International Journal of Advances in Engineering and Management (IJAEM)
Volume 5, Issue 11 Nov 2023, pp: 113-121 www.ijaem.net ISSN: 2395-5252

CO_2 Capture from Flue Gases by Absorption Using Ionic Liquid

Kerem Un[1], Aslı Gunaydin[2], Umran Tezcan Un[3]
[1, 1]Eskisehir Gelisim Science High School, Eskisehir, Turkey
[2]Eskisehir Gelisim Science High School, Eskisehir, Turkey
[3]Eskisehir Technical University, Faculty of Engineering, Departmant of Environmental Engineering, Eskisehir, Turkey,

Date of Submission: 10-11-2023 Date of Acceptance: 20-11-2023

ABSTRACT: In this study, to evaluate the performance of 1-butyl-3-methylimidazolium acetate ([BMIM][AcO]) as a solvent for CO_2 absorption process in bubble column reactor, the absorption capacity and CO_2 removal efficiency were investigated under different operating conditions, including solvent concentration of 0.05-0.1 M, CO_2 inlet concentration of 10000-30000 ppm, and gas flow rate of 0.5-2 L/min. The results show that when the CO_2 concentration was increased from 10000 to 30000 ppm, the removal efficiency and absorption capacity decreased from 87% to 55% and from 9.8 to 4.8 gCO_2/kg solvent, respectively. The CO_2 removal efficiency increased from 55 to 98% when the gas flow rate was reduced from 2 to 0.5 L/min. Similarly, CO_2 removal was improved by increasing the solvent concentration from 0.05 to 0.1 M. The results of this study show that 1-butyl-3-methylimidazolium acetate ([BMIM][AcO]) can be used as a solvent to remove CO_2 from flue gases with high removal efficiency and absorption capacity.

KEYWORDS: Absorption, Ionic Liquid, CO_2 capture, Global warming

I. INTRODUCTION

Human activity has recently resulted in an increase in the average air temperature, creating an important environmental concern. In order to reduce greenhouse gas emissions and associated adverse impacts, such as acidic rain and global warming, many researchers have carried out experiments. Among the greenhouse gases, carbon dioxide is the primarily responsible for the global warming. Therefore, providing effective CO_2 capture techniques has been recognized as a successful climate change strategy. There are three different approaches applied to capture CO_2: pre-combustion, oxy-fuel combustion, and post-combustion. Post-combustion CO_2 capture, one of these approaches, attracted the most interest due to the advantages it provides, including outstanding efficiency for the separation of CO_2 and low partial pressure of CO_2 in gas stream. Up to date, many post-combustion carbon dioxide capture methods such as absorption [1], adsorption [2], cryogenics [3], and membrane technology [4] have been suggested.

Absorption of CO_2 by physical and chemical absorbents was a common industrial method among the methods applied in post-combustion. Between them, amine solutions were attracted considerable attention by numerous researchers. The amine solutions wildly used for CO_2 absorption are monoethanolamine (MEA) [5, 6], diethanolamine (DEA) [7], methyldiethanolamine (MDEA) [8], 2-amino-2-methyl-1-propanol (AMP) [9], and piperazine (PZ) [10]. The first-generation solvent, such as Monoethanolamine (MEA), has a number of challenges, including a limited capacity to capture CO_2, high volatility, equipment corrosion, and negative environmental effects. Although these alkanolamine-based systems are very effective at capturing acid gas, they have a number of disadvantages, including the uptake of water into the recovered acid gas stream, amine loss during reclamation due to their volatility, and amine degradation by small amounts of sulfur-containing compounds. The usage of the alkanolamines at high concentrations is limited by these issues. A new kind of solvent such as ionic liquids has been used as an acid gas capture reagent in recent research studies. It has been shown that 1-butyl-3-methylimidazolium acetate ([BMIM][AcO]), presents very high ability for the absorption of acid gases [11].

In this work, we focus on the CO_2 absorption performance of the 1-Butyl-3-methylimidazolium Acetate ([BMIM][AcO]. Experiments were carried out using a Bubble column reactor, where the gas is continuously flowing and the liquid is a batch system. The effects

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of initial CO_2 concentration, gas flow rate and ionic liquid concentration on the CO_2 capture performance were determined. The absorption capacity (g CO_2/kg ([BMIM][AcO]) and CO_2 removal efficiency were also calculated.

II. EXPERIMENTAL DETAILS

2.1 Calculation of Absorption Capacity and Removal Efficiency

The total amount of CO_2 absorbed by the solution is calculated by the area above the CO_2-time profile graph. The overall gas flow rate and the inlet concentration of CO_2 allowed us to calculate the CO_2 input flow rate. The CO_2 flow rate at the exit can also be calculated by using the gas flow rate and the measured CO_2 concentration at the effluent gas. The detail of the calculation can be found elsewhere [5].

The CO_2 removal efficiency was determined by the difference between gas concentrations, read by CO_2 analyzer, at the input and the output of bubble column reactor (Eq.1).

$$CO_2 \text{ Removal Efficiency} = \frac{C_i - C_e}{C_i} x100 \qquad (1)$$

where C_i is the CO_2 concentration (ppm) of the inlet gas stream, C_e is the CO_2 concentration (ppm) of the effluent gas stream.

2.2 Materials

In this work, 1-butyl-3-methylimidazolium acetate ([BMIM][AcO]) (Sigma-Aldrich) was used as a solvent. Carbon dioxide CO_2 (> 99.95 %, 150 bar, Oksan Gas, Turkey) and Nitrogen N_2 (> 99.99 %, 200 bar, Oksan Gas, Turkey) were mixed and used to simulate the flue gases. The molecular structure of the [BMIM][AcO] which has molecular weight of 198.26 g/mol is shown in Fig.1. In the experimental studies, the solvent concentration was adjusted to be 0.05, 0.08 and 0.1 Molar with distilled water which obtained by ultrapure water device (Thermoscientific, Germany).

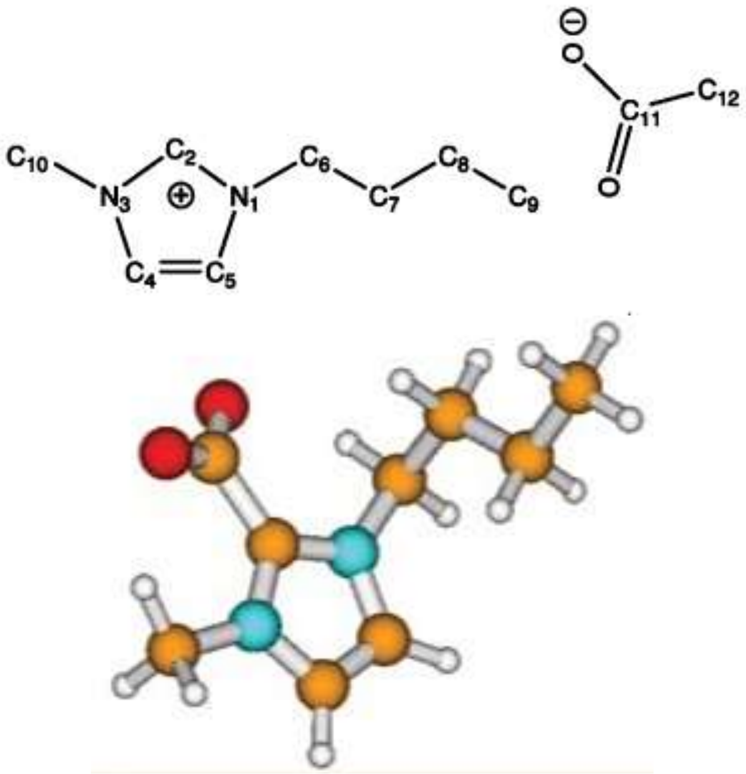

Fig. 1: The molecular structure of the [BMIM][AcO] [12]

2.3 Experimental Set-Up

Bubble column reactor used in this study was a cylindrical vessel with a gas diffuser at the bottom. The gas was dispersed into the liquid phase in the form of bubbles, thus providing high contact areas. Bubble column reactor was preferred over other reactors due to its simple structure, absence of mechanical moving parts, easy use, cost efficiency, high heat and mass transfer rates, and low maintenance requirements. The reactor can be seen from Fig. 2.

The bubble column reactor used in this study was designed and manufactured from plexiglass by a local company. The column is 40 cm high and 5 cm in diameter. To simulate the flue gas, a mixture of CO_2 and N_2 gases was prepared using a

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mass flow controller (MKS Multi Gas Controller 647B, USA). The gas mixture was fed into the solvent through the diffuser placed at the bottom of the reactor. 0.5 L of solvent was pumped into the reactor at the beginning of the experiment and was not changed during the experiment. The gas mixture was continuously fed into the reactor, and the gas flow rate and CO_2 concentration were measured at the inlet and outlet of the reactor via mass flow meters and CO_2 analyzer (Vernier, Labquest 2, USA). The gas mixture leaving the reactor passed through the dehumidifier before entering the CO_2 analyzer. The experimental set up used in the experiments is shown in Figures 3 and 4.

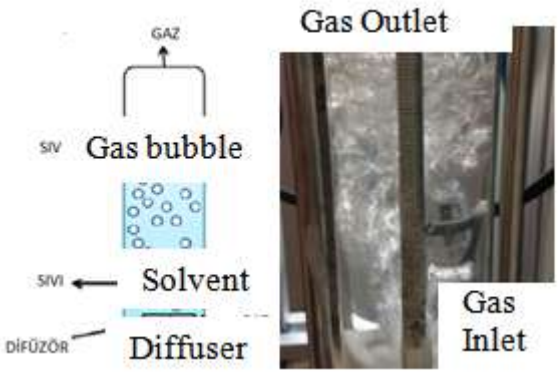

Fig. 2: Bubble column reactor

Fig. 3:Experimental set-up

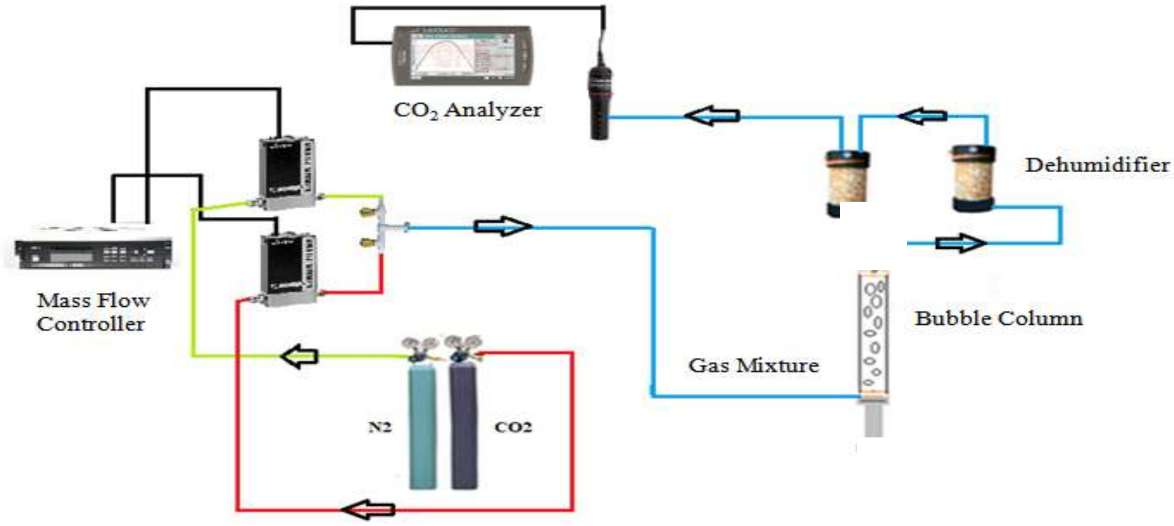

Fig. 4: Flow chart of experimental set-up.

III. RESULTS AND DISCUSSION

3.1 Effect of CO_2 Concentration

The initial CO_2 concentration changes the amount of pollutant loaded into the solvent per unit volume of gas. The change in CO_2 concentration directly affects the CO_2 holding capacity and CO_2 removal efficiency. The effect of CO_2 concentration (C_{CO2}) was search using CO_2 concentrations of 10000 ppm, 20000 ppm and 30000ppm at gas flow rate (G) of 2.0L/min and solvent concentration (**$C_{[bmim][Ac]}$**) of 0.05M. The effects of initial CO_2 concentration on CO_2 effluent concentration, removal efficiency and absorption capacity (g CO_2/g solvent), are given in Figures 5 and 6.

As seen in Figures 5 and 6, CO_2 removal decreased when the initial CO_2 concentration increased from 10000 ppm to 30000 ppm. As the CO_2 concentration increased, the solution reached the saturation in a shorter time and the CO_2 holding capacity was full. The results show consistency when compared with the literature [13, 14].

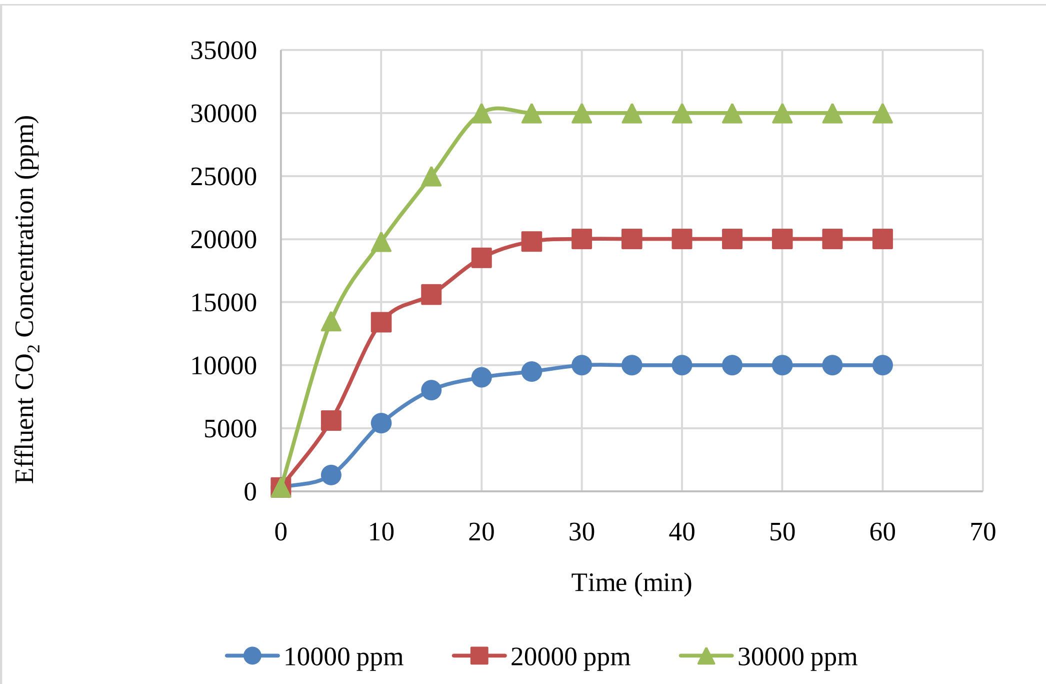

Fig. 5:The changes of effluent CO_2 concentrations with different initial CO_2 concentrations ($C_{[bmim][Ac]}$:0.05 M, G: 2.0 L/min)

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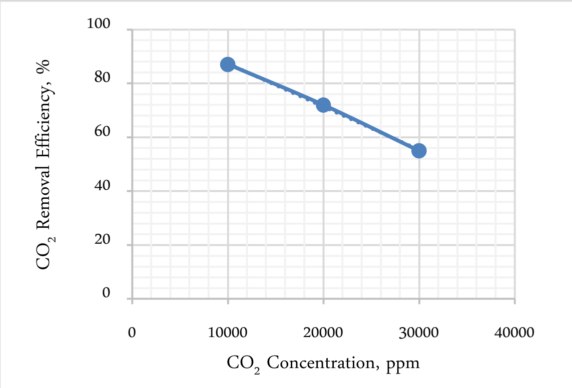
As seen in Fig.6, the CO_2 removal efficiency and absorption capacity decreased with the increase of the CO_2 concentration from 10000 ppm to 30000ppm. The removal efficiency increased from the 55 to 87% when the initial CO_2 concentration decreased from 30000 ppm to 10000 ppm. It is well known in the absorption operation that a lower CO_2 concentration led to a higher CO_2 removal efficiency. The absorption capacity of 9,79 decreased to 4,81 gCO_2/kg solvent with the increase in the CO_2 concentration.



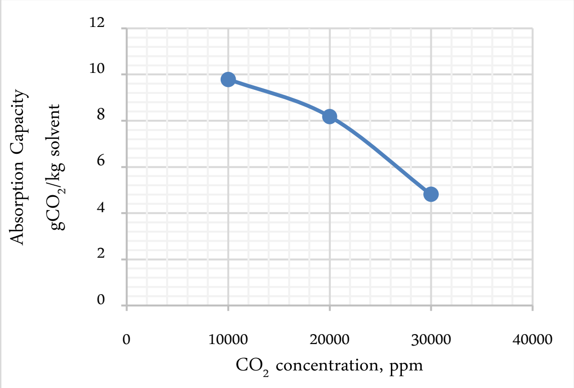


Fig. 6: The effect of initial CO_2 concentration on the absorption capacity and CO_2 removal efficiency

3.2 Effect of Gas Flow Rate

Gas flow rate which conducts with an L/G ratio is an important parameter that affects the CO_2 holding capacity. As the gas flow rate increases, the amount of CO_2 fed to the unit solvent volume per unit time increases. The effect of gas flow rate was searched using three different gas flow rates, 0.5, 1 and 2 L/min at 0.05M solvent concentration and 30000ppm CO_2 concentration. The solvent volume was kept constant as 500mL throughout the experiment, but the feed gas flow rate was increased. The results can be seen from Figures 7 and 8.

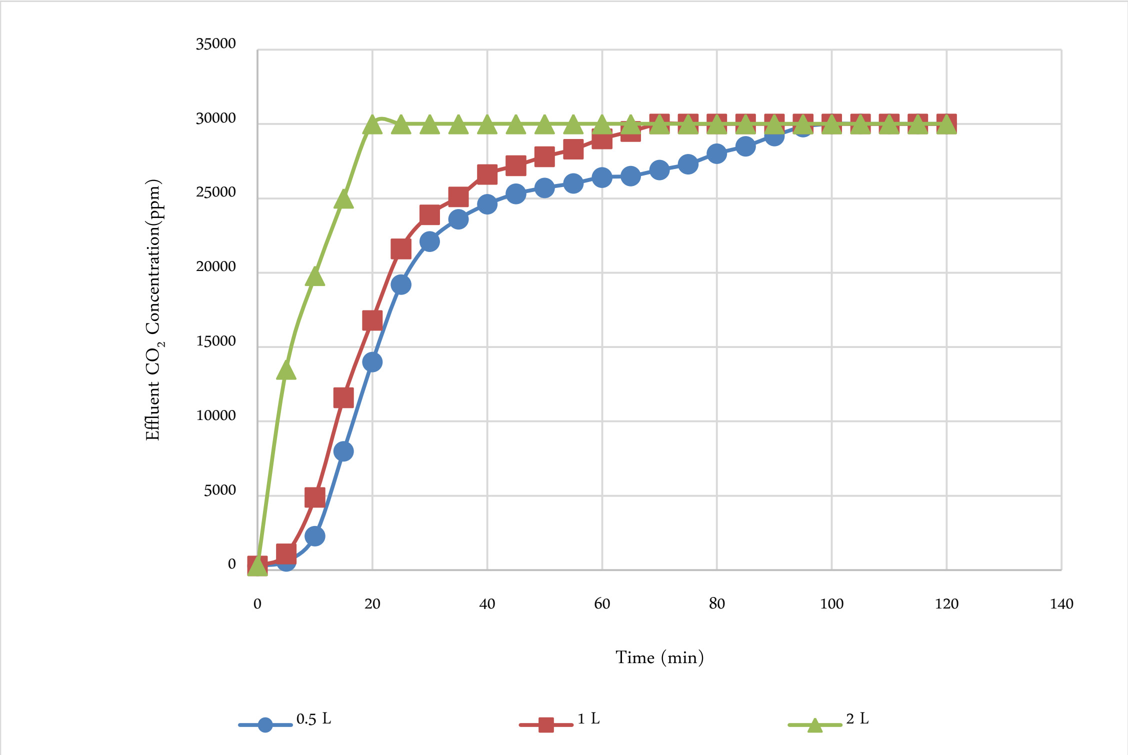


Fig. 7: Effect of gas flow rate on the effluent CO_2 concentration ($C_{[bmim][Ac]}$:0.05 M, C_{CO2}: 30000ppm)

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As can be seen from Fig. 7, the CO_2 holding capacity of the solvent was rapidly consumed with increasing gas flow rate. When the gas with a concentration of 30000 ppm enters the reactor at a rate of 0.5L/min, it took 100 minutes for the run of the CO_2 holding capacity of the solvent out, while the solvent holding capacity was exausted within 20 minutes when it was fed at a rate of 2 L/min.

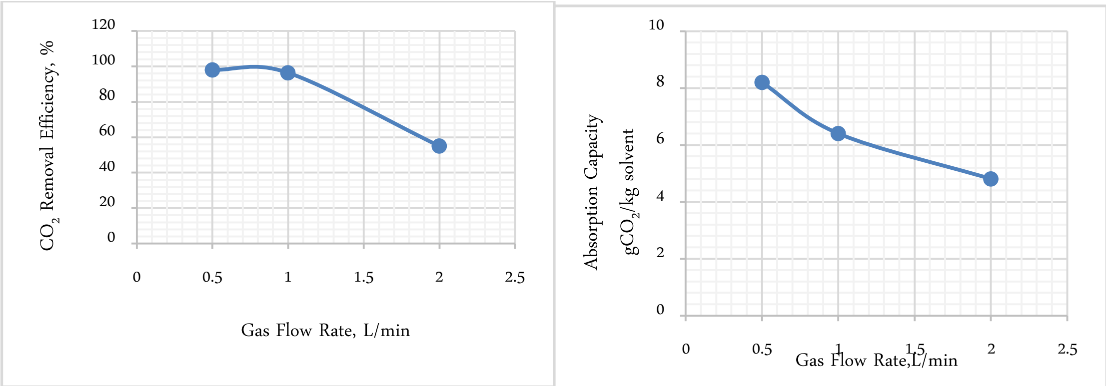

Fig. 8:Effect of gas flow rate on the absorption capacity and effluent CO_2 removal efficiency ($C_{[bmim][Ac]}$:0.05 M, C_{CO2}: 30000ppm)

As seen from Fig. 8, with the increasing gas flow rate, the CO_2 removal efficiency decreased. The removal efficiency increased from 55% to 98% when the gas flow rate decreased from 2 L/min to 0.5 L/min. In general, as the gas flow increases the amount of CO_2 molecules available for the absorption increases which leads to a higher mass transfer flux. Additionally, the gas flow rate determines the detention time of the gas component and effects the mixing regime of the solution. By increasing gas flow rate, the gas-film coefficient increases. This can be explained by the fact that increased gas velocity results in a reduction in film thickness as well as an increase in interfacial turbulence, both of which can improve solute transport from gas to liquid [15]. On the other hand, the amount of CO_2 passed through the system was increased and the contact time between gas and liquid was reduced, these two facts led to negative effects on CO_2 capture efficiency [16]. Therefore, increasing the gas flow rate has a limited influence on the overall mass transfer coefficient [17]. Based on the data obtained in this study, it can be concluded that the negative effects on CO_2 capture efficiency outweighed the positive effects, resulting in a decrease in absorption capacity. A similar trend has been report by Kuntz and Aroonwilas [18]and by Qi et al. [14] for the chemical absorption of CO_2 into MEA solutions.

3.3 Effect of Solvent Concentration

The effect of solvent concentration was searched using three different [BMIM][AcO] concentration at 30000ppm CO_2 concentration and 2 L/min gas flow rate. Results can be seen from Figures 9 and 10.

Concentration of [BMIM][AcO] increases absorption capacity because mass transfer coefficient typically increases as absorbent concentration does. By increasing solvent concentration, a greater amount of active absorbent is available to diffuse towards the gas-liquid interface and react with CO_2. Therefore, increasing the [BMIM][AcO] amount in the solvent increases the chemical reaction. With increasing solvent concentration, CO_2 removal efficiency increases as well. Similar results are also found by the various researchers [19]. The removal efficiency does not double when the solvent concentration double because the relationship between the mass transfer coefficient and the rise in solvent concentration is not totally linear. On the other hand, the viscosity of the solvent is increased by the high solvent concentrations. Therefore, optimization is necessary when determining the solvent concentration.

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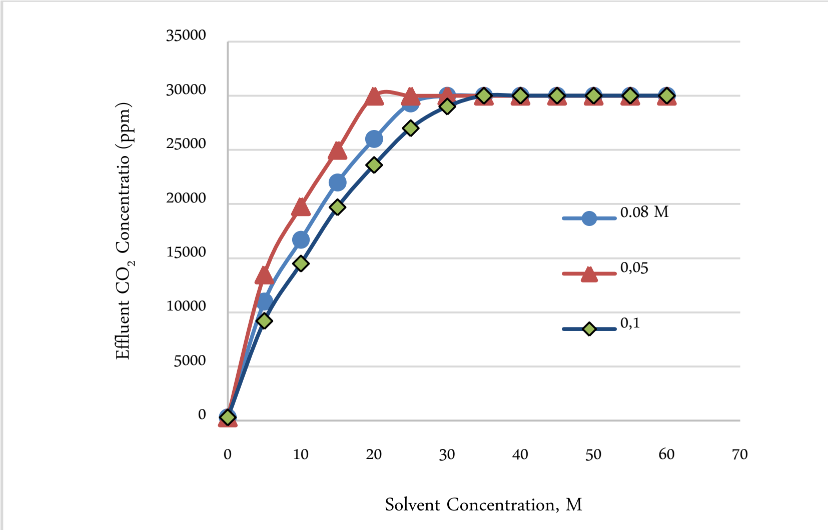

Fig.9: Effect of solvent concentration on effluent CO_2 concentration (G:2L/min, C_{CO2}: 30000ppm)

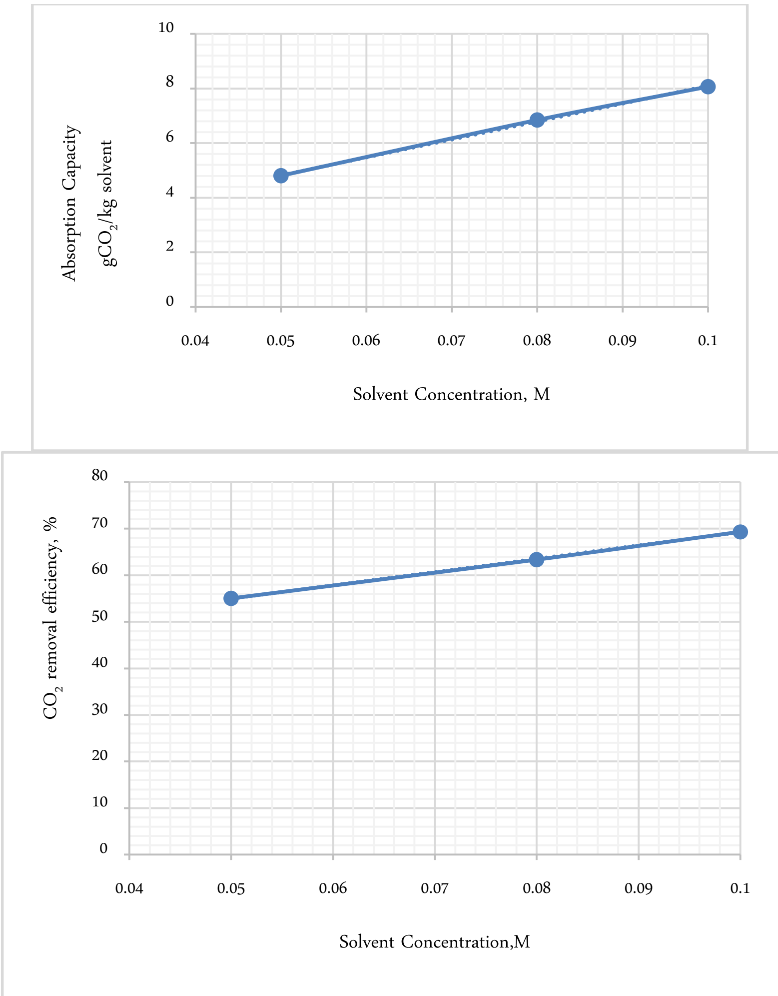

Fig. 10. Effect of solvent concentration on the absorption capacity and the CO_2 removal efficiency

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IV. CONCLUSION

In this work, the absorption of CO_2 into aqueous 1-butyl-3-methylimidazolium acetate ([BMIM][AcO]) solution has been used to CO_2 capture from flue gas. The bubble column reactor was used to determine the effects of several operational parameters such as inlet CO_2 concentration (10000-30000 ppm), gas flow rate (0.5-2 L/min) and solvent concentration (0.05-0.1 M) on the absorption capacity and removal efficiency. The following results were obtained.

* CO_2 removal efficiency and absorption capacity increased from 55% to 87% and from 4.8 to 9.8 gCO_2/kg solvent, respectively, when CO_2 concentration was increased from 10000 to 30000 ppm.

*CO_2 removal efficiency increased from 55 to 98% when the gas flow rate was reduced from 2 to 0.5 L/min. Similarly, CO_2 removal was improved by increasing the solvent concentration from 0.05 to 0.1 M.

The results of this study show that 1-butyl-3-methylimidazolium acetate ([BMIM][AcO]) can be used as a solvent to remove CO_2 from flue gases with high removal efficiency and absorption capacity.

Acknowledgement

This study was supported by Eskisehir Technical University Scientific Research Projects Commission under the grant no:22GAP224

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