	0.02658	99
20	0.2	8.18E-05	0.02658	99
30	0.1	4.09E-05	0.02672	99.5
40	0.1	4.09E-05	0.02672	99.5

Table 80: Results based on using 5 wt% AMP and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	0.8	0.000327	0.02578	96
20	0.5	0.000204	0.02618	97.5
30	0.4	0.000164	0.02631	98
40	0.4	0.000164	0.02631	98

Table 81: Results based on using 5 wt% MDEA and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	13.3	0.005439	0.00899	33.5
20	12.4	0.005071	0.01020	38
30	11.7	0.004785	0.01114	41.5
40	11.1	0.004539	0.01195	44.5

Table 82: Results based on using 10 wt% MDEA and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	12	0.0049071	0.01074	40
20	11	0.0044982	0.01208	45
30	10.3	0.0042120	0.01302	48.5
40	9.7	0.0039666	0.01383	51.5

Table 83: Results based on using 20 wt% MDEA and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	10.3	0.0042120	0.141666	48.5
20	9.5	0.0038848	0.15335	52.5
30	8.8	0.0035986	0.163573	56
40	8.4	0.0034350	0.169415	58

Table 84: Results based on using 5 wt% PZ and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	0.4	0.000164	0.02631	98
20	0.2	8.18E-05	0.02658	99
30	0.1	4.09E-05	0.02672	99.5
40	0.1	4.09E-05	0.02672	99.5

Table 85: Results based on using 5 wt% PZEA and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	0.6	0.000245	0.02604	97
20	0.5	0.000204	0.02618	97.5
30	0.4	0.000164	0.02631	98
40	0.3	0.000123	0.02645	98.5

Table 86: Results based on using 0.5 wt% nanosilica and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	17.2	0.0070336	0.00376	14
20	16.2	0.0066247	0.00510	19
30	15.5	0.0063384	0.00604	22.5
40	14.7	0.0060113	0.00712	26.5

Table 87: Results based on using 1 wt% nanosilica and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	16.9	0.0069109	0.00416	15.5
20	16	0.0065429	0.00537	20
30	15.2	0.0062157	0.00644	24
40	14.5	0.0059295	0.00738	27.5

Table 88: Results based on using 0.05 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	17.1	0.006993	0.00389	14.5
20	16	0.006543	0.00537	20
30	15.2	0.006216	0.00644	24
40	14.4	0.005889	0.00752	28

Table 89: Results based on using 0.1 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	16.5	0.006747	0.00470	17.5
20	15.3	0.006257	0.00631	23.5
30	14.7	0.006011	0.00712	26.5
40	13.9	0.005684	0.00819	30.5

Table 90: Results based on using 0.2 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	15.4	0.006298	0.00618	23
20	14	0.005725	0.00806	30
30	13.7	0.005602	0.00846	31.5
40	13.4	0.005480	0.00886	33

Table 91: Results based on using 0.5 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	13	0.005316	0.00940	35
20	11.6	0.004744	0.01128	42
30	11	0.004498	0.01208	45
40	10.7	0.004376	0.01249	46.5

Table 92: Results based on using 5 wt% MDEA + 0.5 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	12	0.004907	0.01074	40
20	10.5	0.004294	0.01275	47.5
30	10	0.004089	0.01343	50
40	9.6	0.003926	0.01396	52

Table 93: Results based on using 10 wt% MDEA + 0.5 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	11.2	0.004580	0.01181	44
20	10.1	0.004130	0.01329	49.5
30	9.5	0.003885	0.01410	52.5
40	9	0.003680	0.01477	55

Table 94: Results based on using 20 wt% MDEA + 0.5 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	10	0.004089	0.01343	50
20	8.9	0.003640	0.01490	55.5
30	8.4	0.003435	0.01557	58
40	8.1	0.003312	0.01598	59.5

Table 95: Results based on using 0.05 wt% nanosilica + 0.05 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m^2 min))	Removal %
10	17.2	0.007034	0.00376	14
20	16.1	0.006584	0.00524	19.5
30	15.4	0.006298	0.00618	23
40	14.6	0.00597	0.00725	27

Table 96: Results based on using 0.1 wt% nanosilica + 0.1 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	16.8	0.00687	0.00430	16
20	15.7	0.00642	0.00577	21.5
30	15	0.006134	0.00671	25
40	14.3	0.005848	0.00765	28.5

Table 97: Results based on using 0.2 wt% nanosilica + 0.2 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	16.1	0.006584	0.00524	19.5
20	14.6	0.00597	0.00725	27
30	14.4	0.005889	0.00752	28
40	14.2	0.005807	0.00779	29

Table 98: Results based on using 0.05 wt% nanosilica + 0.5 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	13.1	0.005357	0.00926	34.5
20	11.8	0.004825	0.01101	41
30	11.3	0.004621	0.01168	43.5
40	11	0.004498	0.01208	45

Table 99: Results based on using 0.1 wt% nanosilica + 0.5 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	13.6	0.005561	0.00859	32
20	12.3	0.00503	0.01034	38.5
30	11.7	0.004785	0.01114	41.5
40	11.5	0.004703	0.01141	42.5

Table 100: Results based on using 0.2 wt% nanosilica + 0.5 wt% CNT and 0.01 gas (LPM)

Liquid (ml/min)	CO_2 outlet conc. (mol %)	C out (mol/l)	flux (mol/(m² min))	Removal %
10	14.6	0.005970	0.00725	27
20	13.3	0.005439	0.00899	33.5
30	12.8	0.005234	0.00967	36
40	12.6	0.005153	0.00993	37