

## Research Article

# CO<sub>2</sub> Absorbing Capacity of MEA

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We describe the use of a gas bubbler apparatus in which the gas phase is bubbled into a fixed amount of absorbent under standard conditions as a uniform procedure for determining the absorption capacity of solvents. The method was systematically applied to determine the CO<sub>2</sub> absorbing capacity of MEA ( $A_c$ ) at several aqueous MEA ( $\beta$ ) and gas-phase CO<sub>2</sub> concentrations.  $A_c$  approached the nominal CO<sub>2</sub> absorbing capacity of MEA (720 g CO<sub>2</sub>/kg MEA) at very low  $\beta$  levels, increasing from  $447.9 \pm 18.1$  to  $581.3 \pm 32.3$  g CO<sub>2</sub>/kg MEA as  $\beta$  was reduced from 30 to 2.5% (w/w).  $A_c$  did not depend on the CO<sub>2</sub> concentration in the inlet gas stream as long as the gas stream did not include other amine sensitive components. During the bubbling tests the outlet CO<sub>2</sub> concentration profiles exhibited a sigmoidal shape that could be described by an exponential equation characterized by an efficiency factor ( $a$ ) and a form factor ( $n$ ). Statistical analysis based on correlation analysis indicated that in all cases the experimental data fit the equation well when  $a$  was  $6.1 \pm 0.35$  and  $n$  was  $2.5 \pm 0.12$ . The results of these experiments may be used to optimize scrubber designs for CO<sub>2</sub> sequestration from fossil fuel derived flue gases.

## 1. Introduction

There are several industrial applications in which a liquid phase substance (solvent) is used to selectively absorb one or several components (pollutants) from a gas stream passing through an absorbing column (scrubber). One application of increasing interest is CO<sub>2</sub> absorption from fossil fuel derived flue gases in thermal power plants. CO<sub>2</sub> is the most widely produced greenhouse gas (GHG) as a result of fossil fuel combustion to satisfy the world energy demand [1, 2]. Efforts to mitigate global warming include CO<sub>2</sub> sequestration from flue gases for either storage in the sea or empty oil wells or reconversion into CO and O<sub>2</sub> through artificial photosynthesis [3–5]. Although these technologies are still in an early stage of development, amine scrubbing has emerged as the preferred method for CO<sub>2</sub> sequestration [6]. While acid gas removal from process streams using amines is a mature technology [7, 8], flue gas scrubbing presents many new challenges still not adequately met on the scale necessary for GHG abatement [9]. Wet scrubbing techniques must improve to process large volumes of flue gas at acceptable thermal efficiencies and minimal costs [10, 11].

Extensive work has been undertaken to identify the optimum packing material geometry to improve hydrodynamic

mixing and maximize mass transfer in order to minimize the size and pressure drop across the scrubber [12]. The absorption or removal efficiency ( $\eta$ , defined in (1), where  $y_i$  and  $y_o$  are the pollutant concentration expressed as molar fraction at the inlet and outlet, resp.) is a means of expressing the performance of the scrubber. Several authors have erroneously referred to  $\eta$  as a solvent property even though two scrubbers using the same solvent could have different absorption efficiencies. Consider

$$\eta = \frac{y_i - y_o}{y_i}. \quad (1)$$

*Amine Absorbing Capacity.* Amines are ammonia derivatives in which one or more hydrogen atoms are replaced by an organic radical [12]. Monoethanolamine (MEA), diethanolamine (DEA) and methyldiethanolamine (MDEA) are the most commonly used amines in scrubbing applications. The CO<sub>2</sub> absorbing capacity of amines is easily degraded by the presence of SO<sub>2</sub>, NO<sub>2</sub>, HCl, HF, or O<sub>2</sub> in the gas stream. These components form irreversible byproducts that reduce the reaction rate during the absorption process and increase the complexity of the solvent recovery process.

The absorbing capacity is a solvent property defined as the maximum molar amount of pollutant absorbed per mole

of solvent. This property is used to define the appropriate loading (pollutant/solvent molar ratio,  $\alpha$ ) in scrubber designs. Low loadings result in columns with low absorbing efficiencies while high loadings lead to excessive solvent requirements and high operational costs. The  $\text{CO}_2$  absorbing capacity of amines is dependent on the solvent concentration, the composition of the gas stream, and the operating temperature [13].

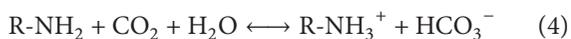
Amines are capable of chemical and physical  $\text{CO}_2$  absorption. Physical absorption is controlled by the thermodynamic equilibrium between  $\text{CO}_2$  molecules in the gas and aqueous phases and is described by Henry's law [8, 14]:

$$P_A = y_A P = H_A x_A, \quad (2)$$

where  $P_A$  is the equilibrium partial pressure of component  $A$  in gas phase,  $P$  the total pressure,  $H_A$  the Henry's law constant of component  $A$ ,  $y_A$  the equilibrium concentration of component  $A$  in gas phase (expressed as molar fraction), and  $x_A$  the equilibrium concentration of component  $A$  in liquid phase (expressed also as molar fraction).

The Henry's law constant is determined in a temperature and pressure controlled sealed chamber by measuring the equilibrium concentration of the component in the gas and liquid phases using spectrophotometric or chromatographic analysis [15]. This method is appropriate for systems undergoing pure physical absorption, for example,  $\text{CO}_2$  absorption in  $\text{H}_2\text{O}$ . However, it is inappropriate when the solvent exhibits chemical absorption since the method does not ensure that the solvent becomes fully saturated. Investigators have employed this method for several years, expressing their results in terms of the equilibrium partial pressure of the gas phase component and referring to these values as the solubility of the pollutant in the solvent. Tong et al. [16] combined experimental work with an extensive literature review to describe the solubility of  $\text{CO}_2$  in 30% (w/w) aqueous solutions of MEA as a function of temperature and loading [17–19]. For the reader's convenience, Figure 1 reproduces the results published. These results cannot be used to describe the absorption capacity of the solvent since the equilibrium conditions under which the data was collected do not ensure saturation of the solvent. Furthermore, these results cannot be used to determine Henry's law constant for the MEA- $\text{H}_2\text{O}$ - $\text{CO}_2$  system since they do not quantify the  $\text{CO}_2$  remaining in molecular form within the liquid phase and because, as mentioned earlier, the system exhibits chemical absorption.

Chemical absorption is based on reactions between  $\text{CO}_2$  and the amine. It has been reported that chemical absorption does not increase significantly with pressure [20]. There are two fundamental mechanisms for the reaction of amines ( $\text{R-NH}_2$ ) with  $\text{CO}_2$  [9]:



For common primary and secondary amines such as MEA and DEA, reaction (3) prevails to form a stable carbamate ( $\text{R-NH-COO}^-$ ), requiring 2 moles of amine per mole of  $\text{CO}_2$  and thus limiting the absorbing capacity of

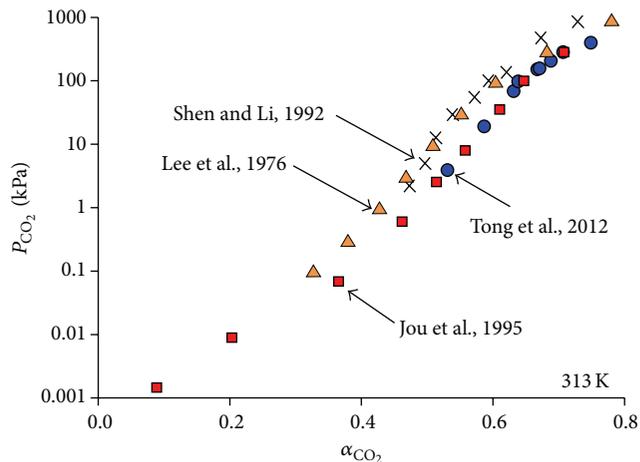


FIGURE 1: Solubility of  $\text{CO}_2$  in 30% (w/w) aqueous MEA solutions at 313 K as a function of loading (moles of  $\text{CO}_2$  per mole of MEA,  $\alpha$ ), from Tong et al. [16].

the amine to 0.5 moles of  $\text{CO}_2$  per mole of amine, that is, 360 g  $\text{CO}_2$ /Kg MEA. However unstable carbamates can hydrolyze to form bicarbonate ( $\text{HCO}_3^-$ ), as described by reaction (4). Under this condition, the nominal MEA  $\text{CO}_2$  absorbing capacity is one mole of  $\text{CO}_2$  per mole of MEA [9], that is, 720 g  $\text{CO}_2$ /Kg MEA. Tertiary amines such as MDEA only follow reaction (4) [21].

The physical and chemical MEA absorption capacities are affected by temperature, pressure, presence of additional gases, and the aqueous MEA concentration.

Yeh and Bai [22] measured the  $\text{CO}_2$  absorption capacity of MEA in a semicontinuous reactor consisting of a 60 mm glass bottle containing 200 mL of solvent. The absorption capacities ranged from 360 to 380 g  $\text{CO}_2$ /kg MEA using MEA concentrations of 7–35% (w/w) and gas flow rates of 2–10 SLPM of 8–16% of  $\text{CO}_2$  diluted in clean air. The reaction temperature varied from 10 to 40°C. Recently, Rinprasertmeechai et al. [23] used a stirred 100 mL reactor containing 50 mL of 30% (w/w) aqueous MEA concentration at 25°C and atmospheric pressure to obtain an absorption capacity of 0.45  $\text{CO}_2$  moles/mole amine (324 g  $\text{CO}_2$ /kg MEA) for a simulated flue gas containing 15%  $\text{CO}_2$ , 5%  $\text{O}_2$ , and 80%  $\text{N}_2$  and flowing at 0.05 SLPM. These two papers neither reported the outlet gas flow nor removed the  $\text{O}_2$  in the gas stream, leading to an underestimation of the  $\text{CO}_2$  absorbing capacity of MEA. Recently Kim et al. [24] reported an absorbing capacity of 0.565  $\text{CO}_2$  moles/mole amine (407 g  $\text{CO}_2$ /kg MEA) using 30 vol%  $\text{CO}_2$  diluted in  $\text{N}_2$  and a fixed flow rate of 1 SLPM monitored by a mass flow controller and gas chromatography to determine  $\text{CO}_2$  concentration at the outlet of the reactor.

The disagreements present in previous results are due to variations in testing methods, amine dilution, solvent temperature and pressure, and inlet gas composition and highlight the need for a standard method to determine the absorbing capacity of solvents. The resulting experimental data are required to optimize scrubber designs for  $\text{CO}_2$  sequestration from fossil fuel derived flue gases. We propose

TABLE 1: Recommended values for variables to be monitored during bubbling tests.

Variable	Resolution	Range	Uncertainty % FS	$A_c$ sensibility	Observations	This work for CO <sub>2</sub> $A_c$ of MEA
Gas composition	<0.5% of pollutant inlet concentration	0–100% of pollutant inlet concentration	0.5 for CO <sub>2</sub>	34%	(i) Use well accepted methods for determining pollutant concentration in the gas stream (ii) Avoid using gases with third components that could also be absorbed by the solvent	(i) 13% CO <sub>2</sub> , 87% N <sub>2</sub> (ii) 21% CO <sub>2</sub> , 15% CH <sub>4</sub> , 64% N <sub>2</sub> (iii) 100% CO <sub>2</sub>
Gas flow	0.1 SLPM	0–2 SLPM	0.2	52%	(i) Use mass flow meter (ii) Ensure gas residence time >60 s	0.1–1.0 SLPM
Temperature	0.5 °C	ND	0.5	3%	Ensure constant temperature within ±2 °C in the bubbler using a proper water bath	25 ± 2 °C
Pressure	1 kPa	ND	0.5	10%	ND	101.3 kPa
Time	1 s	ND	0.5	<1%	ND	0–7200 s
Pore size	ND	ND	ND	ND	1 μm	1 μm
Bubbler size	ND	ND	ND	N/D	(i) 1 L (ii) Ensure no leaks	1 L
Amount of solvent in the bubbler	ND	ND	ND	N/D	0.5 L	0.5 L
Solvent Dilution	0.5%	0–50%	ND	Figure 3	(i) Use analytical grade solvent (ii) Express dilution as weight to weight percentage	0–30% (w/w)

ND: not defined; FS: full scale.

a standard method for the determination of absorbing capacities consisting of a gas bubbler apparatus in which the gas phase substance is bubbled into a fixed amount of absorbent under standard conditions. We systematically applied this method to determine the CO<sub>2</sub> absorbing capacity of MEA as a function of MEA concentration and CO<sub>2</sub> concentration in the gas stream. The saturation curves obtained during the absorption tests exhibited a sigmoidal shape that could be described by an exponential function characterized by two parameters: the shape and efficiency factors. The proper use of these factors could lead to more compact and efficient scrubber designs.

## 2. Materials and Methods

Figure 2 illustrates the methodology proposed to determine the chemical and physical absorbing capacity of solvents. The apparatus consists of a gas bubbler setup in which the gas stream is bubbled through a fixed amount of absorbent under standard conditions. Prior to testing, the system is tested for leaks and purged using an inert gas. Experiments are conducted under standard conditions of pressure and temperature (101 kPa, 25 °C). To ensure constant temperature in the presence of exothermic or endothermic reactions, the system is placed inside a thermostated water bath. The reactor is continuously stirred to prevent stratification or inhomogeneities within the reactor. The inlet and outlet gas composition and flow are measured using well accepted methods. It is important to use a water vapor trap before

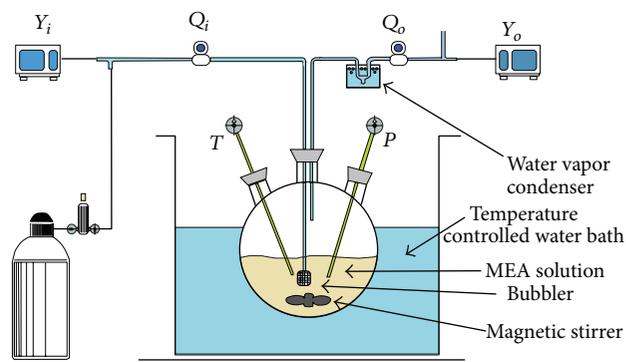


FIGURE 2: Proposed apparatus to determine the absorbing capacity of gas phase components by liquid phase absorbers.

measuring the outlet gas flow to prevent measurement distortions due to the presence of water in the gas stream after the bubbling process. The total gas flow across the bubbler should be as low as possible (<1 SLPM) to ensure a full interaction of the gas with the solvent. The temperature, pressure, and concentration of the absorbing substance are also monitored. The volume of solution in the bubbler is maintained at 0.5 L.

Table 1 describes the variables to be measured and the recommended values for the independent variables as well as the requirements for the sensors in terms of resolution, range, and measurement method. Several trials should be conducted to verify the reproducibility of the results.

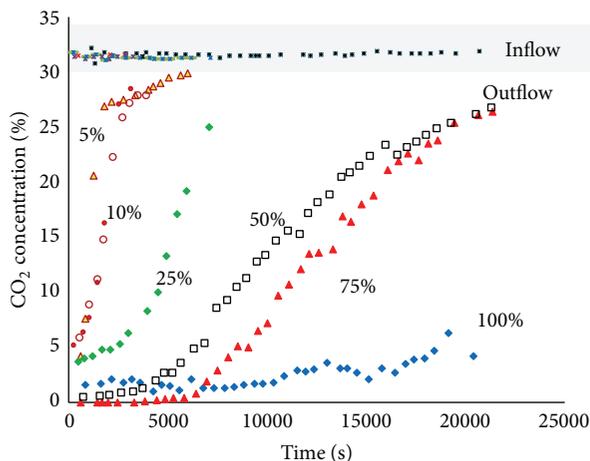


FIGURE 3: Evolution of CO<sub>2</sub> molar concentration at inlet and outlet of bubbler as function of aqueous MEA concentration.

The method was applied to the determination of the CO<sub>2</sub> absorbing capacity of MEA at several aqueous MEA concentrations and gaseous CO<sub>2</sub> concentrations.

### 3. Results

Figure 3 depicts the CO<sub>2</sub> molar concentration of the gas phase stream at the inlet and outlet of the bubbler. It shows that, at an inlet concentration of 30% CO<sub>2</sub>, MEA concentrations lower than 50% (w/w) were not able to absorb 100% of the CO<sub>2</sub> present in the gas stream. This low absorbing efficiency is not a property of the MEA solvent but rather a characteristic of the test apparatus and indicates that the residence time of the gas stream within the bubbler for low MEA concentrations is too low to obtain accurate measurements.

**3.1. CO<sub>2</sub> Absorbing Capacity of MEA.** Using the values of  $y_i$ ,  $y_o$ ,  $Q_i$ , and  $Q_o$  obtained as function of time during the bubbling test (shown in Figure 3), the absorbing capacity of the solvent is determined by

$$A_c = \frac{PM}{R^0 T m} \int_{t_s}^{t_e} (y_o Q_o - y_i Q_i) dt, \quad (5)$$

where  $M$  is the molecular weight of component being absorbed,  $R^0$  is the universal gas constant,  $T$  is the standard absolute temperature,  $P$  is the standard pressure,  $t$  is the time,  $s$  and  $e$  are indices to indicate the start and end of saturation process,  $m$  is the mass of solvent within bubbler,  $Q$  is the gas volumetric flow expressed at standard conditions, and  $i$  and  $o$  are the indices indicating inlet or outlet values.

Figure 4 is a comparison of the values obtained, the data reported in previous works, and the nominal CO<sub>2</sub> absorbing capacity of MEA.

More than 100 complete sets of experiments were carried out by several collaborators. It was found that the CO<sub>2</sub> absorbing capacity of MEA is concentration dependent, increasing from  $447.9 \pm 18.1$  to  $581.3 \pm 32.3$  g CO<sub>2</sub>/kg MEA

TABLE 2: CO<sub>2</sub> absorbing capacity of MEA at 25°C and 101.3 kPa.

$\beta$ %w/w	$A_c$ g CO <sub>2</sub> /Kg MEA	Uncertainty* g CO <sub>2</sub> /Kg MEA
2,5	581,3	32,3
5,0	499,9	37,1
7,5	480,3	12,2
10,0	525,6	14,2
15,0	504,6	16,0
20,0	464,1	11,1
25,0	449,0	15,7
30,0	453,0	16,3

\*with 95% of confidence.

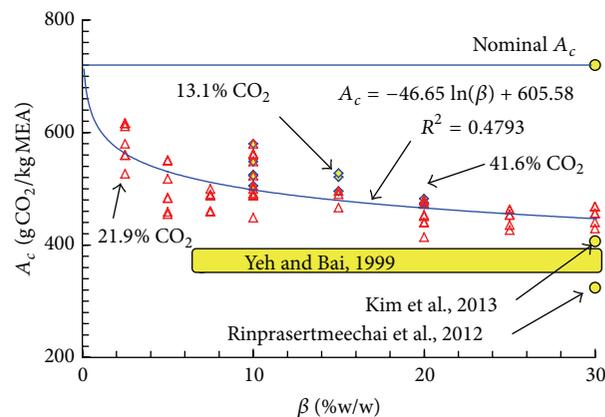


FIGURE 4: CO<sub>2</sub> absorbing capacity of MEA for several levels of aqueous MEA concentration ( $\beta$ ), obtained using the bubbling method. Yeh and Bai [22] used a reactor with 200 mL of solvent and a gas flow rates of 2–10 SLPM of 8–16% of CO<sub>2</sub> diluted in clean air. Temperature varied from 10 to 40°C. Rinprasertmeechai et al. [23] used a stirred reactor containing 50 mL of 30% (w/w) aqueous MEA concentration at 25°C and with a simulated flue gas containing 15% CO<sub>2</sub>, 5% O<sub>2</sub>, and 80% N<sub>2</sub> and flowing at 0.05 SLPM. Kim et al. [24] used a stirred reactor with 1 L of 30% (w/w) aqueous MEA at 25°C with 30 vol% CO<sub>2</sub> diluted in N<sub>2</sub> and a flow rate of 1 SLPM. All works were conducted at atmospheric pressure.

when  $\beta$  was reduced from 30 to 2.5% (w/w) and logarithmically approaching the nominal absorbing capacity of 720 g CO<sub>2</sub>/Kg MEA at very low concentrations. Table 2 lists the average values and the experimental error observed.

Changes in the CO<sub>2</sub> absorbing capacity with solvent dilution were also observed by Yeh and Bai [22] for the NH<sub>3</sub>/H<sub>2</sub>O/CO<sub>2</sub> system. Changes in the CO<sub>2</sub> absorption capacity of MEA with concentration may be explained by considering that excess water favors reaction (4) and that this reaction leads to a nominal absorbing capacity twice that obtained through reaction (3). Therefore, low concentrations of MEA result in maximal CO<sub>2</sub> absorption at the expense of reducing the interaction between the CO<sub>2</sub> and MEA molecules and lower probability of reaching full amine saturation in a reasonable time. Changes in the CO<sub>2</sub> absorption capacity of MEA with solvent dilution could also be due to solvation effects.

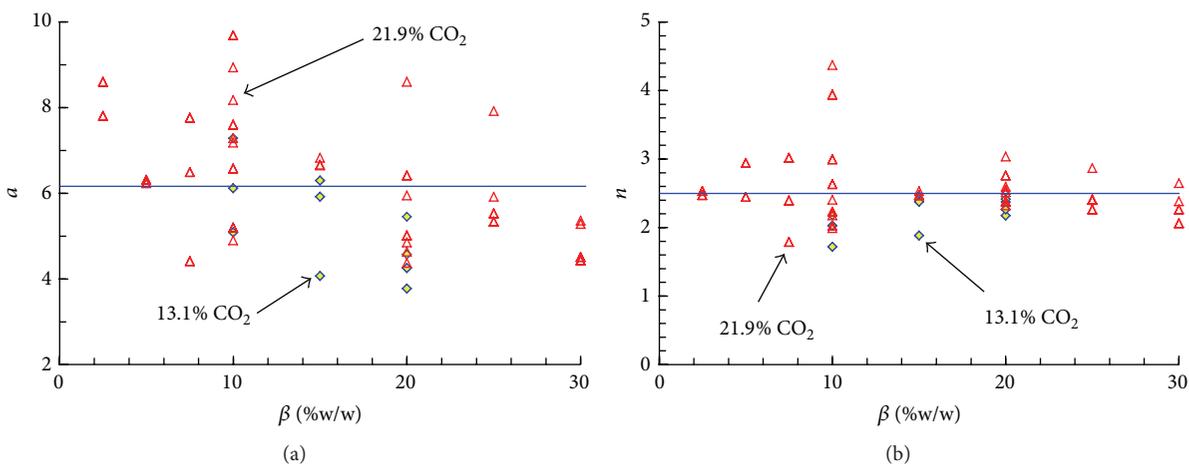


FIGURE 5: Results of curve fitting of CO<sub>2</sub> concentration to (6). The efficiency factor ( $a$ ) is plotted on the left and the form factor ( $n$ ) is plotted on the right as function of the aqueous MEA concentration. The blue horizontal line indicates the corresponding average value.

These results define the technological challenge in establishing optimum scrubber operating conditions. High MEA concentrations ensure 100% removal efficiency but provide low CO<sub>2</sub> absorbing capacities and increase the amount of MEA required in the process. On the other side, low concentrations provide high CO<sub>2</sub> absorbing capacity but low removal efficiency. It is possible that a sequential two-step process could be the most cost-effective means of achieving these opposing objectives.

Figure 4 also compares the CO<sub>2</sub> absorbing capacities of MEA measured in these experiments with those reported in previous works. Although the results are not fully comparable since they were obtained under different conditions, Figure 4 shows that the values are similar. The most relevant difference with Yeh and Bai [22] and Rinprasertmeechai et al. [23] was the presence of O<sub>2</sub> in the gas stream and with Huertas et al. [7] was the presence of H<sub>2</sub>S in the gas stream. Besides CO<sub>2</sub>, MEA can absorb H<sub>2</sub>S, SO<sub>2</sub>, and HCl [22]. MEA is degraded by the presence of O<sub>2</sub>, NO<sub>2</sub>, SO<sub>2</sub>, HCl and HF [25]. Therefore, in the determination of the CO<sub>2</sub> absorbing capacity of MEA it is important to eliminate the interference of these species.

Figure 4 also shows that the absorbing capacity was independent of gas phase CO<sub>2</sub> concentration. It was found that this conclusion is true as long as the gas stream does not include MEA sensitive components such as O<sub>2</sub> and H<sub>2</sub>S.

It could be argued that the increase in MEA absorbing capacity at low concentrations is due to the contribution of the CO<sub>2</sub> absorbing capacity of water. Therefore, a set of experiments was performed to determine the CO<sub>2</sub> absorbing capacity of pure water. Using the present methodology, it was found that water absorbed 0.3 g CO<sub>2</sub>/kg H<sub>2</sub>O, a negligible amount compared to the variations in CO<sub>2</sub> absorption capacity observed in aqueous MEA solutions. Since water is only capable of physical CO<sub>2</sub> absorption, this measurement was compared to the value obtained from Henry's law constant. For the conditions under which the experiment was carried out, Henry's constant is 144 MPa [26] and the CO<sub>2</sub> absorbing capacity of water at standard conditions is 0.375 g CO<sub>2</sub>/kg H<sub>2</sub>O. This agreement demonstrates the ability

of the proposed method to measure both chemical and physical absorption.

**3.2. Characterization of the Saturation Process.** Figure 3 indicates that the outlet CO<sub>2</sub> concentration profiles during the bubbling tests exhibited a sigmoidal shape and could be fitted to the following equation:

$$\frac{Y - Y_s}{Y_e - Y_s} = 1 - e^{-a((t-t_s)/(t_e-t_s))^n}, \quad (6)$$

where  $a$  is the efficiency factor,  $n$  is the form factor,  $t$  is the time, and  $s$  and  $e$  are indices to indicate the start and end of saturation process.  $a$  and  $n$  may be obtained by linear curve fitting when (6) is expressed as follows:

$$\ln\left(-\ln\left(1 - \frac{Y - Y_s}{Y_e - Y_s}\right)\right) = n \ln\left(\frac{t - t_s}{t_e - t_s}\right) + \ln(a). \quad (7)$$

The correlation coefficients obtained from curve fits for all cases were near unity ( $R^2 > 0.97$ ), indicating that the experimental data fit well with (6). This demonstrates that the saturation process was well represented by  $a$  and  $n$  and these two parameters uniquely characterize the solvent absorbing capacity.

Figure 5 contains plots of the results for  $a$  and  $n$ . It can be observed that the factor form  $n$  and the efficiency factor were not concentration dependent ( $a = 6.1 \pm 0.35$  and  $n = 2.5 \pm 0.12$ ).

These factors may be used to estimate the CO<sub>2</sub> absorption capacity of MEA at any aqueous concentration, to compare different solvents and to determine the saturation time during the bubbling test.

**3.3. Sensitivity Analysis.** According to (5),  $A_c$  is a function of pressure, temperature, gas phase CO<sub>2</sub> concentration, volumetric flow rate, and saturation time. Applying the equation of error composition ((8), where  $\partial A_c / \partial q_i$  is the absolute value of the partial derivative of  $A_c$  with respect to each

independent variable  $q_i$  [27]) to (5) and considering the precision of the instruments specified in Table 1 ( $\Delta q_i$ ) and the range of the values typically measured by each variable (also specified in Table 1), the uncertainty of the values obtained for  $A_c$  ( $\Delta A_c$ ) is less than 1% of the reported values. The  $\text{CO}_2$  concentration and volumetric flow had the greatest effect on the absorbing capacity determination, and special attention should be given to the accuracy and precision of instruments used to monitor these two variables. Table 1 includes the approximate percent contribution of each variable to the total uncertainty of the values obtained for  $A_c$  using the bubbling test. Consider

$$\Delta A_c = \sum \left| \frac{\partial A_c}{\partial q_i} \right| \Delta q_i. \quad (8)$$

#### 4. Conclusions

A standard test is described for the determination of the physical and chemical absorbing capacity of gas phase components by liquid phase absorbers. It consists of a gas bubbler apparatus in which the gas stream is bubbled into a fixed amount of absorbent under standard conditions. Sensitivity analysis indicated that gas composition and volumetric flow are the variables with the greatest effect on the absorbing capacity determination and special attention should be given to the accuracy and precision of the instruments used to monitor them.

This method was applied to determine the  $\text{CO}_2$  absorbing capacity of MEA ( $A_c$ ) at several aqueous MEA concentration levels ( $\beta$ ) and gaseous  $\text{CO}_2$  concentrations. It was found that  $A_c$  approaches the nominal  $\text{CO}_2$  absorbing capacity (720 g  $\text{CO}_2$ /kg MEA) at very low  $\beta$ , increasing from  $447.9 \pm 18.1$  to  $581.3 \pm 32.3$  g  $\text{CO}_2$ /kg MEA when  $\beta$  was reduced from 30 to 2.5% (w/w). These results agree with values reported for  $A_c$  in previous studies. As expected, the  $\text{CO}_2$  absorbing capacity of MEA did not depend on the  $\text{CO}_2$  concentration in the inlet gas stream as long as the gas stream did not include other components that could react with the amine, such as  $\text{H}_2\text{S}$  or  $\text{O}_2$ .

During the bubbling tests the outlet  $\text{CO}_2$  concentration profiles exhibited a sigmoidal shape that could be described by an exponential equation containing an efficiency factor ( $a$ ) and a form factor ( $n$ ). Statistical analyses based on correlation analysis revealed that in all cases the experimental data fit well to that equation when  $a$  was  $6.1 \pm 0.35$  and  $n$  was  $2.5 \pm 0.12$  and therefore these two parameters characterize the  $\text{CO}_2$  absorbing capacity of MEA under standard conditions.

#### Symbols

- $a$ : Efficiency factor  
 $A_c$ :  $\text{CO}_2$  absorbing capacity of MEA (g  $\text{CO}_2$ /Kg MEA)  
 $H_A$ : Henry's constant of component A (kPa)  
 $m$ : Mass of MEA within the bubbler (kg)  
 $M$ : Molecular weight of the component being absorbed (kg/kmol)  
 $n$ : Form factor

- $P$ : Standard pressure (kPa)  
 $P_A$ : Equilibrium partial pressure of component A in gas phase (kPa)  
 $Q$ : Gas volumetric flow expressed at standard conditions ( $\text{m}^3/\text{s}$ )  
 $R^0$ : Universal gas constant (kJ/kmol K)  
 SLPM: Standard liters per minute  
 $t$ : Time (s)  
 $T$ : Standard absolute temperature (K)  
 $x_A$ : Equilibrium concentration of component A in the liquid phase expressed as molar fraction  
 $y_A$ : Equilibrium concentration of component A in gas phase expressed as molar fraction  
 $\alpha$ : Loading (moles of  $\text{CO}_2$ /mole of amine)  
 $\beta$ : Aqueous MEA concentration (kg of amine per kg of water)  
 $\eta$ : Removal efficiency (%)  
 $i, o$ : Index for inlet and outlet, respectively  
 $s, e$ : Index to indicate the start and end of the saturation process, respectively.

#### Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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