

PRESSURE SWING ADSORPTION IN THE UNIT OPERATIONS LABORATORY

JASON C. GANLEY

Colorado School of Mines • Golden, CO 80401

Pressure swing adsorption (PSA) is an industrial process typically used for the bulk separation of gas mixtures. An outgrowth of temperature swing adsorption, PSA is one of only a few gas-surface adsorption processes that allows for the separation of mixtures of gaseous species or vapors that exist in relatively high (non-trace) concentrations in respect to one another. PSA has also been coupled to distillation processes for the separation of alcohol-water vapor azeotropes.^[1]

It is interesting to note that, despite serving an important role for many decades in the chemical process industry, PSA is not a central topic discussed in most chemical engineering educational resources, which instead focus on mass transfer unit operations. To the author's knowledge, the present communication represents the first reported incorporation of PSA within an undergraduate unit operations laboratory.

While PSA is commonly used for hydrogen and hydrocarbon systems, it is also a popular process for the separation of air into product streams of enriched nitrogen, or of enriched oxygen. The process of air separation by PSA is an excellent illustration of the principles of gas-solid mass transfer within a unit operations laboratory course—there are no harmful chemicals involved, the operational pressures are not excessively high, the effective gas concentrations are easily measured and distinguished, and the equipment lifetime is practically unlimited (provided that the feed air is properly filtered and dried). The physical and chemical phenomena utilized in a PSA system are quite simple, and PSA units are usually designed to take advantage of one of two distinct aspects.

- 1) *Kinetic Control*: In porous solids, there may be a difference in the rate at which various gases may diffuse to and from regions of the solid surface.
- 2) *Equilibrium Control*: Over a range of partial pressures of species within a mixture of gases, there may be differing equilibrium surface concentrations of adsorbed gases on solid materials that are exposed to the gas mixture.

Therefore, the nature of the adsorbent material will strongly influence the amount of adsorption and the speed at which

adsorption occurs. The selection of a particular type of adsorbent may allow one component of a gas mixture to be preferentially adsorbed, the nature of surface and/or pore diffusion effects may vary for each gas in the mixture, and so on.

PSA is a cyclic operation, and generally involves separation of a gas mixture by taking advantage of differences in adsorption thermodynamics or in diffusion rates that exist for its various components. Cycling between higher and lower pressures allows components of the gas mixture to be removed from (and later released to) the gas phase over designated periods of time. Students in the Unit Operations Laboratory may consider the PSA cycle primarily as a mass transfer (rather than heat transfer) experiment. The packed beds used in commercial PSA units are designed to be isothermal over an entire cycle. That is, although there are usually large exotherms for gas adsorption (and large endotherms for desorption), the adsorption exotherms are used to provide the necessary heat for desorption of the same gases during pressure reduction or purge steps later in the cycle. Additionally, large systems usually have sufficient heat capacity (or thermal mass) so that large temperature variations do not develop within the system.

In this laboratory exercise, students use a custom-built, four-column PSA system; one pair of columns contains carbon molecular sieve (CMS) adsorbent, and the other pair is filled with 13X molecular sieve (sodium alumina-silicate). Students are able to vary a wide range of experimental parameters within the system. These include, but are not limited to:

- Adsorption pressure
- Purge gas type, flow rate, and pressure

Jason Ganley is an associate teaching professor of chemical engineering at the Colorado School of Mines. He earned a B.S. degree from the University of Missouri-Rolla and M.S. and Ph.D. degrees from the University of Illinois at Urbana-Champaign, all in chemical engineering. His current research focuses on the production of alternative fuels from renewable energy.



- Feed and product flow rates/gas residence time
- Column flow configuration/cycle style

A more detailed description of the experimental apparatus and its operation will follow.

INDUSTRIAL PRACTICE AND LITERATURE REVIEW

PSA was developed independently by the Air Liquide and Exxon corporations in the 1960s. Since then, it has proven to be a versatile and effective process for separation or purification of many gas systems; high final product purities are routinely achieved. The application of PSA to air separation can produce nitrogen products of 99.9+% purity, and oxygen product purities exceeding 95%.^[2] Since its introduction to the chemical process industry, research and development of PSA processes have led to several significant process improvements and variations, most of which are simply timing or sequence modifications to the earliest pressure swing cycles.^[3] The various cycles and their modifications are most easily illustrated in terms of systems with two columns packed with adsorbent. In such a system, these columns may be used independently, or in tandem. Two of the more common industrial cycles for two-column systems are illustrated in Figure 1.^[4]

Figure 1 illustrates two different pressure swing cycles with a two-column system. Figure 1(b) does not illustrate a direct interaction between the two columns, although it is worth noting that multiple

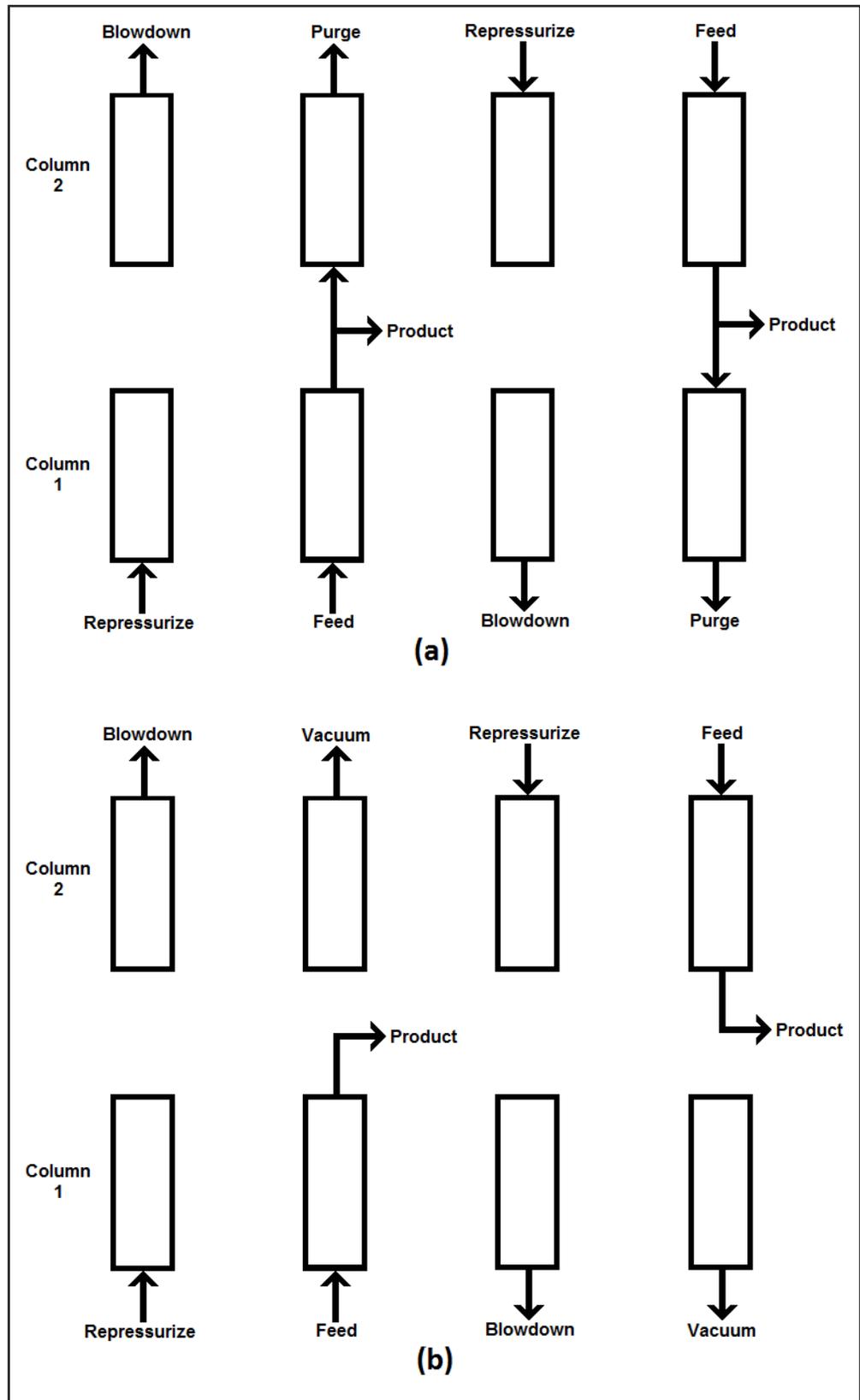
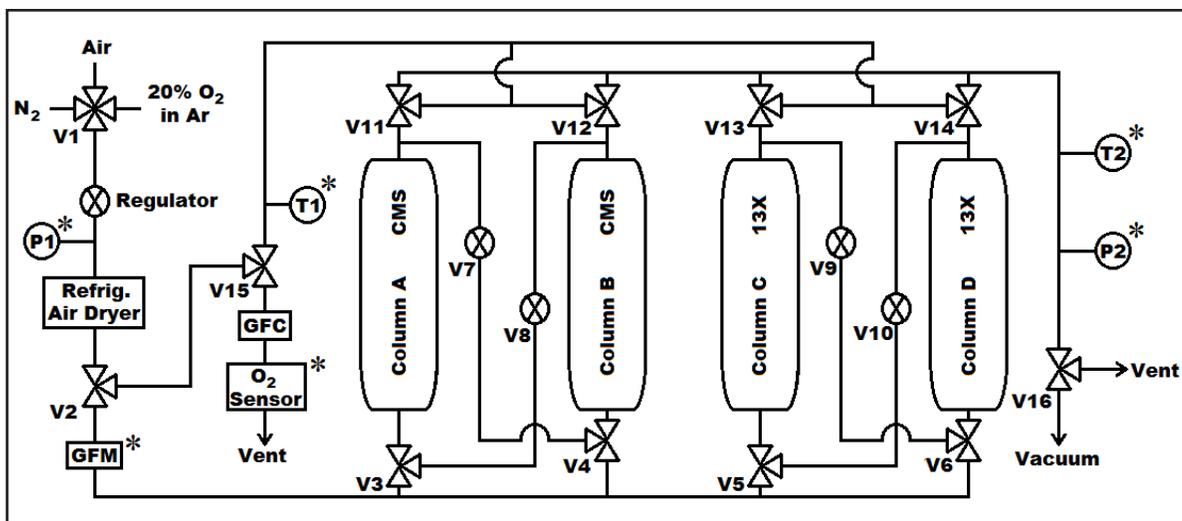


Figure 1. Example PSA cycles: (a) backfill cycle, (b) vacuum swing cycle.

Figure 2. PSA experimental process flow schematic. Measurements with an asterisk (*) indicate sensors with automatically logged analog outputs.



columns would be required to allow for continuous product collection. As an operational example, consider the backfill cycle in Figure 1(a) as applied to nitrogen production. In this case, the adsorption packing is chosen and used to preferentially hold up oxygen (rather than nitrogen) in the column during the period of product collection. Below, a short description of each process step in the cycle is described, along with an associated statement of gas/surface interaction.

Step 1: Freshly purged and at a low (*e.g.*, atmospheric) pressure, Column 1 is quickly pressurized with an air feed stream to the system's selected working pressure. Simultaneously, Column 2 is saturated with adsorbed oxygen at the working pressure, and is vented to the atmosphere (blowdown). In Column 1, the adsorption packing quickly fixes oxygen onto its surface, allowing proportionally more nitrogen to remain in the gas phase. As the column pressure increases, the equilibrium surface concentration of adsorbed oxygen rises correspondingly. In Column 2, the drop in total pressure reduces the partial pressure of oxygen in the gas phase, changing the system gas/surface equilibrium in the opposite direction; oxygen gradually desorbs from the packing and exits the column until a new gas/surface equilibrium condition is reached at atmospheric pressure.

Step 2: The product valve is opened for Column 1, and an initially nitrogen-rich stream is sent for collection. A small amount of this product stream is diverted to Column 2, where it surrounds the packing with a low-pressure, oxygen-deficient environment; this causes further oxygen desorption in accordance with the continuing gas/surface equilibrium approach. The vent valve from Column 2 remains open, allowing for the continued purging of the column. The stream diversion to Column 2, which serves to further purge its adsorbed oxygen, is known in practice as "backfilling." In Column 1, oxygen from the feed air continues to adsorb on the packing at the system's operating pressure until the packing nears saturation.

Step 3: When the nitrogen purity of the product gas nears its lower allowed limit, the product release valve is closed. The feed to Column 1 and the purge valve for Column 2 are both closed, and Column 2 is now charged with feed air while Column 1 is blown down.

Step 4: Column 2 provides backfilling to Column 1 while generating more nitrogen-rich product gas until the minimum product purity is once again reached. Closing the product, feed, and purge valves once again resets the system to the cycle's beginning (Step 1).

Industrial pressure swing adsorption systems operate by continuously repeating such cycle steps, executing them with automated valves and some form of integrated product gas storage.^[5] Typical systems may take many complete cycles to reach a round trip steady-state operation^[6,7] as well. The time-intensive impact of each of these characteristics indicates that an experimental system designed for student laboratory operation should be designed for the direct study of cycle steps, rather than system performance over a number of complete cycles. Following this logic, a pressure swing adsorption system for the separation of air in the Unit Operations Laboratory was built to achieve flexible operation through hands-on manipulation and automated data acquisition.

LABORATORY SETTING AND EXPERIMENTAL MODULE

The instructional goals and teaching methods for the Unit Operations Laboratory at the Colorado School of Mines (CSM) has been thoroughly described elsewhere.^[8,9] The primary functional difference between the laboratory at CSM and its counterparts at most other universities is that it is offered as a stand-alone summer (field session) course, which allows students an extended experimental work time versus what is generally possible for typical lab courses offered during an academic semester or quarter. The scheduled lab times enable

students to work on a given experiment for a period of up to 8 hours. Longer lab periods provide significant freedom for team-by-team experimental design decisions, and additionally make possible the use of larger, more flexibly applied laboratory modules.

An operational schematic of the PSA experiment in use for the Unit Operations Laboratory at CSM is shown in Figure 2. Six process measurements are continuously logged using a commercial data acquisition system (DataTaker model DT85): feed pressure (P1), purge pressure (P2), product temperature (T1), purge temperature (T2), input gas flow, and product oxygen concentration. Students are provided with a selection of feed gases for the system: compressed air, nitrogen, and a 20% oxygen mixture in argon. The compressed air is available from building utility lines (~80 psi), and the other gases are sourced from compressed gas cylinders (regulated to ~20 psi). The process feed gases are supplied to a four-way valve (V1) with check valves to prevent backflow during gas interchange. The selected feed is manually regulated, and the feed pressure is automatically logged with a pressure transducer (Omega model PX309-100GV). The feed gases are dried sequentially by refrigeration (Parker model PRD15-A11516016TXU) and calcium sulfate desiccant packing. A bypass option is provided at V2 to allow the feed stream to go directly to the exit line, which is a useful method for verifying the feed composition.

Feed flow to the columns is measured using a thermal mass flow meter (Aalborg model GFMS-011327). The flow pathways to and from the columns are controlled using the valves on the various control panels located around the PSA assembly. Three-way input valves (V3 – V6) allow each column to be provided with fresh feed gas or the product of its counterpart through lines equipped with manual threaded flow-adjustment valves (V7 – V10). This allows for a number of experimental options—a small amount of product gas may be used to purge a saturated column (backfilling), pressure may be equalized between columns as an independent cycle step, or two columns may be connected in series when flow-adjustment valves are fully open.

The adsorption columns are four steel pipes (schedule 40, 10.2 cm ID), each 152 cm in length. The columns are vertically wall-mounted, and contain randomly packed pellets of molecular sieve. The leftmost columns, designated Column A and Column B, each contain a porous carbon molecular sieve (CMS, Hengye CMS 260). CMS has pores with microporous openings^[10]; these pore mouths allow gases with smaller kinetic diameters (such as O₂) easier access to the internal surface than molecules with a larger kinetic diameter (such as N₂). The rightmost columns, designated Column C and Column D, each contain zeolite 13X (13X, Hengye 13X812MS), which is a silica-alumina clay with a significant amount (up to 20%) of sodium oxide. Nitrogen molecules have a much greater surface equilibrium concentration than oxygen

molecules on 13X, resulting in an initially oxygen-rich gas phase when the zeolite is exposed to air.^[11] The availability of both packing types enables students to examine the stepwise performance of a system controlled either kinetically (CMS, nitrogen production) or by surface/gas equilibrium (13X, oxygen production). The study of cycle steps is isolated to either nitrogen or oxygen production, so Columns A and B are not used in cycles with Columns C and D, and vice versa. Columns A and B contain 7.5 kg of CMS (packing density = 0.559 g cm⁻³, void volume = 9.35 L), and Columns C and D contain 8.6 kg of 13X (packing density = 0.637 g cm⁻³, void volume = 9.83 L).

Exiting streams from the column may be routed to either an exhaust line or to a product line using another series of three-way valves (V11 – V14). The exhaust line may either vent to the atmosphere, or be connected to house vacuum (ca. -12 psig) using V16. On the product line, flow is controlled with a thermal mass flow controller (Tylan General model FC-261V-4S). The exit composition is measured with an electrochemical oxygen sensor (Vernier model O2-BTA), which has been provided with a higher excitation voltage (12 DC volts vs. the stock 5 DC volts) to increase its span from 0 – 27% O₂ to 0 – 100% O₂.

STUDENT EXPERIMENTAL WORK AND DATA ANALYSIS

The instruction style for the Unit Operations Lab at CSM requires students to thoroughly familiarize themselves with the overall system before creating a list of experimental objectives as well as a detailed plan for achieving those objectives. After a cursory analysis of the experimental system, students quickly realize the critical role of the oxygen sensor. Coupled with the feed and exit flow measurements, the oxygen sensor allows material balances to be carried out over time on oxygen—enabling students to determine, for example, the amount of oxygen held up in the column during an absorption trial, or the amount of oxygen released to the atmosphere during a blowdown step after solving an oxygen balance on all other steps. Stepwise oxygen balances (and the implication of these balances for inferred nitrogen or argon balances) are the common elements of a wide range of experimental designs. These designs may include:

- *Isolation of enriched nitrogen or enriched oxygen of a specified purity*
- *Purging of one column with product gas from another (backfilling)*
- *Application of vacuum for vacuum swing adsorption (VSA) study*
- *Use of columns in series or parallel arrangement*
- *Pressure equalization between columns, or traditional 4-step cycles*

For the purposes of the present communication, the experimental goals and data analysis for one student-designed experimental set are presented: the production of high-purity nitrogen from air using CMS. In this case, students chose to examine the effects of adjusting system working pressure on the production of nitrogen from a PSA air separation cycle using CMS. The selected cycle style has four steps, and would in practice be very similar to the cycle shown in Figure 1(a). However, as there is no product storage vessel, purging is accomplished by using nitrogen from a compressed gas cylinder. Monitoring of effluent gas from the column in use with the oxygen sensor is possible for every step in the cycle except blowdown, in which case the gas must be released very rapidly to the atmosphere from the column. The oxygen balance for the blowdown step will therefore be determined by first completing balances for the other three steps: how much oxygen enters the column during pressurization, how much oxygen builds up during product collection, and how much is released from the surface during purging.

An important consideration for the students involves argon (1% of the entering air) within the system. A literature review of CMS quickly reveals the nature of its operation in a kinetically controlled adsorption system when applied to air separation: It is expected that oxygen will be held up in the column owing to the microporous packing combined with oxygen's smaller kinetic diameter versus nitrogen (3.64 Å vs. 3.46 Å). Considering that argon has a similar kinetic diameter to oxygen gas (3.40 Å),^[12] it follows that the column will effectively screen out oxygen and argon—thus, a 0% O₂ reading at the sensor would imply a 100% N₂ product stream.

The main process variable adjusted in this particular case was the system working pressure. While house compressed air is available at nearly 90 psig, compressor cycling and house air use by other laboratory experimental stations creates a practical upper regulated limit of about 80 psig. The students designed a series of three experiments with working pressures of 25, 50, and 75 psig. In each case, the column was purged with nitrogen gas at atmospheric pressure before beginning the experimental trial. Flow from the columns was always limited to 10 L min⁻¹ using the exit flow controller. The process steps were carried out as follows:

1. **Pressurization:** *The air feed pressure was adjusted using the regulator to match the selected working pressure, and the column inlet valve was opened with the exit valve closed. The rate of air entering the column was monitored, and when the value was equivalent to the chosen product flow rate (10 L min⁻¹), the product valve was opened.*
2. **Production:** *The composition of the gas leaving the column was monitored until its instantaneous oxygen composition reached about half of the value for air (10.5%). The column feed was then closed, and the column exit was redirected to the exhaust line's atmosphere vent.*

3. **Blowdown:** *The column is returned to atmospheric pressure as quickly as possible. When the pressure in the exhaust line reaches zero, the column exit is redirected to the product line, and low-pressure nitrogen is introduced as feed.*
4. **Purge:** *Pure nitrogen is introduced into the column at a rate of 10 L min⁻¹ to rinse the packing of adsorbed oxygen. The oxygen sensor is monitored, and the nitrogen feed is stopped when the exit oxygen concentration reaches zero.*

The system outlet flow is controlled and constant, while both the feed flow and the outlet oxygen concentration are directly measured and automatically recorded. Analysis of the column's performance is typically expressed in terms of nitrogen recovery, net product purity, adsorption analysis, and cycle design through proposed step-by-step timing. Where applicable, the oxygen concentration, feed and exit flow rates, and elapsed time for each cycle steps may be used to track the oxygen and nitrogen in the system, allowing for simple evaluation of product purity and product recovery. For the case of nitrogen production, monitoring the oxygen concentration for a known total product flow over time during the production step permits the direct calculation of the net product purity. The calculation of nitrogen recovery requires only a determination of the amount of nitrogen in the product as a fraction of the sum of nitrogen sent to the column (as air) during the pressurization and production steps, as well as the amount of nitrogen used during the purge step.

Adsorption analysis is a general examination of the column's performance during the pressurization and production steps. Generally, students find that the generation of breakthrough curves can provide a number of useful system insights; examples of these are how much capacity the adsorbent has under various conditions, how much of the bed may be saturated after a given time, and how all of this information might apply to scaling up the PSA system to meet a specific production target.

The assigned text for our Unit Operations Lab^[13] provides some general background for the analysis of adsorption in packed beds. Some of the most useful material for students performing the PSA experiment is the discussion of concentration profiles in a column during adsorption, which may be inferred from breakthrough curves. An important general result relates the saturation capacity of the packing (W_{sat}) to the amount of time that would be required for the solute to break through in the absence of both axial dispersion and mass transfer resistance (t^*):

$$u_0 c_0 t^* = L \rho_b (W_{\text{sat}} - W_0) \quad (1)$$

Here, the superficial velocity of the fluid and its solute concentration (u_0, c_0) are considered along with the physical properties of the packed column: its length (L), the bulk density of the particles within (ρ_b), and finally the saturation and initial

(W_0) capacities of solute on the packing. It is worth noting that this basic approach to analysis of a PSA system focuses on material balances and system performance/scale up, so that students must make simplifying assumptions regarding complicated phenomena such as axial dispersion and molecular diffusivity in both the gas and surface phases. A more complete treatment of PSA modeling is found elsewhere.^[14]

In the case of removal of oxygen from air by adsorption on CMS, the initial loading of oxygen on the column packing is determined using a material balance for the air introduced into the column during pressurization.

If the initial exit oxygen concentration of the product air is zero, then it is reasonable for the students to assume that all of the oxygen from the pressurization air has been adsorbed, determining the value for W_0 . The concentration of oxygen in the incoming (dried) air is known ($c_0 = 209$ ppt), and the superficial velocity is determined by dividing the volumetric flow entering the column by the nominal section area of the pipe (~ 82.1 cm²). The packing length and bulk density are provided (see the Laboratory Setting and Experimental Module section above). Students may therefore calculate the saturation capacity (W_0) of the column by measuring breakthrough curve data up to the ideal time (t^*). If a symmetric breakthrough curve is assumed, t^* will be the exit oxygen

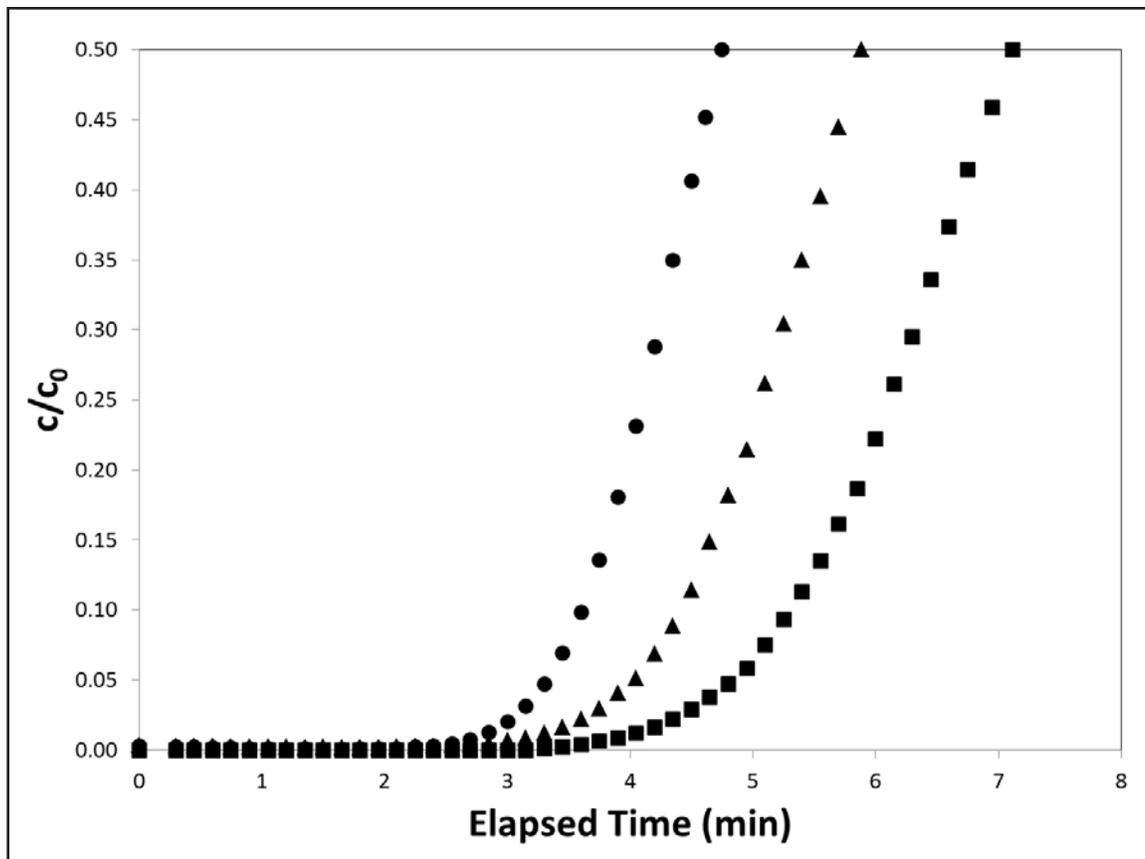


Figure 3. Partial breakthrough curves for oxygen adsorption on CMS at column working pressures (dot) 25 psig, (triangle) 50 psig, and (square) 75 psig.

Working Pressure (psig)	Net N ₂ Purity	N ₂ Recovery	t^* (s)	W_0 (g O ₂ /kg CMS)	W_{sat} (g O ₂ /kg CMS)
25	98.3%	8.4%	285	2.2	4.2
50	98.3%	16.9%	353	3.9	6.4
75	98.2%	23.0%	427	5.2	8.2

concentration of 104.5 ppt designated by the students as the production step endpoint in the experimental design.

Figure 3 shows the partial breakthrough curves obtained from experiments with 25, 50, and 75 psig working pressures. Each trial has an identical superficial velocity of 2 cm s⁻¹. The initial amounts of oxygen adsorbed on the CMS (from pressurization) are 2.2, 3.9, and 5.2 g O₂ (kg CMS)⁻¹, respectively. The ideal times (t^*), or times to reach a concentration ratio (c/c_0) of 0.50, are, respectively, 285, 353, and 427 seconds. Table 1 summarizes the calculated outcomes for each trial.

The net purity of the nitrogen product is very nearly the same in each case, which is a consequence of the common exit composition endpoint for each trial ($c/c_0 = 0.50$). However, it

is clear that the gas efficiency of the process is increased as pressure is increased; more of the nitrogen that is fed to the system is recovered as product. Although the associated material balances must cover pressurization, production, and purging, students observe that the removal of waste oxygen from the packing during blowdown is greatly reduced at lower working pressures. This requires a great deal more nitrogen use in purging, and reduces the fraction of nitrogen recovered accordingly.

The experimental data may be analyzed in additional ways to provide information related to adsorber design and scale up. The adsorption isotherms for zeolites or other porous media used in PSA systems generally exhibit adsorption isotherms that are classified as “favorable,” and the moving concentration profile does not change shape throughout the adsorption bed.^[13] This allows for straightforward scaling calculations to be carried out based on the bed length and representative time frames observed during breakthrough trials. The end time for the production step in a PSA cycle, based on overall product purity design requirements, is known at the break-point time (t_b). The ratio of the break-point time and the amount of effective bed length saturated at the break-point time (L_u) will be in proportion to the ideal time and the total length of the bed:

$$\frac{t_b}{t^*} = \frac{L_u}{L} \quad (2)$$

This relation is easily applied to breakthrough curve data. For example, should the students choose a break-time concentration of $c/c_0^{-1} = 0.10$ for the 75 psig working pressure, a net product purity of 99.9% N_2 would result. The data show that this break-point concentration ratio occurs at a time of 318 seconds (5.3 minutes), which is 74.5% of the ideal time. Therefore, an effective 114 cm of the column length will have been saturated. Similarly, if a production step time of 1300 seconds is required for proper cycle timing, a larger column with the same diameter must provide an ideal time of close to half an hour—and through the proportionality stipulated by Eq. (1), it will require a length of about 6 meters.

STUDENT EXPERIENCES AND LABORATORY ASSESSMENT

The PSA system in our Unit Operations Laboratory is an excellent example of the type of experimental system that works very well in a laboratory setting in which students are given a great deal of freedom in the creation of an experimental design and also in the selection of experimental objectives. Since its construction and commissioning in the summer of 2013, the PSA system has proven to be extremely flexible in its application.

Students have chosen to study N_2 or O_2 production, overall cycle design or cycle step evaluation, the study of system scale up or the investigation of overall mass transfer coefficients, and so on. Although most of the routine measurements are

automatically logged by the computerized data acquisition system, the manual style of operation keeps an entire working group of three students actively involved in the experiment without overwhelming them.

In most chemical engineering departments, the junior- and senior-level laboratories are primarily regarded as the places in which the principles delivered in lecture courses are put into practice; students get hands-on experience with process equipment, and see things with their own eyes. At CSM, the Unit Operations Laboratory is additionally used as a means for driving the overall curriculum. A stand-alone, intensive summer lab course with extended laboratory working hours and a special emphasis on experimental design has allowed our department to make it the centerpiece of our B.S. degree program. As an example, the introduction of a PSA experiment in the laboratory spurs the inclusion of fixed-bed adsorption material in the junior-level Mass Transfer (Separations) and senior-level Transport Phenomena courses. As a result, all students performing the PSA experiment for the first time have received some instruction related to the theory and practice of industrial gas purification by adsorption.

To assist in course learning outcome assessment, students are required to complete two concepts quizzes during the Unit Operations Laboratory—one at the course orientation, and another on the final day of the session. To examine the students’ progress in mastering the fundamental concepts behind PSA systems and their design, specific questions related to the experiment were created. Table 2 shows that students in recent lab sessions have shown improvement in both theory and applied system-related questions; generally, a much greater improvement is observed in the practical aspect. Conversations with students over the course of the session indicate that an improvement of practical system understanding is a result of the in-depth literature reviews required for report introductions. Additionally, students appear to make better connections between theory and experiment after performing detailed data analysis and evaluation in these reports.

Student feedback regarding the experiment itself has been generally positive. In end-of-session course reviews, the PSA system is often referred to in terms such as “the experiment I learned the most from, but which was the most difficult to conceptually understand.” Students also indicate an appreciation of the provided data-acquisition system, which gives freedom to the entire team to manipulate the experiment throughout the course of the day. There is always a special focus on explaining deviations in observed data trends from theory or pre-lab expectations. The availability of extensive automatic data sets has often provided students with additional material for analysis and explanations of such deviations. More often than not, this leads to a deeper understanding of the physical/chemical phenomena around which PSA systems are designed.

TABLE 2
PSA-related concept quiz questions and correct response rates from summer field sessions 2014-2016.
The total number of student responses is 343.

Concept Question	Question Type	Pre-course Correct Response Rate	Post-course Correct Response Rate
(T/F) In a PSA system, it is typical for multiple layers of adsorbed gas to form on the surface.	Theoretical	66%	87%
(T/F) Reversible gas adsorption is best achieved with the physical adsorption of species, rather than chemisorption.	Theoretical	71%	92%
Use a sketch to show the effect of axial dispersion on a breakthrough curve in a PSA system.	Theoretical	24%	54%
How may an adsorption isotherm be modeled at low solute pressures or concentrations?	Theoretical	36%	60%
List three types of adsorbents used in gas separation processes.	Applied	15%	90%
Briefly describe the importance of a stable column temperature in a PSA system.	Applied	38%	94%
A PSA adsorption bed requires 6 kg (10 L) of packing. Is it better to use a column with $h = 2$ m and $d = 8$ cm, or $h = 8$ m and $d = 4$ cm? Why?	Applied	29%	85%
You are designing a PSA system, and may choose molecular sieve stock with either a 5 mm or 0.5 mm average diameter. List one advantage (or disadvantage) of each potential packing.	Applied	77%	94%

CONCLUSIONS

Air separation by PSA is a very effective, inherently safe, and extremely flexible teaching and learning tool for the Unit Operations Laboratory. This experiment illustrates several interrelated principles of mass transfer, and does so as a system that uses no harmful chemicals, produces no waste, and requires essentially no maintenance. Through several summers of use, students have explored a wide variety of experimental designs for both oxygen and nitrogen production cycles. Written and oral reports prepared by the students performing the PSA experiment involve the theoretical aspects of solid/gas adsorption equilibrium and kinetics while placing appropriate focus on the real-world aspects of functional PSA system design, operation (cycle) specification, and scale up. Finally, questioning the students on system concepts shows that this laboratory module is very helpful in terms of experiential learning—allowing students to build on the foundational knowledge delivered in earlier, lecture-based transport courses.

REFERENCES

1. Pruksathorn, P., and T. Vitidsant, "Production of Pure Ethanol from Azeotropic Solution by Pressure Swing Adsorption," *Korean J. Chemical Engineering*, **26**(4), 1106 (2009)
2. Ruthven, D.M., and S. Farooq, "Air Separation by Pressure Swing Adsorption," *Gas Separation and Purification*, **4**, 141 (1990)
3. Hassan, M.M., N.G. Raghavan, and D.M. Ruthven, "Pressure Swing Air Separation on a Carbon Molecular Sieve – II. Investigation of a Modified Cycle With Pressure Equalization and No Purge," *Chem. Eng. Science*, **42**(8), 2037 (1987)
4. Liow, J-L., and C.N. Kenney, "The Backfill Cycle of the Pressure Swing Adsorption Process," *AIChE Journal*, **36**(1), 53 (1990)
5. Shin, H-S., and K.S. Knaebel, "Pressure Swing Adsorption: An Experimental Study of Diffusion-Induced Separation," *AIChE Journal*, **34**(9), 1409 (1988)
6. Raghavan, N.S., M.M. Hassan, and D.M. Ruthven, "Numerical Simulation of a PSA System Using a Pore Diffusion Model," *Chem. Eng. Science*, **41**(11), 2787 (1986)
7. Lee, J-G., J-S. Lee, and C-H. Lee, "Air Separation by a Small-Scale Two-Bed Medical O₂ Pressure Swing Adsorption," *Industrial & Engineering Chemical Research*, **40**, 3647 (2001)
8. Miller, R.L., J.F. Ely, R.M. Baldwin, and B.M. Olds, "Higher-Order Thinking in the Unit Operations Laboratory," *Chem. Eng. Ed.*, **32**(2), 146 (1998)
9. Ganley, J.C., "Enhanced Experiential Learning in the Unit Operations Laboratory," *Proceedings of the ASEE Rocky Mountain Section Conference*, 114 – 123 (2016)
10. Hassan, M.M., and D.M. Ruthven, "Air Separation by Pressure Swing Adsorption on a Carbon Molecular Sieve," *Chem. Eng. Science*, **41**(5), 1333 (1986)
11. Farooq, S., D.M. Ruthven, and H.A. Boniface, "Numerical Simulation of a Pressure Swing Adsorption Oxygen Unit," *Chem. Eng. Science*, **44**(12), 2809 (1989)
12. Baron, G.V., M. Van de Voorde, H. Verelst, J. Martens, and P. Jacobs, Diffusion in Zeolite Adsorbents. In M. Suzuki (Ed.), *Fundamentals of Adsorption*, vol. **80** (pp. 49) Tokyo, Japan: Kodansha. (1993)
13. McCabe, W.L., J.C. Smith, and P. Harriot, *Unit Operations of Chemical Engineering*, 7th Ed. New York: McGraw-Hill (2005)
14. Ruthven, D.M., S. Farooq, and K.S. Knaebel, *Pressure Swing Adsorption*, Weinheim, Germany: Wiley-VCH (1993) □