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Influence of Flow Parameters on Capture of Carbon Dioxide Gas by a Wet Scrubber

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Abstract

There is currently much concern over the issues of carbon dioxide emissions and climate change. Economic growth has driven carbon dioxide emission to 6 billion tonnes annually. Analysis has shown that carbon dioxide forms 13 to 15% of the combustion exhaust gases that are released directly into the atmosphere. Such concentrations can be effectively reduced using wet scrubbing. This is a capture mechanism involving the interaction of a liquid and a gas phase in a counter flow configuration. This paper presents the performance of a wet scrubbing system based on variation in flow properties. The results show that an increase in liquid and gas flow rate causes a 19% in carbon dioxide absorption. This resulted from proper mixing of gas and liquid phases within the absorber facilitated by the packed bed surface. Heating of the carbon dioxide gas caused an increase in absorption of more than 10% for varying liquid flow rate and of 14% for varying gas flow rate. This was attributed to an increase in heat energy for the reaction of carbon dioxide and water.

Keywords: Global warming, Carbon dioxide capture, Wet scrubbers, Absorption rate

1. Introduction

The rise in energy demand in the world has resulted in continuous rise in the use of fossil fuels in transport, industry and power generation. This has caused a rise in emission of carbon dioxide at to an annual rate of 6 billion tonnes [1]. The resulting increase in atmospheric concentration of carbon dioxide has been found to be a driving force behind global warming. Some of the major consequences of global warming include a global reduction in the quantity of water. It has been observed that a 1°C rise in air temperature increases water retention capacity of air by 6 to 7% [2]. Other consequences of global warming include a rise in sea levels, acidification of oceans and a reduction of glaciers in snow-capped mountains [3–6]. To curb these effects, emissions of carbon dioxide into the atmosphere must be reduced.

In a typical combustion device 13 to 15% of the exhaust emission is carbon dioxide [7]. Such low concentrations are effectively reduced using liquid absorption. This is also called wet scrubbing and has been in operation since 1836 [8]. Several researchers have studied the effects of flow conditions on absorption of carbon dioxide. Among them is Adisorn et al. [9] who found that an increase in liquid flow rate enhanced the absorption of carbon dioxide. This was attributed to increased wetting of the gas-liquid interface. In addition, an increase in gas flow rate had no effect on the absorption of carbon dioxide from a

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flow gas. This was despite the increase in turbulence caused by high gas flow rates that is expected to facilitate mixing within the absorber. Meikap et al. [10] using a slightly different configuration (a multi-stage bubble column scrubber) found that an increase in volumetric gas flow rate caused a corresponding improvement in absorption rate. This disagrees with Adisorn's findings making it an area suitable for further study.

Turbulence is an important parameter for improving the absorption rate of carbon dioxide. Chia et al. [11] enhanced it by use of a rotating packed bed (RPB) absorber, which caused the absorption rate to increase. This was attributed to reduced mass transfer resistance of the liquid. This was confirmed by Shabani et al. [12] who found that high gas flow rate increased turbulence, which further improved the mixing of phases within the absorber. Moreover, high liquid flow rate caused an increase in absorption of gas due to the continuous renewal of the gas liquid boundary layer.

Adisorn found that increasing the temperature of the liquid up to 35°C enhanced carbon dioxide absorption [9]. This was attributed to the increased kinetic energy of the molecules of the gas and liquid phase. However, Zare et al. [13] and Lars [14] found an inverse relationship between temperature and absorption rate. This was attributed to relocation of the reaction zone to the upper stages of the absorber. This suggests that the position of the reaction zone ultimately determines the rate of absorption of gas by the scrubbing agent. This can only be confirmed by studying the mechanism of reaction within the absorber.

From the foregoing, gas flow rate play a limited role in absorption of carbon dioxide by a solvent, but it is expected to facilitate mixing between the gas and liquid phase. Also it is unclear why temperature has a non uniform effect on absorption of carbon dioxide while being a catalyst for reactions. This means that there is a complex relationship between flow parameters and carbon dioxide absorption. Therefore, further study needs to be done to optimize the absorption process.

In this paper the performance of an absorber used for scrubbing of carbon dioxide from a simulated flue gas is presented. The rig is designed to have provision for control of flow parameters such as gas and liquid flow rate as well as temperature of gas.

2. Experimental Setup and Method

A packed absorber was designed, fabricated and used in the absorption of carbon dioxide gas from a simulated flue gas. The system consists of an arrangement gas flow and the liquid distribution systems are configured in such a way that there is counterflow interaction. A set up of this type is shown in Figure 1.

2.1. Design and Fabrication

The design of the system utilized a procedure based on Schenelle and Brown [15]. In this Henry's law and mass balance across the absorber were estimated using the following two equations.

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

where y and x are the mole fractions of the pollutant in the carrier gas mixture and in the liquid respectively while H is the Henry's constant.

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

where G and L are the gas and liquid molar flow rates respectively. Further details of the procedure are explained in [16].

The gas distribution system consists of a carbon dioxide source connected to the absorption unit using a flexible steel pipe. The gas used was 100% carbon dioxide released into the absorber at a pressure in the range of 0 to 100 mbar above atmospheric. This gas was industrial grade carbon dioxide and packed as a compressed liquid by Carbacid Ltd. Though the temperature and pressure were low, they nevertheless simulated what happens in real situations as they were above ambient conditions.

The absorption unit consisting of an absorber shell (upper and lower sections) was constructed as a cuboid having cross-sectional dimensions of 350×310 mm and a height of 1380 mm. Inside the absorber were a corrugated packed bed, a mist eliminator and nozzles. The bottom of the absorber formed the solvent sump. The solvent distribution system consisted of a network of galvanized iron

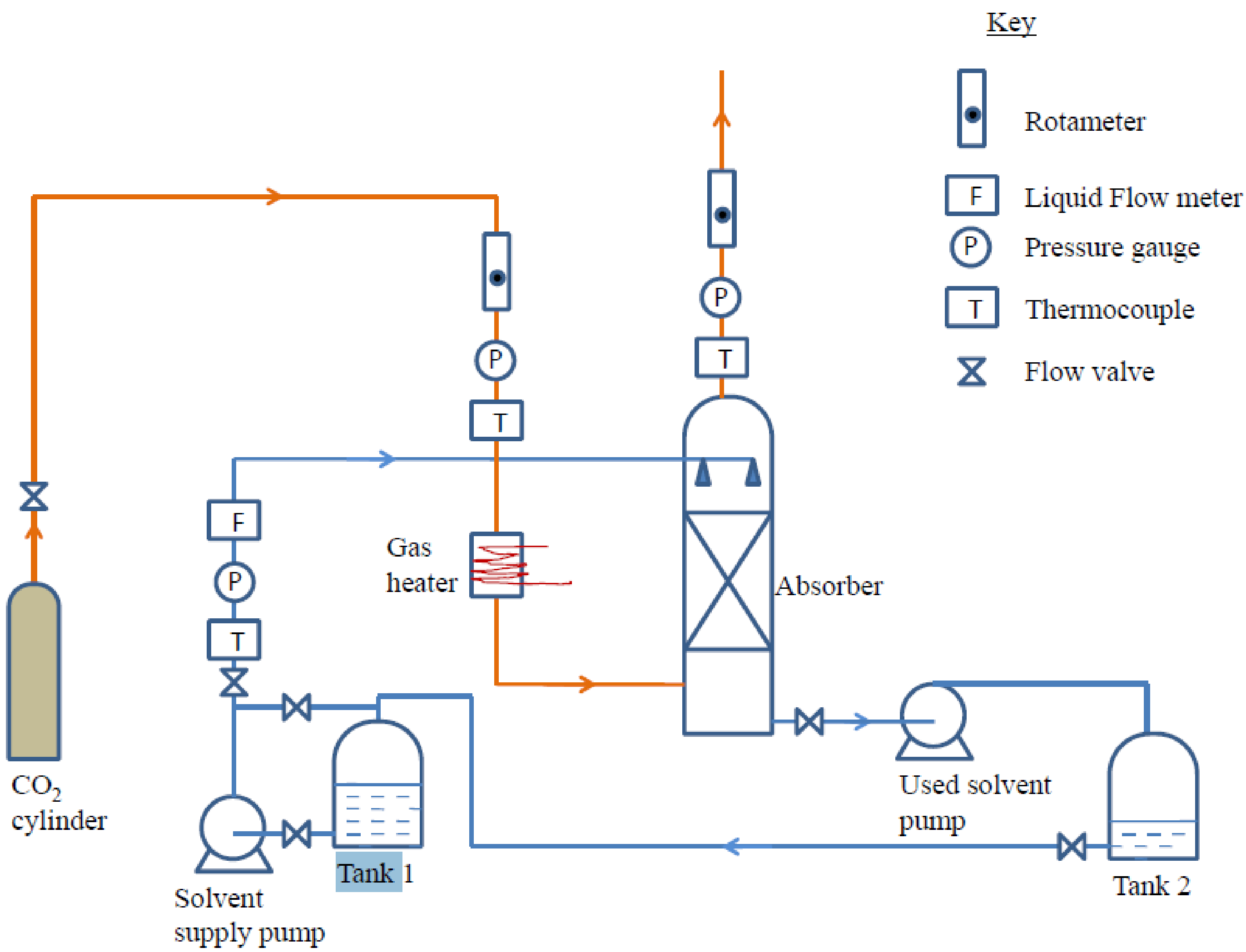

Figure 1: Layout of the CO_2 absorption plant

pipes joining the fresh solvent and used solvent tanks to the absorption unit.

The instrumentation system consisted of all the devices that were used to monitor the performance of the model plant and control of heating process. A detailed description of the interaction of the components making the absorber unit is provided in the flow procedure below.

2.2. *Flow Procedure*

Carbon dioxide was discharged from the gas cylinder and passed through the series of apparatus shown in Figure 1. The gas was released from the cylinder through a pre-heater that was supplied with a regulator to dry off any entrained liquid droplets and ensured the gas condition at the upstream section was at ambient temperature (25 ± 3°C). The required gas flow rate was set using the regulating valve integral to the rotameter after which it passed through a gauge and a thermocouple for pressure and temperature measurement respectively. Before injection into the absorber, carbon dioxide flowed through the main heater for further heating above ambient conditions (this heating was done for tests involving temperature variations).

Within the absorber, carbon dioxide gas flowed downstream through the packing channels contacting with the solvent in a counter flow configuration. A mist eliminator removed moisture before carbon dioxide exited at the top of the absorber. Downstream of the absorber were a set of measuring instruments (thermocouple, pressure gauge and rotameter) for determination of condition before final discharge of gas to the atmosphere.

Liquid was pumped using the supply pump from the fresh solvent tank as shown in Figure 1 and the flow rate was set using a flow valve mounted upstream of the absorber. The liquid then flowed through the upstream measuring instruments for flow determination before discharge into the absorber through a pair of nozzles. After interacting with the gas, used solvent was collected at the absorber sump and then pumped to the solvent collection tank using the second hydraulic pump. A liquid pipe connecting the two tanks allowed recirculation to establish the number of runs required to saturate the solvent with carbon dioxide.

2.3. Performance Parameters

The parameters that were measured to track the performance of the rig were temperature, pressure and flow rates. Their effect on absorption rate is through the equation of state of a perfect gas as shown in Equation 3.

$$A = \frac{1}{\bar{R}}\left(\frac{P_i V_i}{T_i} - \frac{P_o V_o}{T_o}\right) \tag{3}$$

where A, P, V, T and $\bar{R}$ are the absorption rate of CO_2 in moles per unit time, pressure, volume flow rate, temperature and universal gas constant respectively, while subscripts i and o denote the absorber inlet and outlet conditions respectively.

The absorption efficiency of carbon dioxide gas was computed from Equation 4.

$$\eta_a = 100\left(\frac{A}{N_i}\right) \tag{4}$$

where A and N are the absorption rate and molar flow rate respectively.

Solvent flow rate was obtained from Equation 5

$$Q_l = 60\left(\frac{L}{t}\right) \tag{5}$$

where Q is the liquid discharge in liters per minute, L is the liquid volume in liters and t is the time in seconds.

2.4. Uncertainty

Measured data utilizing an array of instruments has a level of uncertainty. Therefore it is necessary to evaluate this uncertainty. In this research two types of uncertainty, instrumental and experimental were evaluated based on Equations 6 and 7.

$$\frac{\xi}{A} = 100\left(\sqrt{(\beta_P)^2 + (\beta_V)^2 + (\beta_T)^2}\right) \tag{6}$$

where ξ_P, ξ_V and ξ_T were the uncertainties from each of the measuring instruments (rotameter, pressure gauge and the multi-channel digital recorder) that were respectively stated as 5%. Also $\beta_P = \frac{\xi_P}{P}$, $\beta_V = \frac{\xi_V}{V}$ and $\beta_T = \frac{\xi_T}{T}$ respectively.

$$\sigma = 100\left(\frac{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(A_i - \bar{A})^2}}{\bar{A}}\right) \tag{7}$$

where N was the number of repeated measurements, A was the molar absorption rate and $\bar{A}$ was the average molar absorption rate given by Equation 8.

$$\bar{A} = \frac{1}{N}\sum_{i=1}^{N} A_i \tag{8}$$

Evaluation of these uncertainties helped to establish the capacity of the rig to produce uniform results. The instrumental and experimental uncertainties were computed and found to be 2.5% and below 4.7% respectively. This was within the range of the accuracies of the instruments that were quoted as 5%.

3. Results and Discussions

The effects of variation of flow rate (gas and liquid) on carbon dioxide absorption are presented. Later, effects of temperature on absorption rate are examined. The liquid utilized throughout these tests is water.

3.1. Effect of Liquid Flow Rate

Shown in Figure 2 is the carbon dioxide absorption behavior as liquid flow rate is increased from 0.8 to 2 liters/min. It is observed that the absorption improves by more than 19% at a given liquid flow rate. This is attributed to the increased quantity

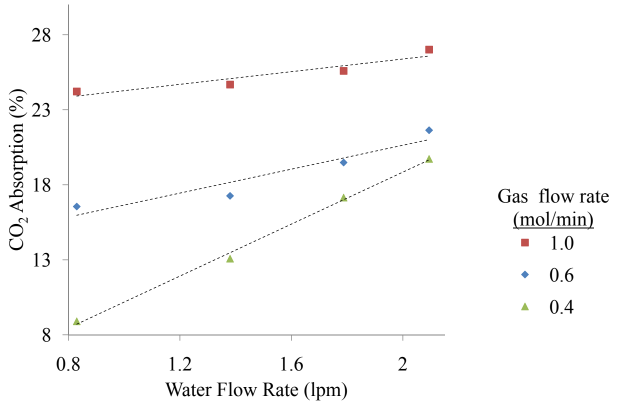

Figure 2: Absorption profiles due to liquid loading

Table 1: Change of (λ) with inlet gas flow rate

Gas flow Rate, mol/min	0.4	0.6	1.0
λ, gradient	8.66	3.99	2.11

of solvent causing greater wetting of the corrugated packing. The resulting higher concentration of water molecules reacts with carbon dioxide causing formation of carbonic acid as shown in the Equation 9.

$$CO_{2(g)} + H_2O_{(l)} \rightarrow H_2CO_{3(aq)} \tag{9}$$

This observation corresponds with findings made by Adisorn et al. [17] who attributed it to enhanced bulk absorption capacity of the liquid due to the increase in liquid molecules.

Further, the increase in gas flow rate is observed to cause a reduction in absorption rate for every liter of solvent atomized in the absorber. This is computed as a slope of the curves obtained from Equation 10.

$$\lambda = \frac{\delta A}{\delta L} \tag{10}$$

where A and L are the carbon dioxide absorption and solvent flow rates respectively.

At low gas flow rate the slope is more than four times that at higher gas flow rates. The behavior suggests that low gas flow rates have better spreading capacity than higher gas ones and thus mass transfer is superior. In this respect liquid loading has less effect on mass transfer process at high gas flow rates.

3.2. *Gas Flow Rate Variation*

Shown in Figure 3 is the carbon dioxide absorption behavior as the gas flow rate is increased from 0.4 to 1 mol/min. It is observed that more than 19% of carbon dioxide passing through the absorber is scrubbed at a given gas flow rate.

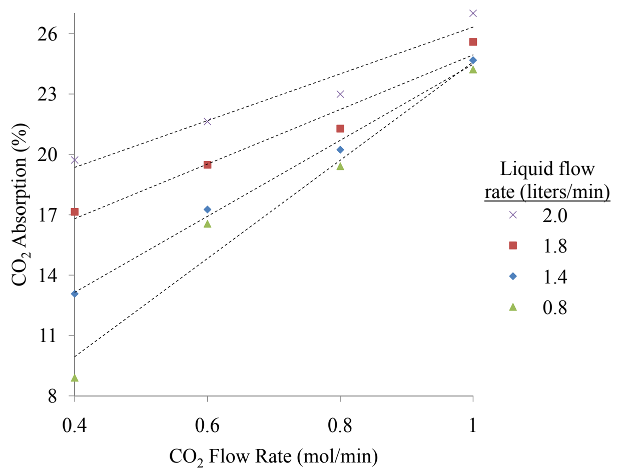

Figure 3: Absorption profiles due to gas loading

The results indicate more reaction and generation of carbonic acid as in Equation 9. The increasing quantities of gas enhances absorption for the range of gas flow variations used. The relationships (curves) illustrate a tendency to converge beyond a gas flow rate of 1 mol/min. This suggests that a limiting gas flow rate exists beyond which further increases in liquid pumping energy would not contribute positively to controlling emissions.

Adisorn et al. [9] found that when using a packed scrubber and an alkanolamine solvent the gas loading had no influence on absorption of carbon dioxide. Indeed, an increase in gas flow rate caused a constant amount of carbon dioxide gas to be absorbed. This was attributed to the diffusion of carbon dioxide within the liquid phase being constant even as the concentration increased within the gas phase. The difference in results in the present research and that of Adisorn may be attributed to the type of packing used. The corrugated packing used had sheets staggered at an angle of 90° to each other. Staggering of this type has been found to increase resistance within the gas phase interfering with the mass transfer process according to Wen et al. [18]. In this research, packing sheets were not staggered relative to one another, which allows an uninhibited flow of gas within the absorber thus facilitating mass transfer.

3.3. Heating Effect at Varying Liquid Loads

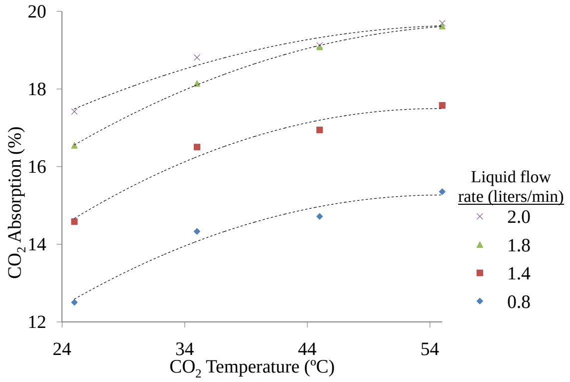

Figure 4: Heating effect on carbon dioxide absorption (G = 0.6 mol/min)

Shown in Figure 4 is carbon dioxide absorption upon heating in the range between 25 to 55°C. This is at constant liquid flow rates (ranging from 0.8 to 2 liters/min) at a gas flow rate of 0.6 mol/min. It is observed that an increase in absorption of more than 16% occurs at a given temperature. This is found to be about 10% of the absorption at ambient conditions. This is attributed to the faster diffusion of molecules towards the reaction zone (surface of the packed bed) facilitated by heat supply. Hot flowing carbon dioxide causes transfer of heat energy to the two phase mixture, which provides heat for the reaction facilitating faster formation of carbonic acid (assumed to be as in Equation 9). This confirms that like turbulence, the increase in temperature enhances mixing and subsequent reaction between the two components.

3.4. Heating Effect at Varying Gas Loads

The absorption of carbon dioxide in water as inlet gas flow rate is varied as shown in Figure 5. This gas flow variation is between 0.4 and 1 mol/min at a liquid flow rate of 1.4 liters/min.

It is observed that for a gas flow rate of 0.4 mol/min absorption of more than 17% of carbon

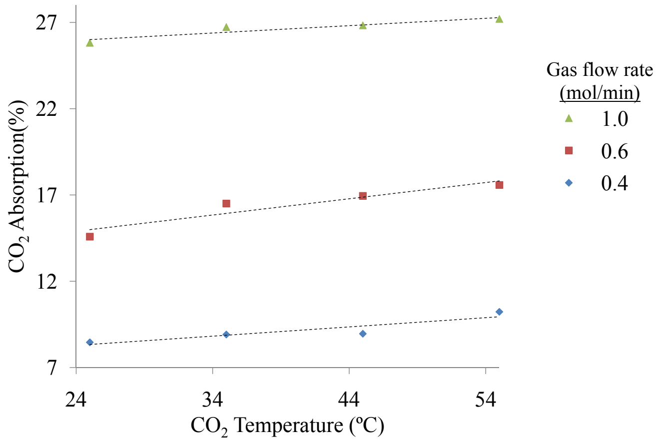

Figure 5: Heating effect on carbon dioxide absorption (L = 1.4 liters/min)

dioxide occurs at a given temperature. This is found to be more than 14% of the absorption at ambient conditions. This suggests that the heat of reaction played a significant role in aiding the absorption reaction. The increased quantity of hot gas from 0.4 to 1 mol/min results in increased frequency of collision of molecules thereby enhancing the absorption of carbon dioxide.

4. Conclusion

The rig can scrub more than 19% of carbon dioxide at a given liquid flow rate. This implies that for an absorber having a cross-section of 350×310 mm and a height of 1380 mm, the range of liquid flow rate of 0.8 to 2 liters/min would lead to sufficient interior wetting and thereby en-hance the absorption of carbon dioxide. Gas loading also causes an increase of more than 19% at a particular liquid flow rate. For the same size of absorber, a gas flow range of 0.4 to 1 mol/min would ensure proper turbulent mixing and subsequent absorption of carbon dioxide.

Tests on the system's behavior following the heating of carbon dioxide show that absorption is 10% higher than ambient temperature. This occurs as the liquid flow rate is increased from 0.8 to 2 liters/min. Moreover, an increase in flow rate of heated gas from 0.4 to 1 mol/min results in absorption being over 14% higher than at ambient temperature. This leads to the conclusion that a range of heating of 25 to

55°C adequately stimulates the absorption of carbon dioxide for the size of the designed absorber.

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