Effect of Heating on Absorption of CO_2 as Greenhouse Gas in a Structured Packed Scrubber

H.M. Ndĩritũ, K. Kĩbicho and B.B. Gathitũ

Abstract—Increase in greenhouse effect in which more infra-red radiations are getting trapped within the earth has been traced to fossil fuel emissions. Among these emissions, carbon dioxide has been the driving force behind this heating, currently standing at more than 380 ppmv and rising by 2 ppmv per year. Since fossil fuels continue to form 80% of energy in the foreseeable future, efforts must be sustained towards reduction of resulting greenhouse gases. Research has shown that post combustion absorption using a suitable solvent can reduce carbon emission from an exhaust stream. This research involves developing a laboratory model of carbon capture technique based on absorption in a packed bed column. Tests have shown that increase in temperature, besides gas and liquid loading, facilitates absorption of the CO_2 gas.

Keywords—Greenhouse effect, Structured packing, Absorption rate,

I. INTRODUCTION

SINCE industrial revolution, fossil fuels (coal, petroleum and natural gas) have formed the main source of energy in the transport and industrial sector. This has led to a rise in emissions among them CO_2 gas that have accelerated the global warming problem. Global warming is the increase in atmospheric temperature due to trapping of infra-red radiations by the atmosphere [1]. Some of the consequences of global warming are disruptions including floods, prolonged droughts resulting to hunger as well as melting of snow and ice caps in mountains and polar regions causing a rise in sea level [2]. With greater energy demand for economic growth in various countries, more emissions will be released and it is essential that these emissions releases are addressed. Clean energy sources widely viewed to be potential replacements of fossil fuels have so far had limited impact (forms less than 20% worldwide). As other replacements are sought, post combustion capture of carbon dioxide using absorbers (wet scrubbing) provides an avenue for reducing emissions from industries and power plants [3]. In this paper, the performance of a wet scrubber, designed and fabricated for carbon dioxide absorption has been presented. Its has been tested based on influence of liquid and gas loading (flow rate) as well as variations in temperature of gas to optimize absorption of carbon dioxide.

Scrubbers rely on diffusion of gas particles to the liquid phase due to concentration gradient. A large surface area, that provide turbulent mixing and high diffusion gradients is essential for efficient transfer [4]. This surface is provided by use of interior elements called packing, that distribute gas and liquid appropriately [5]. Besides the surface area, gas and liquid loading (increase in flow rate) and temperature determine absorption capacity. Though several researchers have investigated gas liquid absorption, influence of loading (liquid or gas flow rate) and temperature is still unclear. Ardisorn [6], while investigating such a packed scrubber found that increased liquid loading raised CO_2 absorption rate while gas loading had no effect. Though the former behavior was attributable to increased wetting of packing it was unclear why more molecules of gas had no effect yet they created a concentration gradient and turbulence within the absorber. Meikap et al [7] and Shabani et al [8] found that gas and liquid loading caused an increase in absorption rate. In the former case, a multi-stage bubble column reactor was used and this could explain the difference in findings. An essential element that missed in these gas liquid interactions was how each condition influences the other as this has a bearing on the overall absorption rate of carbon dioxide.

Ardisorn also established that an increase in liquid temperature up to 35°C enhanced the absorption rate attributing it to improved reaction rate. However, it was not clear why beyond 35°C a reduction in absorption rate occurred for the monoethanolamine solvent used given that heating enhances reactions. Zare et al [10] and Lars [11] observed an inverse relationship between temperature and absorption rate attributing it to relocation of reaction zone within the absorption column. On using ammonia solvent, Yong et al [12] found that high temperatures (up to 50°C) favored absorption capacity when ammonia solvent was used to absorb carbon dioxide. This was due to improved reaction mechanism within the absorber. This suggest that different solvents have varying performance upon heating and that the mechanism of reaction is influenced by temperature of the both phases.

From the foregoing review, absorption rate of CO_2 is a phenomenon involving a complex relationship between time, turbulence and temperature. All these conditions not only influence the overall absorption rate but also affect each other thus further investigations need to be done to establish how this occurs.

II. EXPERIMENTAL DESIGN AND METHOD

In the scrubbing process, a structured packing was used to increase mass transfer between gas and liquid phases. The system consisted of counter current flow arrangement in which the most dilute liquid from the upper side of the absorber contacted the upward flowing gas.

Shown in figure 1 is an illustration of the laboratory model that was designed. The procedure used for determining the

H.M. Ndĩritũ, Department of Mechanical Engineering, JKUAT (e-mail: hndiritu@eng. jkuat.ac.ke).

K. Kĩbicho, Department of Mechanical Engineering, JKUAT (e-mail: kkibicho@eng. jkuat.ac.ke).

B.B. Gathitũ, Department of Mechanical Engineering, JKUAT (e-mail: bbg@eng. jkuat.ac.ke)
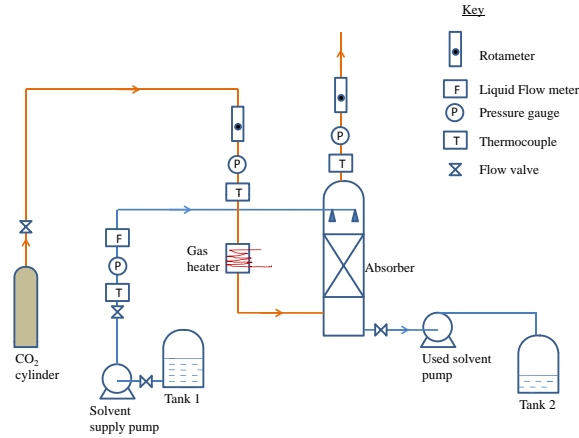
Fig. 1. Layout of the CO_2 absorption plant

Parameter	Quantity
Carrier gas composition	85% N_2
	15% CO_2
Carrier gas discharge	10 m^3/min
Henry's constant	3.4×10^2
Gas discharge	10 m^3/min
Gas density	1.17 kg/m^3
Liquid density	1000 kg/m^3

in figure 2 and made from galvanized iron in which the base is equal to the crimp height. Tests on different types of

Fig. 2. Corrugated sheet features

cross-sectional area of the absorber is briefly explained as this affects the size of other devices in the plant.

A. Design of Absorber

The absorber unit was a cuboid having a cross-section area of 310 mm by 350 mm and a height of 1380 mm. This cross-sectional area was estimated based on gas and liquid flow parameters within an empty absorber. Using Schenelle and Brown [13] procedure, the Henry's law, equation 1 and material balance (both gas and liquid phases) between inlet and outlets as shown in equation 2, the gas liquid flow rate ratio (Q/N) was obtained as below.

$$y = Hx \tag{1}$$

$$Gdy = Ldx \tag{2}$$

where y and x are the mole fractions of the pollutant gas in carrier gas mixture and in the liquid respectively, H is the Henry Law constant, while G and L are the gas and liquid molar flow rates respectively. The gas velocity was obtained as shown in equation 3.

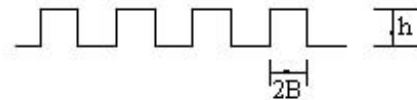$$V_g = \frac{C_s}{\left(\frac{\rho_g}{\rho_l - \rho_g}\right)^{0.5}} \tag{3}$$

where V_g, C_s, ρ_g and ρ_g are the gas velocity, capacity factor, gas density and liquid density respectively. The capacity factor C_s, is obtained from the expected pressure drop within the absorber, a Sherwood correlation as well as the liquid gas flow rate ratio. The cross-sectional area of the empty absorber was computed using additional parameters as shown in table I.

This cross-sectional area allowed estimation of the size of interior devices such as packed bed and mist eliminator. The packed bed (having a height 488 mm) consisted of corrugated sheets stacked vertically. Each sheet had a profile as shown

corrugated packing sheet have shown that vertically inclined surfaces have better solvent distribution and absorption efficiency compared to other geometries [14], [15]. The packed bed was located within the absorber at a height of 500 mm from bottom, the region below it formed the solvent sump and a space for gas entry into the absorber (measuring 310 mm by 350 mm by 500 mm). At a height of 250 mm above the packed bed, a pair of hydraulic nozzles were installed to distribute the solvent. Above the nozzles was a mist eliminator also made from galvanized iron, and consisting of blades set at an angle of 90° to allow moisture loss upon sudden change of direction [5].

B. Flow Procedure

From the cylinder, the gas (Industrial grade CO_2) was released through a pre-heater[1] that vaporized any entrained CO_2 liquid droplets. The released gas flowed through the rotameter (a 15 turn regulating valve integral to the rotameter allowed flow regulation)[2] and passed through the pressure gauge and thermocouple for pressure and temperature measurement. Pressure was determined using Cewal pressure gauges having an accuracy of $\pm 5\%$. Thermocouple sensors connected to an Advantest multichannel digital recorder, model TR2724, whose accuracy was $\pm 5\%$, were installed to measure temperature. The rotameters were calibrated using manufacturers supplied data.

Before injection into the absorber, CO_2 flowed through a PID controlled heater whose capacity was 1500W. Within the absorber CO_2 flowed upwards through the packing channels contacting the solvent in a counter flow configuration. Later CO_2 passed through a mist eliminator for moisture removal

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[1]Manufacturer supplied
[2]Model 6G10R3 from Omega Instruments Inc.

before exit from the absorber. After absorption, the remaining gas was discharged to the atmosphere through the final measuring insturments of temperature, pressure and volume flow rate.

Liquid solvent was pumped using the supply pump[3] from the tank shown in figure 1, its flow rate set using a regulating valve mounted downstream of the pump. The flow rate was measured using analogue flow meter, model Super H000620 and a digital stop clock (accuracy of $\pm 0.5\%$). Upon interacting with the gas, solvent was collected in the absorber sump and pumped to the used solvent tank using a second hydraulic pump.

To determine the absorption rate the flow conditions were measured using the equations below

$$A = \frac{1}{\bar{R}}\left(1 - \frac{\beta_o}{\beta_i}\right) \quad (4)$$

$$L = 60\left(\frac{K}{t}\right) \quad (5)$$

$$C = \frac{n}{K} \quad (6)$$

where

$$\beta = \frac{PV}{T} \quad (7)$$

The absorption of carbon dioxide was expressed as an efficiency in the form below.

$$\eta = 100\left(1 - \frac{A_o}{A_i}\right) \quad (8)$$

Data was collected at steady state condition in which all instruments were allowed four minutes to display constant readings. This was determined after repeated measurements. Water was chosen as a solvent for base line data due to its availability. Absorption of carbon dioxide was tested based on ambient conditions and later heated conditions for comparison.

III. RESULTS AND DISCUSSIONS

A. Base Line Test

The absorption rate of CO_2 was doubled for liquid loads ranging between 0.8 and 2 lpm as shown in figure 3. This was attributed to improved wetting within the packed bed in which more solvent molecules react with carbon dioxide. For other inlet gas flow rates (0.6 and 1 mol/min) absorption of carbon dioxide improved by 31% and 4%. This signified that increased gas molecules had little time to react with liquid molecules.

The type of reaction that occurred was given by

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (9)$$
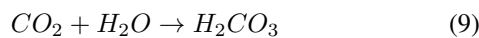
The product on the right hand side is a carbonic acid that was noticeable from irritating fumes[4] within the used solvent tank. Adisorn et al [18] attributed the increase to enhanced bulk absorption capacity of the liquid. This suggest that as the liquid quantity increases the concentration gradient builds up increasing absorption rate. Indeed the improved liquid flow
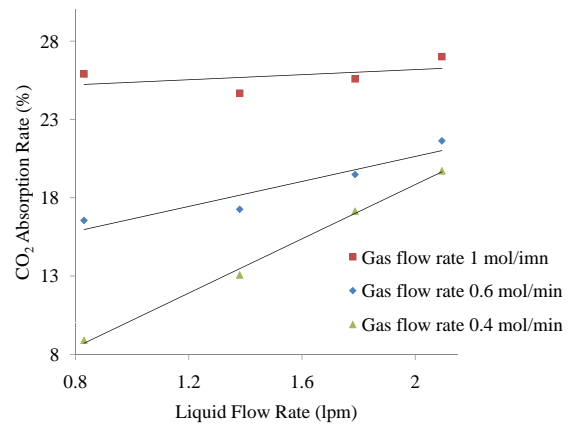

Fig. 3. Influence of liquid load on carbon dioxide at varying gas loads

rate increased droplets within the absorber that created more reaction sites.

When the gas flow rate becomes the independent variable, the absorption increases by 3 times for a doubling in the inlet gas flow rate. This is captured in Figure 4 for a liquid flow rate of 1.4 lpm, signifying that increase in carbon dioxide causes turbulent mixing within the absorber. The result is thus more reaction and generation of carbonic acid as in Equation 9. This observation is contrary to that observed by Ardisorn et al [6] in which gas flow rate had no effect on absorption of carbon dioxide. At a liquid flow rate of 1.4 and 1.8 lpm, the absorption increases by 89 and 49% respectively, as shown in Figure 4. In
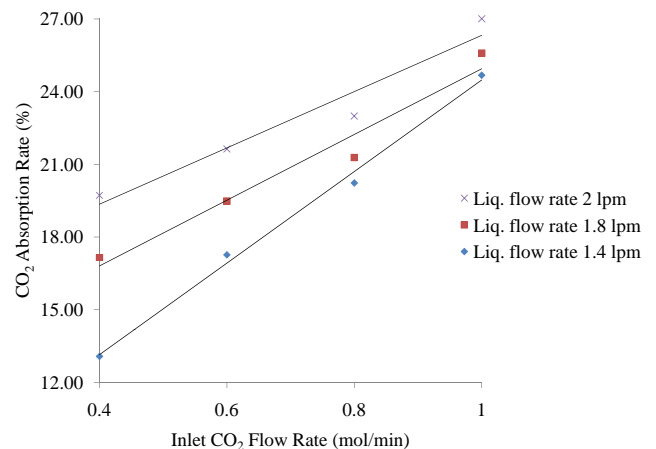

Fig. 4. Effect of inlet gas flow on carbon dioxide absorption

industrial design of absorbers this signifies that for large fossil fuels based power plants require low quantities of solvents. With the increasing need for water and energy conservation this translate to an improved plant efficiency. On the other hand for a small plant (generating less CO_2 gas) higher liquid flow rates eliminates more emissions. This however is at the expense of pumping energy hence reducing plant efficiency.

B. Absorption of Heated CO_2

CO_2 was heated at the range between 25 and 55° C and the effect is as shown in figure 5 for various liquid loads. A

[3]Grundfos pumps, model GR26E-07/07
[4]Leading to use of gas mask and goggles

linear increase of 33% is noted at a liquid load of 0.8lpm that could be attributed to faster diffusion of molecules towards the reaction zone (surface of the packed bed) due to the resulting kinetic energy. As hot CO_2 flows, heat is transferred to the mixture enhancing formation of carbonic acid.

Further liquid loading (1.4 and 1.8lpm) reduces the effect of heating since absorption rate increases by 20% and 3%. This observation suggests that higher liquid volumes cools the mixing fluids inhibiting reaction kinetics of the mixtures. The absorption rate for gas flow rate of improves as shown in figure 6 and
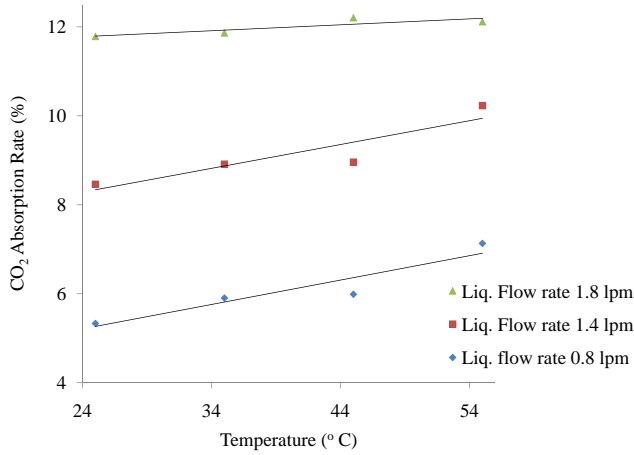

Fig. 5.   Temperature variation CO_2 absorption rate relationship at various liquid flow rates (Gas inlet flow rate = 0.4 mol/min)
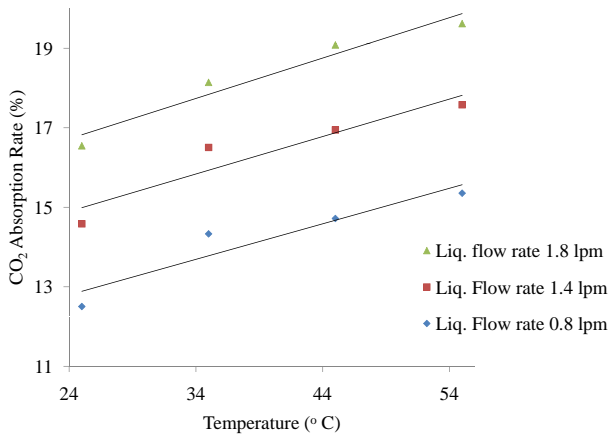

Fig. 6.   Effects of temperature variation on carbon dioxide absorption rate (Gas inlet flow rate = 0.6 mol/min)

The effect of temperature on carbon dioxide absorption rate for various gas flow rates of 0.6mol/min and 1mol/min is observed in Figures 6 and 6 respectively. The difference in absorption rate can be obtained from λ_T given by equation 10.

$$\lambda_T = \frac{\delta A}{\delta T}. \qquad (10)$$

where A is CO_2 absorption rate and T is the temperature of CO_2 at the inlet to the absorber. At the lowest gas flow rate of 0.4 mol/min, λ_T reduces by a factor of 10 for a liquid load of 2 lpm. The significance of this is that absorbers should
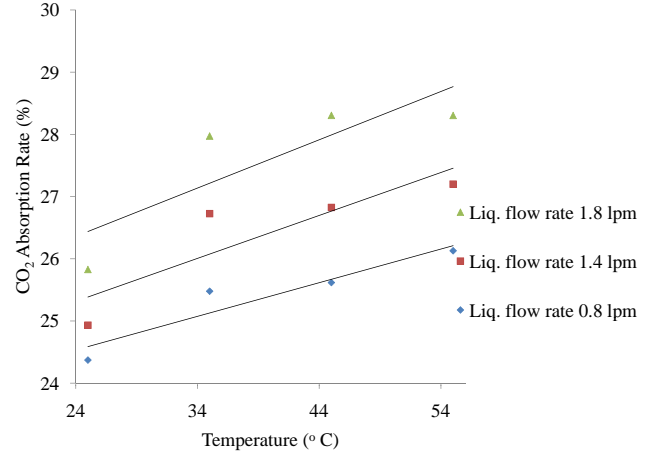

Fig. 7.   The relationship between temperature variation and carbon dioxide absorption rate at various liquid flow rates (Gas inlet flow rate = 1 mol/min)

be installed as close as possible to the combustion device, to retain the exhaust heat that facilitates absorption rate of gas. Alternatively flue gas duct systems should be properly insulated.

At higher gas flow rates the influence of temperature is maintained as shown in table II where the change λ_T has the same order of magnitude. This means that increased gas molecules ensure sufficient heating of gas liquid mixture.

TABLE II
PARAMETER λ_T FOR HIGHER GAS LOADINGS

Liquid flow rate (lpm)	0.8	1.4	1.8	2
λ_T at 0.4 mol/min	0.055	0.054	0.013	0.0075
λ_T at 0.6 mol/min	0.089	0.0942	0.102	0.071
λ_T at 1 mol/min	0.078	0.069	0.054	0.068

IV. CONCLUSION

As pointed out in the introduction, fossil fuels will continue to be a key source of energy yet they have effects on the environment. This study is intended to make a contribution to ways of reducing carbon dioxide as other alternative sources of energy are sought.

The results indicate that liquid loading increases the absorption rate of carbon dioxide, due to increased wetting within the absorber. For the same range of liquid load this reduces as gas flow rate increases. Increase in gas loading causes an increase in absorption rate of CO_2 attributed to turbulent mixing within the absorber. Comparatively gas loading has a greater influence on gas absorption rate than liquid loading.

Heating gas increases the rate of absorption of CO_2, attributed to increase in heat of reaction on the two phase mixture. However at high liquid flow rates influence of temperature reduces for low gas flow rates. For heating effect to be maintained gas flow rate should be raised to overcome cooling resulting from increased liquid flow rate.

ACKNOWLEDGEMENT

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