

# Sustainable Engineering for the Future: a Laboratory Experiment on Carbon Dioxide Adsorption from a Carbon Dioxide-Nitrogen Gas Stream\*

NADA M. ASSAF-ANID, PETER J. LINDNER, JOHN M. IAROCCHI and NATALIE IVEZAJ  
*Chemical Engineering Department, Manhattan College, Riverdale, NY 10471, USA.*  
E-mail: nada.assaf-anid@manhattan.edu

*Undergraduate engineering students have an important role to play in curbing greenhouse gas emissions and global warming. This paper tackles the societal concern of carbon dioxide emissions from power plants by introducing a simple junior or senior-level experiment that illustrates the phenomenon of gas adsorption as a tool for carbon dioxide separation from a gas stream that simulates power plant flue gas emissions. The experiment familiarizes chemical and environmental engineering students with the characteristics of gas separation by adsorption with activated alumina, zeolite 13X, and soda lime, while highlighting its potential for carbon dioxide reduction at ambient conditions and at a relevant concentration (partial pressure) of carbon dioxide. This should be of interest to faculty who teach unit operations-type laboratory courses; they will find it an excellent 'sustainable engineering' hands-on addendum to traditional curricula.*

**Keywords:** carbon dioxide sequestration; gas adsorption; mass transfer; unit operations experiment

## INTRODUCTION

CONCENTRATIONS OF CARBON DIOXIDE (CO<sub>2</sub>) in the atmosphere have increased rapidly in the past two centuries from around 270 ppmv in 1800 to 330 ppmv at present. This increase has led the Air Resources Board of the State of California (CARB) to be the first in the US to consider CO<sub>2</sub> in its regulation of air emissions in 2002, and several other States to follow suit and sign CO<sub>2</sub> reduction bills at the State level [1]. CO<sub>2</sub> is a major contributor to the greenhouse effect, which allows all frequencies of light to reach the earth's surface, but restricts long frequencies from returning to the atmosphere, thus keeping the earth's surface at a normal temperature of 60°F. However, increased CO<sub>2</sub> emissions are causing more of the long frequencies to be trapped in the atmosphere, resulting in global warming [2].

Engineering students have an important role in devising technologies and air pollution control systems for CO<sub>2</sub> reduction. One such technology is separation by adsorption on a solid adsorbent surface. Adsorbents normally used to remove CO<sub>2</sub> are zeolite 4A, zeolite 13X, soda lime, carbon molecular sieves, silica and activated alumina [3, 4, 5, 6]. In addition, chemically modified silica has been tested at varying temperatures to determine optimal CO<sub>2</sub> removal conditions from the atmosphere [7]. Although the temperature of the adsor-

bent may be elevated for increased efficiency, normally it is cost effective to keep the temperature ambient [8]. While examples of liquid-solid and gas-solid adsorption experiments exist in the chemistry education literature [9, 10], we describe an experiment that familiarizes chemical and environmental engineering students with the characteristics of gas separation by adsorption. We also illustrate the potential of adsorption as a pollution control technology for CO<sub>2</sub> reduction from a mixed CO<sub>2</sub>-nitrogen stream at ambient conditions and at a specific CO<sub>2</sub> concentration (partial pressure), using common adsorbents (activated alumina, carbolime, soda lime). Before the experiment, the students are required to acquaint themselves with the theory and principles of the adsorption process. Specific objectives are to: determine and compare adsorbent characteristics, develop breakthrough curves and calculate the mass transfer zone for CO<sub>2</sub> adsorption, determine adsorbent capacity and adsorbent bed characteristics such as empty-bed-contact-time, superficial velocity and number of bed volumes at saturation.

## THEORY

Gas-solid adsorption is a separation process in which a target gas component (i.e. CO<sub>2</sub>), the adsorbate, is removed from a mixture (i.e. CO<sub>2</sub>-nitrogen) through accumulation onto the surface of a solid adsorbent. The gas mixture flows

\* Accepted 11 September 2007.

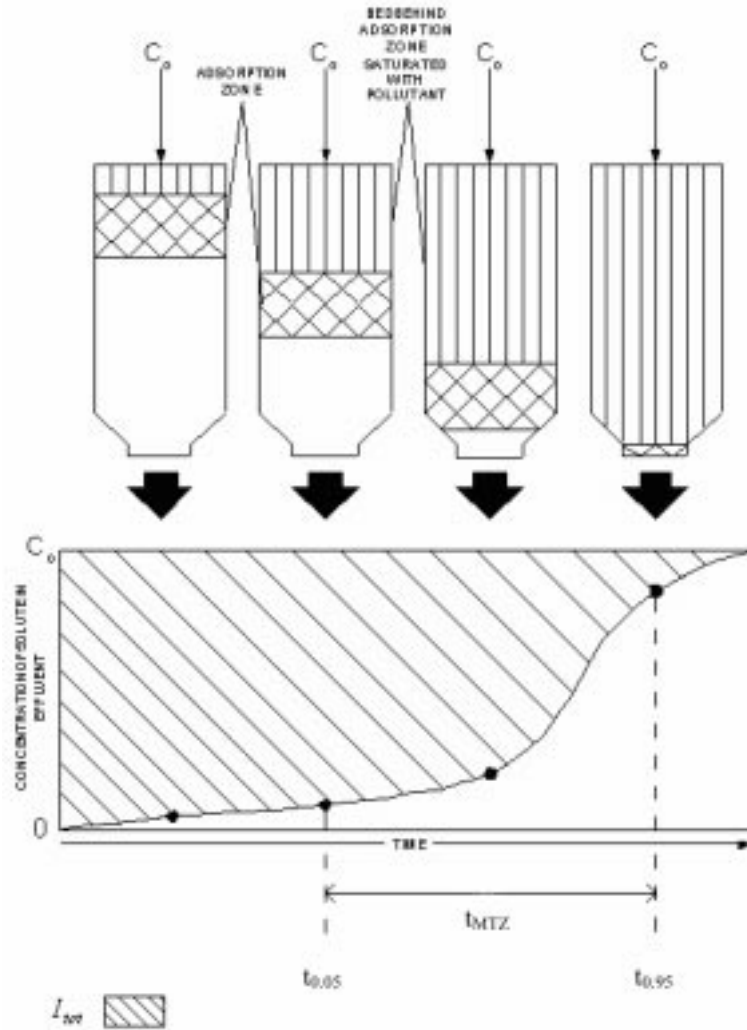


Fig. 1. Theoretical breakthrough curve.

through an adsorption bed (columns or cartridges) filled with adsorbent particles with some type of restrainer on each side. Ideally, the gas mixture flows out of the bed free of the target component as illustrated schematically in Fig. 1. Several key terms are defined and discussed below.

The Bulk Density ( $\rho_{bulk}$ ) is the amount of adsorbent material per unit volume that it occupies. This calculation must be performed on each of the adsorbents to gain information on void space. A small bulk density indicates a large porosity, while a large bulk density indicates small porosity. Less void space means more contact time, but a bigger pressure drop and greater channeling in localized areas [11]. The bulk density may be calculated as follows:

$$\rho_{bulk} = \frac{W_{bed,1}}{V_{bed}} \quad (1)$$

Where,  $\rho_{bulk}$  = bulk density, g/mL  
 $V_{bed}$  = bed volume (including voids), mL  
 $W_{bed,1}$  = bed weight, g

Porosity ( $\epsilon$ ) is the ratio of the volume of all the pores in a material to the volume of the whole. The following equation will be used to determine the porosity on the bed:

$$\epsilon = \left( 1 - \frac{\rho_{bulk}}{\rho_{particle}} \right) \quad (2)$$

Where,  $\rho_{bulk}$  = bulk density, g/mL  
 $\rho_{particle}$  = particle density, g/mL  
 $\epsilon$  = porosity, dimensionless

The Breakthrough Capacity (BC) is defined as the point where an appreciable amount of CO<sub>2</sub> is present to a point (breakthrough point) right before saturation and is calculated according to:

$$BC = CAP \left[ \frac{(Z - MTZ)}{Z} \right] + 0.5(CAP) \left[ \frac{MTZ}{Z} \right] \quad (3)$$

Where, BC = breakthrough capacity, g CO<sub>2</sub>/kg adsorbent  
 CAP = saturation capacity, g CO<sub>2</sub>/kg adsorbent

Z = height of adsorption bed, cm  
 MTZ = mass transfer zone, cm

The Working Capacity (WC) provides a numerical value for the actual adsorbing capacity of a bed of height Z under operating conditions [11]. It is given by:

$$\begin{aligned} WC &= CAP \left[ \frac{(Z - MTZ)}{Z} \right] + 0.5(CAP) \left[ \frac{MTZ}{Z} \right] \\ &\quad - HEEL \\ &= BC - HEEL \end{aligned} \quad (4)$$

Where, WC = working capacity, g adsorbate/kg adsorbent  
 CAP = saturation capacity, g CO<sub>2</sub>/kg adsorbent  
 Z = bed height, cm  
 MTZ = mass transfer zone, cm  
 HEEL = residual adsorbate present in the bed following regeneration, g adsorbate/kg adsorbent

The HEEL term is not applicable to this experiment, since regeneration is not a factor, so it is assumed to be zero. Therefore, WC and BC are equivalent (WC = BC) for this experiment.

The Saturation Capacity (CAP) is the maximum amount of 'contaminant' that the adsorbent can hold. It is equal to the mass of adsorbed contaminant at saturation divided by the total mass of adsorbent used. From a plot of C(t) vs. t, CAP is calculated as follows:

$$CAP = \frac{Q\rho_{CO_2} \int_0^{t_x} [C_{feed} - C(t)] dt - C_{feed} V_{pore} \rho_{CO_2}}{W_{bed,1}} \quad (5)$$

Where, Q = volumetric flow rate of CO<sub>2</sub>, L/min  
 $\rho_{CO_2}$  = CO<sub>2</sub> density, g/mL  
 $C_{feed}$  = feed concentration, mL of CO<sub>2</sub>/L  
 $C(t)$  = concentration at time t, mL of CO<sub>2</sub>/L  
 $V_{pore}$  = pore volume, L  
 CAP = saturation capacity, g CO<sub>2</sub>/kg adsorbent  
 $\int_0^{t_x} [C_{feed} - C(t)] dt = I_{tot}$  in equation (14) and equals the area above the curve in Fig. 1.

$V_{pore}$  is defined as:

$$V_{pore} = \varepsilon * V_{bed} \quad (6)$$

Where,  $\varepsilon$  = porosity, dimensionless  
 $V_{bed}$  = bed volume, mL

Another important concept is the Mass Transfer Zone (MTZ). The MTZ is the part of the bed where diffusion occurs. It exists due to a

non-uniform velocity profile, a non-uniform packing, the rate of adsorption, and hot spots. When using air with an activated carbon adsorption bed, the MTZ ranges from 2–4 inches [12], and for this experiment, a value of two inches is assumed. The equation below shows the relationship between the MTZ, Z, the fraction of saturation within the mass transfer zone and the CAP.

$$MTZ = \left( \frac{1}{1-x} \right) \left[ 1 - \frac{CAP_B}{CAP_S} \right] Z \quad (7)$$

Where, MTZ = mass transfer zone, cm  
 x = fraction of saturation within the mass transfer zone, dimensionless  
 Z = bed height, cm  
 $CAP_B$  = capacity at breakthrough, g CO<sub>2</sub>/kg adsorbent  
 $CAP_S$  = saturation capacity, g CO<sub>2</sub>/kg adsorbent

The MTZ can also be calculated using information from the saturation curve obtained during the lab. This is a more accurate calculation and is shown below.

$$MTZ = (t_{MTZ})(Q)/(S) \quad (8)$$

Where, MTZ = mass transfer zone, cm  
 $t_{MTZ}$  = time from 95% saturation minus time at 5% saturation, min (shown in Fig. 1)  
 Q = volumetric flow rate of CO<sub>2</sub>, mL/min  
 S = cross-sectional area of the adsorbing cartridge, cm<sup>2</sup>

The Empty Bed Contact Time (EBCT) is the time it takes the fluid to travel through the bed while it is empty and is calculated using the following equation:

$$EBCT = \frac{V_{bed}}{Q} \quad (9)$$

Where, EBCT = empty bed contact time, min  
 $V_{bed}$  = bed volume, mL  
 Q = volumetric flow rate of CO<sub>2</sub>, mL/min

The Superficial Velocity ( $V_s$ ) is the velocity of the flow through an empty column. Below,  $V_s$  is defined as the volumetric flow of the gas divided by the cross-sectional area.

$$V_s = \frac{Q}{S} \quad (10)$$

Where,  $V_s$  = superficial velocity, cm/min  
 Q = volumetric flow rate of CO<sub>2</sub>, mL/min  
 S = cross-sectional area of the adsorbing cartridge, cm<sup>2</sup>

The Throughput Volume at Saturation ( $V_{sat}$ ) is

the amount of gas that passes through the bed until saturation. It is defined by the following equation:

$$V_{sat} = (F_i)(t_{sat}) \quad (11)$$

Where,  $V_{sat}$  = throughput volume at saturation, mL  
 $F_i$  = influent gas flow, mL/min  
 $t_{sat}$  = time at saturation, min

The Number of Bed Volumes at Saturation (N) may be calculated from the throughput volume at saturation. N is equal to the number of times the flow passes through the adsorbent bed until saturation. It is given by the following equation:

$$N = \frac{V_{sat}}{V_{bed}} \quad (12)$$

Where,  $N$  = Number of bed volumes at saturation, dimensionless  
 $V_{sat}$  = throughput volume at saturation, mL  
 $V_{bed}$  = bed volume, mL

Finally, the diameter of the adsorbent particles is important during adsorption. If the particles are too large, the porosity will be large and there will not be adequate contact between the flow and adsorbent. To prevent this problem it is suggested that the particle diameter be at least 1/25th of the cross-sectional area of the adsorber [3].

Laboratory report sample questions to be answered by the students after performing the experiment are shown in Table 1 and have been incorporated in Manhattan College's Laboratory manual [13].

Table 1. Laboratory report sample questions

- 
1. Calculate and tabulate the bulk density and find the approximate surface area for each type of adsorbent in literature. Explain and compare the effect that these properties have on adsorption.
  2. Create and analyse a breakthrough graph of concentration vs. time for each run. Discuss any unusual trends and point out the breakthrough point and saturation point. Also use the information on the graph to determine the MTZ.
  3. Create and analyse a breakthrough graph of C/Co (which is the concentration at a given time over the initial concentration at that time) vs. time for each run. Explain how each graph compares to the first set of graphs and discuss their importance. Which graph better represents saturation?
  4. Calculate and tabulate the saturation capacity, breakthrough capacity, and working capacity for each of the runs. Analyse these results and determine the most efficient and least efficient adsorbent.
  5. Determine the EBCT, superficial velocity, and throughput volume at saturation for each of the adsorption. Explain the significance of these calculations.
  6. Calculate the number of bed volumes at saturation. Explain the quality of each of the adsorbents relative to each other and describe how this conclusion was determined.
- 

## EXPERIMENTAL SYSTEM

The experimental setup is shown in Fig. 2. It includes a tank with pure nitrogen, a tank with a N<sub>2</sub>-CO<sub>2</sub> mixture, a flowmeter for each tank to regulate the flow, an adsorption cartridge connected to tubing with two elbows and hose barbs, an effluent flowmeter, a LICOR-820 CO<sub>2</sub> analyser from LICOR in Lincoln Nebraska, and a computer to collect data.

## EXPERIMENTAL PROCEDURE

This procedure is described briefly as follows: Calibration, Measuring Adsorbent, Initial Preparation, Adsorption Run and Data Analysis. A more detailed description is available as supplemental material to this paper and online on the Manhattan College: Department of Chemical Engineering website.

**Calibration:** the LI-820 CO<sub>2</sub> Analyser is initially calibrated in order to determine the concentration of the influent stream properly. A stream of pure nitrogen is sent through the analyser to purge any residual carbon dioxide until the software reads a concentration of zero. At this point, the analyser is 'zeroed', which sets the concentration of CO<sub>2</sub> to its minimum value on the data range. The CO<sub>2</sub> - N<sub>2</sub> mixed stream is then introduced to the system with the pure N<sub>2</sub> stream, forming an overall CO<sub>2</sub> concentration of 15,000 ppmv and the analyzer is spanned for this value.

**(1) Measuring Adsorbent:** ten grams of the adsorbent to be investigated (soda lime, zeolite 13X, activated alumina) is measured and then baked to remove moisture and cooled in a dessicator. When cooled, the adsorbent's volume and mass are recorded and then placed rapidly into the adsorbing cartridge to ensure that it does not adsorb any CO<sub>2</sub> from the atmosphere.

**(2) Initial Preparation:** the cartridge is first filled with a ball of cotton, loaded with the adsorbent and followed by another ball of cotton. Upon loading, the cartridge is tightly sealed with Teflon tape. Data collection folders on the computer are created for each student so as to differentiate between their different runs.

**(3) Adsorption Run:** the mixed gas stream containing a CO<sub>2</sub> concentration 15,000 ppmv is then sent through the adsorbent bed. Data collection begins at the moment of the introduction of gas stream to the bed and a real-time chart is viewed as the analyser reads the effluent of the gas stream after it leaves the bed. The adsorption run is concluded when the effluent concentration is approximately equal to the influent concentration and the adsorbent bed is weighed.

**(4) Data Analysis:** the data collected from the analyser, given in Text form, are imported to Microsoft Excel and analysed. From a plot of CO<sub>2</sub> Concentration versus Time, the saturation capacity, taken from the initial time to the satura-

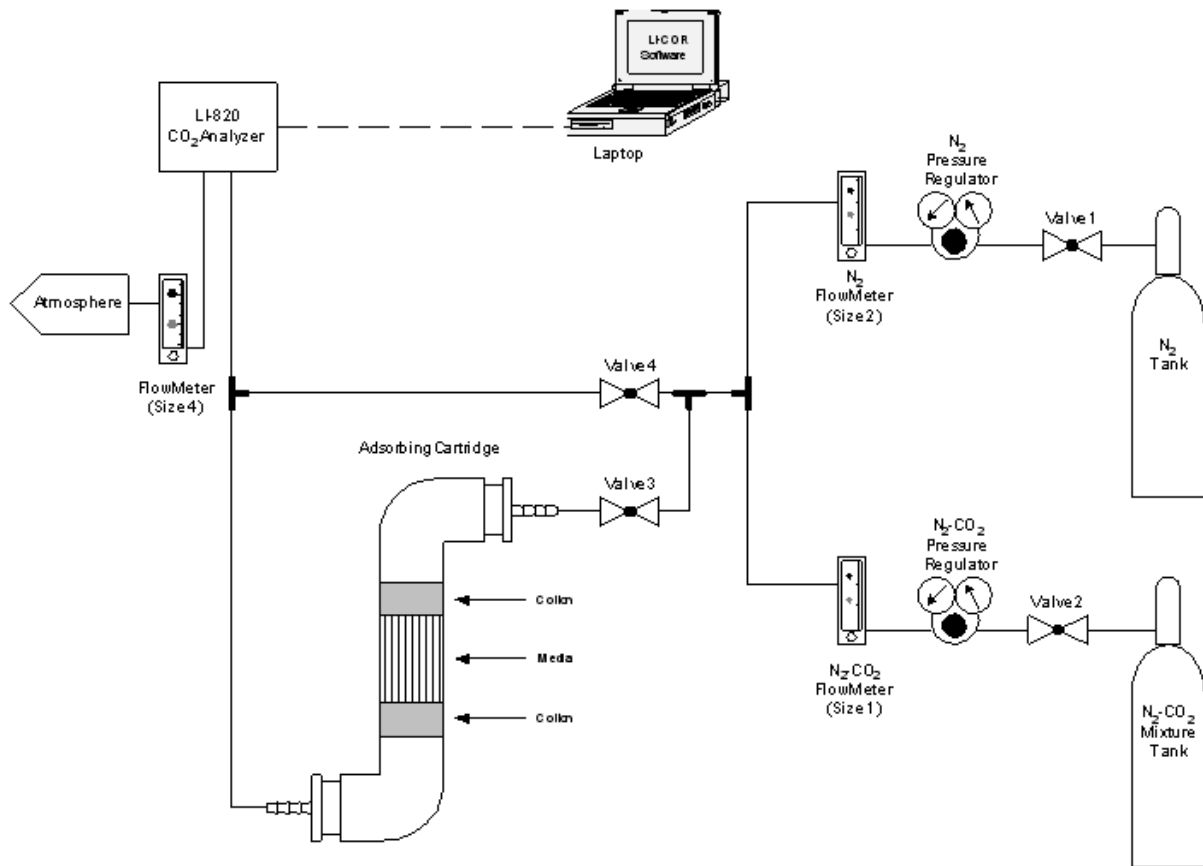


Fig. 2. Experimental system.

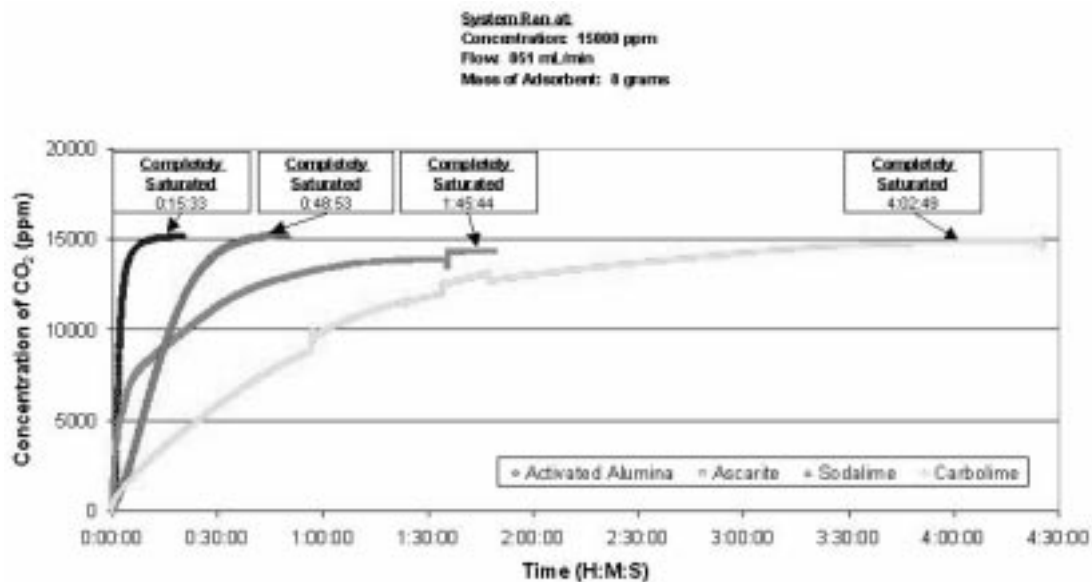


Fig. 3. Student sample results.

tion time which denotes the time when the effluent equals the influent concentration, can be determined. The area above the curve is the CO<sub>2</sub> that is being collected by the adsorbent. When the area above the curve is compared to the total area, the

ratio of CO<sub>2</sub> captured to total CO<sub>2</sub> is found. From the volumetric flow rate, density and concentration of CO<sub>2</sub> it is possible to find the total mass of CO<sub>2</sub> entering and the ratio of captured to total, will give mass adsorbed.

### TYPICAL RESULTS AND STUDENTS' FEEDBACK

Laboratory sample results are shown in Fig. 3 and agree with the literature, with carbolime exhibiting the highest capacity for CO<sub>2</sub>, followed by soda-lime, ascarite and activated alumina, respectively.

A survey was sent to seniors and Master's students asking them to comment on the experiment. The student answers to question three below indicate that they overwhelmingly found that the experiment creates awareness about the role of engineers in curbing greenhouse gas emissions. About two-thirds of the students found that the experiment is a good addition to the curriculum and most found that it illustrates the principles of mass transfer ( $n = 14$ ). In the summary shown in Table 2 below, a score of 5 indicates total agreement with the statement, and 1 indicates disagreement.

Specific student comments included:

'I really enjoyed performing the carbon dioxide adsorption experiment. I got a chance to learn how to adsorb CO<sub>2</sub> from a mixed gas stream using different adsorbents. It was a good opportunity to be

exposed to chemical engineering practices that take into account contemporary environmental concerns such as CO<sub>2</sub> industrial emissions.'

'This experiment will help chemical engineers explore new frontiers of engineering as CO<sub>2</sub> capture is becoming essential to fight global warming; what I liked is how theory is applied to a real-world problem.'

'This experiment provides a hands-on understanding of the very important process of adsorption and the underlying principles of mass transfer as well as flow properties and reactor design.'

### KNOWLEDGE GAINED AND ENRICHMENT

Student comments strongly suggest that the experiment did familiarize them with the characteristics of gas separation by adsorption with various adsorbents, while illustrating its potential for CO<sub>2</sub> reduction at ambient conditions and at a specific concentration (partial pressure) of CO<sub>2</sub>. The experiment also reinforced the theory and principles of the adsorption process. The specific objectives were clearly met: a comparison of adsor-

Table 2. Results of student assessment survey

Question	5	4	3	2	1
1. The inclusion of a Unit Operations Laboratory Experiment on Carbon Dioxide Separation by Adsorption is a beneficial addition to the Chemical Engineering curriculum	65%	21%	7%	7%	0%
2. This experiment illustrates well the principles taught in mass transfer and the process of gas adsorption as a technology for carbon dioxide separation from a mixture	56%	33%	11%	0%	0%
3. This experiment creates awareness about the role of engineers in curbing greenhouse gas emissions	79%	21%	0%	0%	0%

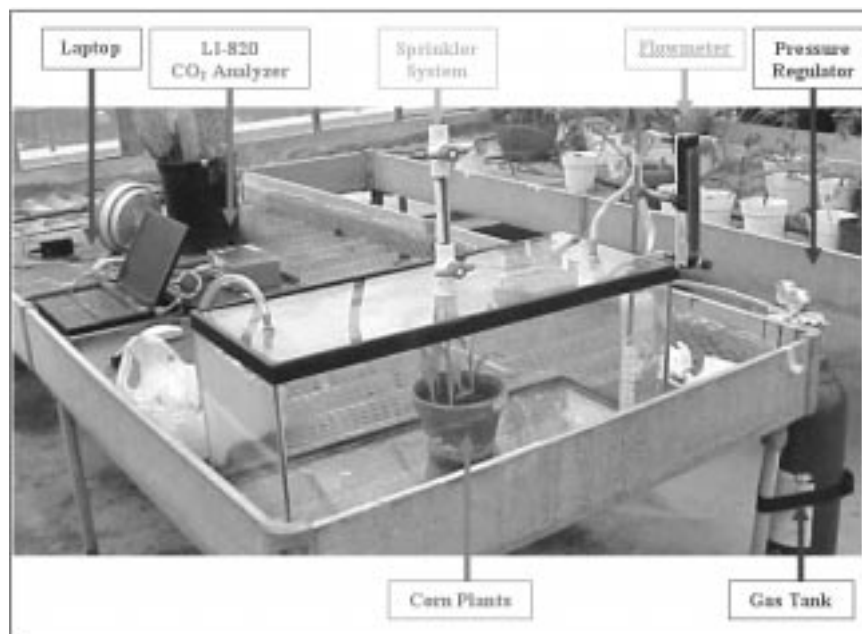


Fig. 4. Experimental system using plants for CO<sub>2</sub> removal.

bent characteristics (density, capacity) was possible, breakthrough curves were developed, calculations of the mass transfer zone were performed and adsorbent bed characteristics (EBCT, superficial velocity, number of bed volumes at saturation) were determined.

At Manhattan College, follow-up assignments were given to the students as added enrichment to challenge the students and create greater awareness about the contemporary and pressing issue of climate change and the greenhouse effect using the engineering fundamentals introduced in this laboratory experiment. Students were asked to perform the theoretical design and experimental implementation of a desorption step following adsorption. The goal being the regeneration of the adsorbent while removing the captured CO<sub>2</sub> so that it can be reused in a succession of adsorption-desorption cycles. Suggested downstream uses of the desorbed CO<sub>2</sub> were carbonation of soft drinks and water, beer brewing, etc. The results of this follow-up work are being prepared for a research publication where thermal swing was found to be the method of choice for CO<sub>2</sub> desorption by Zeolite 13X.

In addition, students were also requested to design a biological process for CO<sub>2</sub> removal. To that end, they designed a controlled greenhouse shown in Fig. 4. where plants that use the C4-photosynthesis pathway, were chosen for the process. Such plants have astounding growth rates, no detectable photorespiration and high net CO<sub>2</sub> use, and are well suited to capture CO<sub>2</sub>.

An economic analysis of the entire process is planned as an assignment in the Chemical Engineering senior-level Engineering Economics course where students will be asked to do a cost analysis for both systems described above: the inert adsorption-desorption system and the CO<sub>2</sub> biological adsorption by corn.

One possible follow-up assignment might include a computer simulation of the experiment using Aspen Chromatography, as illustrated by Wankat [14, 15] to further illustrate the underlying theory of gas separation by adsorption.

## CONCLUSIONS

This experiment is an excellent introduction of chemical and environmental engineering students to the field of CO<sub>2</sub> reduction using novel materials. It provides them with hands-on understanding of the theory of adsorption while engaging them in solving a current problem of global significance. The requirements were only basic mass transfer concepts learned in mass transfer courses in the traditional chemical engineering curriculum, with the benefit of a practical application to sometimes abstract mass transfer concepts. Another benefit is that the students obtain an appreciation of scientific testing and analysis. Additionally, the experiment gives the students a sense of satisfaction in

that they apply engineering principles to the study of an important issue they hear about in the news on a daily basis and may encounter during their professional careers.

Lastly, as worded by Mohan *et al.* [16] 'research and development will require a workforce that is well educated and trained to develop the technologies necessary for a sustainable future'. The experiment described in this paper demonstrates that such training at the undergraduate level is possible through a simple three-hour laboratory experiment. Lastly, the experiment has contributed to enriching the Chemical Engineering curriculum at Manhattan College and allowed undergraduate students to experience the thrill of finding solutions to problems in the pressing area of sustainability.

## SUPPLEMENTAL MATERIAL

### Detailed Experimental Procedure

#### Valve Control

1. Valve 1 controls the flow of influent coming from the nitrogen tank alone.
2. Valve 2 controls the flow of influent coming from the N<sub>2</sub>-CO<sub>2</sub> mixture tank alone. When zeroing, this valve must be closed.
3. Valve 3 is the valve that allows or restricts the flow to come into contact with the adsorbent. When calibrating, this must remain closed.
4. Valve 4 is the valve controlling the flow directly to the analyzer. This must be open during the calibration, but closed during the runs.

#### Calibration

Make sure valve 3 is closed, and valve 4 is open. Open the nitrogen tank valve 1 and set the nitrogen flowmeter to 140 (800 mL/min). To determine if the flow is proper, make sure the effluent flow meter slightly fluctuates. On the computer program hit the connect module icon (Seen in Fig. 3) and click connect when the window pops up. Go to view on the toolbar, calibration and click on zero. Click ok to zero the gas. When the program is done zeroing, set the CO<sub>2</sub>-N<sub>2</sub> mixture flowmeter to 92. Wait at least two minutes and then type 15,000 into the box for the span value and click ok. If the readings are not around 15,000 ppmv after spanning, span it again until the values are close to 15,000.

#### Measuring Adsorbent

Measure out 10 grams of the first adsorbent (soda lime). Bake the 10 grams at 110°C to remove the moisture. After the moisture is removed, weigh out 8 grams and let it cool in a desiccator. Record this weight exactly; this is the weight of the bed. Fill a graduated cylinder with the adsorbent and slightly shake it until the particles are packed in nicely. Record the volume at the top of the particles; this is the volume of the bed.

Finish this step as quickly as possible. It is important to place the adsorbent into the cartridge and away from the atmosphere as soon as possible to minimize the risk of adsorption.

#### Initial Preparation

Open the adsorbing cartridge by twisting the sides and fill one side with some cotton. Load



Fig. 5. Adsorbing cartridge.

the measured 8 grams of soda lime into the cartridge after the cotton. Fill the other side of the cartridge with cotton as well. Close the cartridge using Teflon tape to seal the connections on each side if necessary as shown in Fig. 5.

Turn on the computer, hitting cancel when it asks for a user name. Create a folder on the desktop with your group number so that your files may be saved in the same location. Open the start menu, go to programs, and then click on LI-820. Open this program and plug in the LI-820 module. A green light should appear on the analyser to indicate that it is on. If this does not turn on, or other lights turn on as well, please inform the laboratory technician.

#### Adsorption Run

When the reading is close to the span value, begin logging. This is accomplished by going to logging on the toolbar and clicking start. Enter a file name and save it to the folder created earlier on the desktop. Next, a chart should be viewed to see the run in its entirety. This can be done by going to view and clicking charting. In this window a time of 90 minutes should be entered with the y axis going from zero to a value higher than the influent concentration (16,000 ppmv). Click start to begin charting. This allows the user to view the graph as it is being recorded. When the red line appears on the graph, open valve 3 and close valve 4 to begin the experiment and allow the carrier gas plus CO<sub>2</sub> to travel through the media and be analysed. The concentrations will become higher with time until the effluent concentration is approximately equivalent to the influent concentration. This concludes the first run of the experiment. Click stop on the charting graph, and click stop on the logging

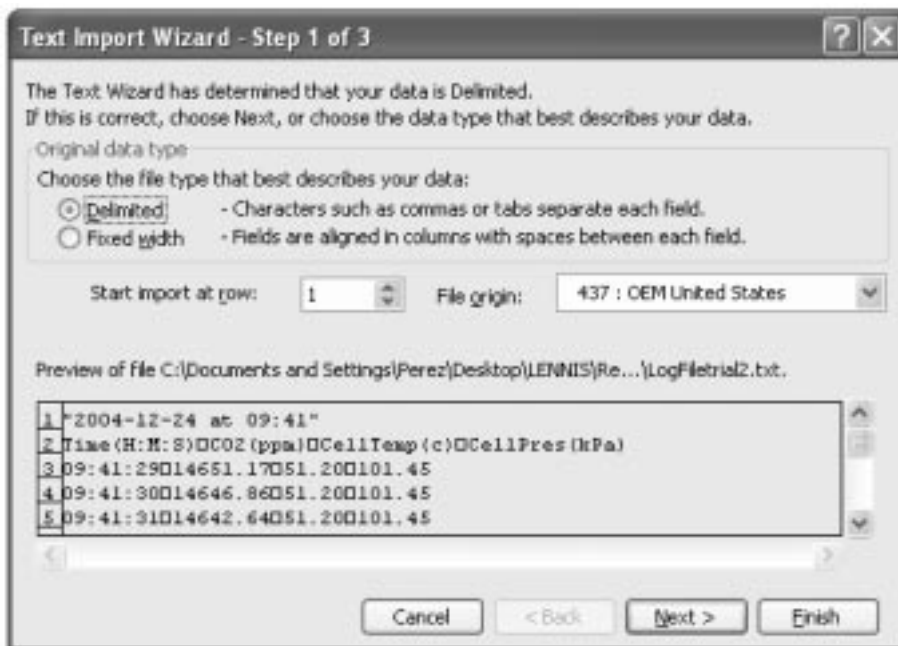


Fig. 6. Text import wizard window



	N	O	P	Q	R	S	T	U	V
9				Influent, ppm	15200.01				
10									
11			<b>Sodalime</b>						
12			Time(H:M:S)	Time	CO2(ppm)	Area under the curve	Area Above the curve		
13			22:46:14	0:00:00	-50				
14			22:46:15	0:00:01	-50	-0.000579	0.176505		
15			22:46:16	0:00:02	-49.77	-0.001156	0.353008		
16			22:46:17	0:00:03	-37.68	-0.001662	0.52944		
17			22:46:18	0:00:04	-28.59	-0.002046	0.70575		
18			22:46:19	0:00:05	-21.75	-0.002337	0.881967		
19			22:46:20	0:00:06	-15.98	-0.002555	1.058112		
20			22:46:21	0:00:07	-11.2	-0.002713	1.234195		
21			22:46:22	0:00:08	-7.09	-0.002818	1.410227		
22			22:46:23	0:00:09	-3.49	-0.00288	1.586214		
23			22:46:24	0:00:10	-0.57	-0.002903	1.762164		
24			22:46:25	0:00:11	1.97	-0.002895	1.938082		

Fig. 7. Spreadsheet showing sample data for sodalime run.

section of the toolbar. Close valves 1 and 2. Go to file in the toolbar and click disconnect.

Open the cartridge and weigh the adsorbent. Be careful to weigh all of the adsorbent and not any cotton (or anything else).

Repeat steps 3 to 5 for zeolite 13X and activated alumina. Each should be weighed out at 8 grams. It is not necessary to recalibrate between runs unless unusual results appear.

#### Data Analysis with Microsoft Excel

In this experiment saturation capacity is found graphically. This is done by opening the data processed from the LI-820 software as an Excel spreadsheet file. It might be necessary to use Text Import Wizard if the data don't separate automatically (shown in Fig. 6).

In Text Import Wizard, the first step will ask to choose between delimited and fixed length. Delimited will separate automatically according to characters like commas or tabs already in the document. The LI-COR software puts tabs between each of the columns so delimited is the best choice.

Now that this file has been imported into an Excel spreadsheet it is ready for analysis. In Excel, there will be four columns present, entitled as Time, CO<sub>2</sub>, CellTemp, and CellPres. CellTemp and CellPres columns give the temperature and pressure inside the analyser in Celsius and kilopascals. These columns are not necessary so they can be removed from the spreadsheet. The Time

and CO<sub>2</sub> columns give time in H:MM:SS and CO<sub>2</sub> concentration in ppmv.

A column showing the time difference should be created alongside the original Time column. This column begins with 0:00:00 where CO<sub>2</sub> is at a minimum. This new Time column is then used to give the time difference between each point.

The first group of points from the Excel data can be used as the influent concentration, assuming both flow meters are kept constant during the experiment. This value of influent concentration can be used to find the saturation time. As the experiment is ran, the CO<sub>2</sub> concentration will vary when it reaches its initial concentration. This is the saturation time.

Once an initial time and saturation time have been determined, it is necessary to find the saturation capacity. In the plot of CO<sub>2</sub> Concentration vs. Time the saturation capacity is defined as the area above the curve. The area above the curve is the CO<sub>2</sub> that is being collected by the adsorbent, and not going through the analyser. To find this area the trapezoidal rule is implemented from the initial time to saturation time. The area of a trapezoid is found from the following equation.

$$I = \frac{(b_1 + b_2)}{2} * h \quad (13)$$

Where,  $I$  = area of a trapezoid  
 $b_1$  = first base of trapezoid  
 $b_2$  = second base of trapezoid  
 $h$  = height of trapezoid

Using this calculation the area of each trapezoid is calculated and summed together to find the area as a whole. In this problem, each trapezoid is calculated by using the change in time as the height, and the difference from influent to actual CO<sub>2</sub> concentration as each base.

$$I_{tot} = \frac{(C_i - C_1) + (C_i - C_2)}{2} * (t_2 - t_1) \quad (14)$$

Where,  $I$  = total area above the curve, equal to integral in equation (5)

$C_i$  = influent concentration of CO<sub>2</sub>

$C_1$  = CO<sub>2</sub> concentration at point 1

$C_2$  = CO<sub>2</sub> concentration at point 2

$t_1$  = time at point 1

$t_2$  = time at point 2

In the Excel spreadsheet shown in Fig. 7, a column should be made for each of these areas, and a column of their sums as show on the sample spreadsheet below.

Note that the area above the curve for a specific time can be calculated as shown above. The cell that has been selected shows how the equation is inputted to calculate the area at that specific time. The total sum at saturation time gives the area over the curve. When the area above the curve is compared to the total area, the ratio of CO<sub>2</sub> captured to total CO<sub>2</sub> is found. From the volumetric flow rate, density and concentration of CO<sub>2</sub> it is possible to find the total mass of CO<sub>2</sub> entering and the ratio of captured to total, will give mass adsorbed.

## REFERENCES

1. E-Wire, Environment, Health, Science, Technology. *BAT International Inc. Discusses First U.S. CO<sub>2</sub> Reduction Bill; California Governor Gray Davis Signs Bill.* (2002). [http://www.ewire.com/display.cfm/Wire\\_ID/1255](http://www.ewire.com/display.cfm/Wire_ID/1255)
2. L. Theodore and M. Theodore, *Major Environmental Issues Facing the 21st Century*, Prentice Hall, Upper Saddle River New Jersey, 1996. (Currently available through Theodore Tutorials, East Williston, NY).
3. P. C. Wankat, *Separation Process Engineering, 2nd ed*, Prentice Hall, Englewood Cliffs, NJ, (2007).
4. J. Reynolds, J., L. Theodore and Jeris, J., *Handbook of Chemical and Environmental Engineering Calculations*, John Wiley & Sons, Hoboken, NJ, (2002).
5. Z. Yong, V. Mata and A. E. Rodrigues, Adsorption of CO<sub>2</sub> on Basic Alumina at High Temperatures. *Journal of Chemical Engineering Data*. **45**(6), 2000, pp. 1093–1095.
6. H. Song, K. Cho and K. Lee, Adsorption of CO<sub>2</sub> on the Chemically Modified Silica Adsorbents. *J. Non Crystal Solids*. **24**(22–3), 1998, pp. 69–80.
7. H. Song and K. Lee, Adsorption of CO<sub>2</sub> on Chemically Modified Carbon Adsorbents. *Separation Science Technology*. **33**(13), 1998, pp. 2039–2057.
8. Z. Yong, V. Mata and A. E. Rodrigues, Adsorption of CO<sub>2</sub> at High Temperature—a review. *Separation Purification Technology*. **26**(2–3) 2002, pp. 195–205.
9. D. Fernandes and A. Xavier, Dynamic and equilibrium adsorption experiments. *J. Chem. Educ.* **82**(6), 2005, pp. 919–923.
10. L. Tribe and B. C. Barja, Adsorption of Phosphate on Goethite. An Undergraduate Research Laboratory Project. *J. Chem. Educ.* **81**(11), 2004, pp. 1624.
11. W. L. McCabe, J. C. Smith and P. Harriott, *Unit Operations of Chemical Engineering*, 7th ed., McGraw Hill, New York, (2005).
12. L. Theodore, Personal Communication.
13. J. Famularo, A. M. Flynn, H. C. Hollein, C. S. Slater, N. Assaf-Anid and L. Theodore, *CHML-403/404 Chemical Engineering Laboratory Manual*, Manhattan College Press, Riverdale, NY, (2006).
14. P. C. Wankat, Integrating the use of commercial simulators into lecture courses. *J. Eng. Educ.* **54**, 2002, pp. 19–23.
15. P. C. Wankat, Using a Commercial Simulator to Teach Sorption Separations. *Chem. I Eng. Educ.* **40**(3), 2006, pp. 165–172.
16. M. A. Mohan, N. May, N. M. Assaf-Anid and M. J. Castaldi, Biomass as a Sustainable Energy Source: An Illustration of Chemical Engineering Thermodynamic Concepts. *Chem. I Eng. Educ.* **40**(4), 2006, pp. 259–267.

**Nada Marie Assaf-Anid** is Associate Professor and Chairperson of the Chemical Engineering Department at Manhattan College. She earned her BS and MS in Chemical Engineering from the Royal Institute of Technology in Stockholm, Sweden, and her Ph.D. in Environmental Engineering from the University of Michigan in Ann Arbor. Her research and teaching interests are in separations, biochemical engineering, hazardous chemicals remediation, thermodynamics and water purification. She is Director of the ASEE Chemical Engineering Division and of the Environmental Division of AIChE.

**Peter John Lindner** graduated from Manhattan College in May 2005 with a BS in Chemical Engineering, and received his MS from Manhattan College in Chemical Engineering in December 2006. As a student he was an active member of the AIChE and contributed much of his time to research on air pollution and the greenhouse effect. He is currently working as a Commercialization Engineer for PepsiCo.

**John Matthew Iarocci** graduated from Manhattan College in May 2005 with a BS in Chemical Engineering, and received his MS from Manhattan College in Chemical Engineering in September 2006. His undergraduate research work was on adsorption techniques, particularly for the removal of arsenic from drinking water and led to several presentations at regional and national conferences. He is currently working as a Validation Engineer for Wyeth Pharmaceuticals.

**Natalie Ivezaj** graduated from Manhattan College in May 2005 with a BS in Chemical Engineering, and received her MS from Manhattan College in Chemical Engineering in December 2006. Her research is in computational chemistry, particularly in structural activity relationships for polybrominated diphenyl ethers. She is currently working as a Packaging Engineer for Victoria's Secret.