# Novel Design and Performance of a Medical Oxygen Concentrator Using a Rapid Pressure Swing Adsorption Concept

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*DOI 10.1002/aic.14518*

*A novel design of a compact rapid pressure swing adsorption system consisting of a single adsorber enclosed inside a product storage tank is proposed for application as a medical oxygen concentrator (MOC). A self-contained test unit for the process is constructed which is capable of directly and continuously producing 1–3 sl/m of 90% $O_2$ from compressed air. Pelletized LiLSX zeolite is used as the air separation adsorbent. Steady state process performance data [bed size factor (BSF) and $O_2$ recovery (R) as functions of total cycle time ($t_c$)], as well as transient, cyclic, adsorber pressure, and temperature profiles are presented. A four-step Skarstrom-like pressure swing adsorption cycle was used. Two options for column pressurization, (a) using compressed feed air cocurrently or (b) using a part of the oxygen-enriched product gas counter-currently were evaluated. Option (b) exhibited superior performance. The optimum total cycle time for option (b) was 5–6 s where the BSF was lowest (∼45 kgs/TPD $O_2$) and the corresponding R was ∼29.3%. These numbers indicate that the adsorbent inventory of a MOC can be potentially reduced by a factor of three while offering a ∼10–20% higher $O_2$ recovery compared to a typical commercial unit.* © 2014 American Institute of Chemical Engineers *AIChE J*, 60: 3330–3335, 2014

*Keywords: rapid pressure swing adsorption, medical oxygen concentrator, LiLSX zeolite, process performance*

## Introduction

One of the recent commercially successful applications of pressure swing adsorption (PSA) technology for bulk gas separation is direct production of 1–10 sl/m of ∼90% $O_2$ from a compressed air stream for medical use by patients with chronic obstructive pulmonary disease and other lung disorders.[1–3] Rapid pressure swing adsorption (RPSA) processes using total cycle times ($t_c$) of less than 10 s are generally used for this application.[2,3] Pelletized, $N_2$ selective LiX or LiLSX zeolite is often used as the preferred air separation adsorbent in these RPSA systems.[4,5]

A list of published experimental as well as numerically simulated studies of various RPSA process performances for this application can be found elsewhere.[4] Several corporations market different designs of RPSA medical oxygen concentrators (MOC) using various PSA process schemes for portable or stationary home use.[2,3]

The key design goals for a MOC are (a) reduction of the bed size factor [BSF, total amount of adsorbent in the unit/ton per day of oxygen production rate, (kgs/TPD $O_2$)] which lowers adsorbent inventory resulting in a more compact and lightweight unit, (b) enhancement of percentage $O_2$ recovery *R* by the process [amount of $O_2$ in product gas/amount of $O_2$ in feed air per cycle × 100 (%)] to decrease the air compressor size and power which result in lighter unit and longer battery life (portable units), and (c) assembly of a compact, lightweight, and easy to operate unit.

Variations of the classical four-step Skarstron PSA cycle[6] are usually adapted for use in these RPSA schemes. The typical steps include (1) selective adsorption of $N_2$ from compressed air by flowing air at a super-ambient adsorption pressure ($P_A$) over a packed column of the zeolite to produce an $O_2$ enriched effluent gas which is partly withdrawn as the product gas, (2) counter-current depressurization of column to a near ambient final desorption pressure level ($P_D$), (3) counter-current back purge of the column at $P_D$ with a part of the $O_2$ enriched product gas, and (4) repressurization of column from $P_D$ to $P_A$ using either fresh compressed air (cocurrent) or a part of the $O_2$ enriched product gas (counter-current) or both. The cycle is then repeated. The $N_2$ enriched column effluent gases from Steps (2) and (3) are wasted.

The conventional approach to reduce the BSF is to reduce the total cycle time ($t_c$) of the RPSA system to increase the cyclic frequency of operation and, hence, enhance the net rate of $O_2$ production.[4] A higher $O_2$ recovery is generally obtained by preserving a portion of the air-like void gas in the column at the end of Step (1) using it to partially pressurize a companion column (pressure equalize) before Step (2) begins to reduce the loss of void gas $O_2$ during Step (2). The amount of back purge gas is also minimized while maintaining the product gas purity to reduce BSF and increase $O_2$ recovery.[7]

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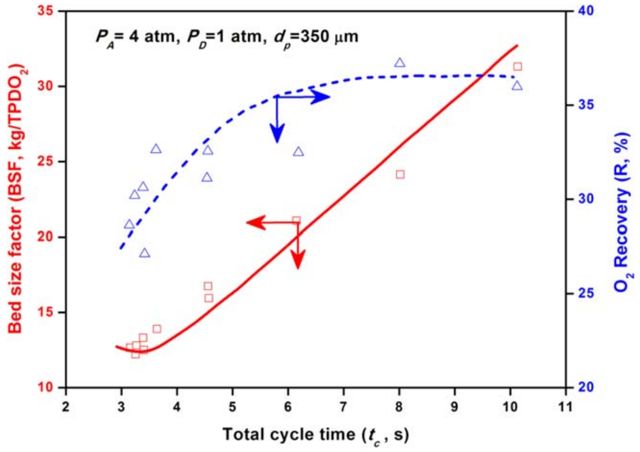

**Figure 1. Plots of BSF and $O_2$ recovery vs. total cycle time at $P_A$=4 bar, $P_D$ ~ 1 bar, $d_p$= 350 µm measured using mini-adsorber system.**

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At least two parallel adsorbent columns are needed in a PSA system to accommodate the pressure equalization step.[7] At least two columns are also necessary to produce a continuous product stream so that when one column is undergoing Step (1), the companion column carries out Steps (2)–(4). However, synchronized control of operation of two columns in a rapid cycling situation may not be easy. A product buffer tank is often necessary for smoothing out product gas flow rate and composition.

Recently, we experimentally studied the performance of a four-step Skarstorm-like RPSA process as described above using a single mini-adsorber column [0.4 cm diameter × 10.8 cm long containing only 1 gm of a commercial LiLSX zeolite sample (Oxysiv MDX from UOP)].[4] The column was filled with adsorbent particles of uniform diameter ($d_p \sim 350$ µm) obtained by screening the as-received zeolite sample ($d_p \sim 200$–600 µm). Dry, $CO_2$, and Ar free air (21% $O_2$ + 79% $N_2$) at different adsorption pressures ($P_A$, atm) were used as feed. The product gas was ~90% $O_2$. The back purge Step (3) was carried out at a pressure slightly above ambient ($P_D \sim 1$ atm), and the gas was supplied from an external gas tank containing 90% $O_2$. Compressed air was used for the pressurization Step (4). The total cycle time ($t_c$) was varied between 2 and 10 s. Steady state process performance data (BSF and $O_2$ recovery vs. total cycle time) were gathered albeit in an experimentally simulated, semicontinuous manner for making 90% $O_2$ product for different $P_R = P_A/P_D$ ratios and adsorbent particle sizes.[4] The total helium void volume of the adsorber was ~6.1 cc/g of adsorbent.

Figure 1 reproduces one data set from Ref. 4 showing that the BSF decreases with decreasing $t_c$ but it cannot be reduced indefinitely by lowering $t_c$ due to impediments created by nonidealities-like nonisothermal column operation, finite gas-solid ad(de)sorption mass transfer resistance, and column pressure drop which have detrimental effects on the RPSA process performance. These effects become more pronounced in the low $t_c$ region which causes the BSF to increase with further reduction in $t_c$ as shown by Figure 1.[4] Our subsequent model simulation studies on efficiency of $N_2$ desorption by rapid depressurization of a LiX column and by rapid purge with $O_2$ provided more insights on the relative influences of the above-described nonidealities.[8,9] It may be seen from Figure 1 that a low BSF value of ~13.6 kgs/TPD $O_2$ could be achieved for production of 90% $O_2$ under certain conditions of operation of our RPSA process when $t_c$ is between 3 and 4 s. Conversely, Figure 1 shows that the $O_2$ recovery initially increases with increasing $t_c$, and then, it levels off at higher values of $t_c$.

The most important feature of practical interest implied by Figure 1 is that a BSF of ~13–30 kgs/TPD $O_2$ in conjunction with a $R$ value of 25–35% can potentially be achieved simultaneously for production of ~90% $O_2$ enriched product gas using our RPSA system operating with a total cycle time of 3–5 s. This combination of performance for a RPSA $O_2$ generator has not been reported in the literature.[4] A rapid vacuum swing adsorption process design may exceed this performance but the use of a vacuum pump in a MOC application may not be appropriate due to size, weight, and being a potential source of leakage.[4]

We also tested a commercially available two-column RPSA–$O_2$ generator (Invacare $XPO_2$) which produced ~0.7–0.9 sl/m of ~90% $O_2$ in a pulsed discontinuous mode with a BSF of 91–123 kgs/TPD $O_2$ and an $R$ of 23–29%. The total cycle time was ~10–14 s, and a product buffer tank was used. Thus, the performance exhibited by our mini-adsorber system indicates that the adsorber size can potentially be reduced by a factor of 3–4 while matching or improving the $O_2$ recovery by ~20% provided that they are verified in a scaled-up, self-sustained, continuous RPSA process unit.

## Design of a Novel RPSA Unit for Medical Use

Consequently, we constructed a larger RPSA cyclic test-unit based on a novel "single column enclosed inside a product gas storage tank" design concept. Figure 2 is a schematic drawing of the experimental setup. It consisted of a single adsorbent column (diameter = 0.0498 m, Length = 0.127 m, containing 0.148 kg of LiLSX) surrounded by a coaxial gas storage space (volume = 1.54 sl) which was used to store the $O_2$ enriched effluent gas from Step (1). The column length was comparable to that of the mini-adsorber. Parts of the stored gas were used in Steps (3) and (4) of the process if required, and a part was continuously withdrawn as the product gas through a separate port. The adsorbent was obtained from the same batch that was used in the mini-adsorber. It was used as-received ($d_p$ = 200–600 µm) after thermal regeneration at ~350°C under dry $N_2$ flow. The helium void of the adsorber was 1.65 cc/g. The scale-up factor was ~140.

The figure also shows the locations of different valves [four two-way 1/2 in. solenoid ($C_v = 4$), and one check], mass flow meters and controllers, pressure sensors, controller, and gauges. A PLC (Eaton Corp) was used for cycle times setting and process control. An Omega data acquisition system was used for data measurement, collection, and storage in an integrated computer. The transient adsorbent temperature was measured using a 1/16 in. exposed-tip thermocouple located at the center point inside the adsorber. A $ZrO_{2000}$ continuous analyzer using an $O_2$ selective membrane (Manufactured by ALPHAOMEGA Instruments) was used to continuously measure the $O_2$ concentration of the product gas, and the effluent steams during Steps (2) and (3). The pressure of the gas storage tank ($P_s$) cyclically increased and decreased during the RPSA cycle but always maintaining a super-ambient pressure level in the tank.

A photograph of the completely assembled RPSA unit is shown in Figure 3. The unit was capable of producing a

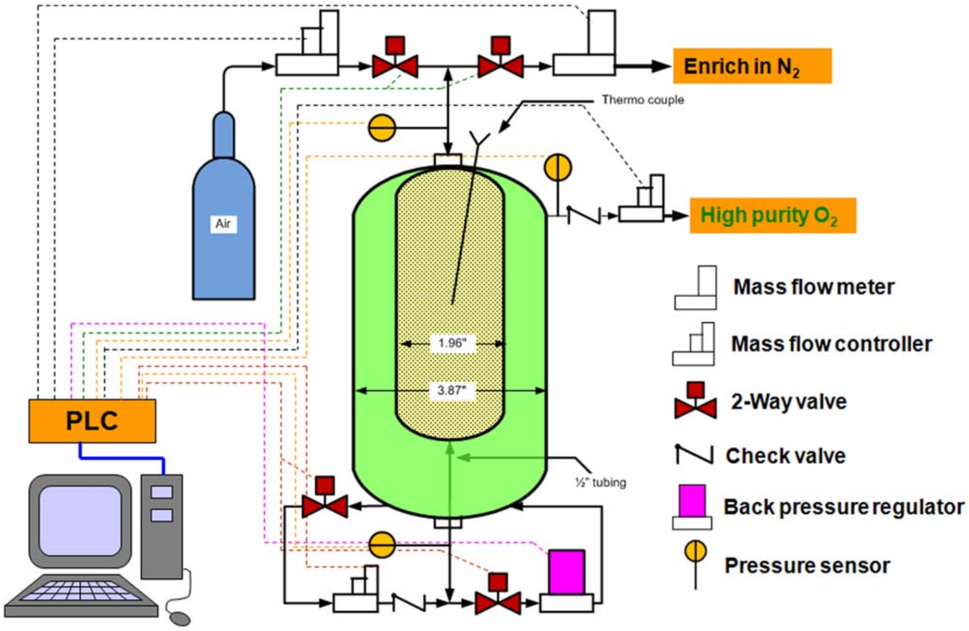

**Figure 2. Schematic drawing of single-adsorber RPSA process system.**

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continuous stream of 90% $O_2$ from a compressed air gas source using a total cycle time of 2.5 s or more. It is fully instrumented for measurement of process performance by operating it in a continuous manner. It can be used for process optimization as well as for comparative performance studies of different air separation adsorbents.

Major advantages of a single-adsorber RPSA process design include compact size, lesser number of switch valves, and easier process control due to the absence of synchronized operation of two or multicolumn systems. This introduces more flexibility in selection of individual step times of the RPSA process so that each step can be operated more efficiently. Furthermore, the present design permits a continuous product withdrawal which is preferred over pulsed product flow offered by many commercial portable units.

## Process Performance Data

The cyclic steady-state performance of the unit shown in Figure 3 was extensively studied. Cyclic steady state runs were conducted using a synthetic air (21% $O_2 + 79\%$ $N_2$) feed gas with and without ~1% Ar and a product gas containing $90 \pm 1.0\%$ $O_2$ was continuously produced. A four-step Skarstrom-like PSA cycle described earlier was used. Column pressurization (Step 4) was carried out using either (a) compressed feed air or (b) a part of the $O_2$ enriched product gas from Step (1). The adjustable variables were feed air pressure, flow rates for feed, product and back purge gases, and times for individual process steps and total cycle. Cyclic steady state was usually reached after 50 cycles of operation. Only those runs where the over-all and component ($O_2$) mass balances between inlet and outlet flow streams closed within ±5.0% were accepted. The unit was capable of continuously supplying 1–3 sl/m ~90% $O_2$ product, which was comparable or better than the supply rate of a typical commercial unit.

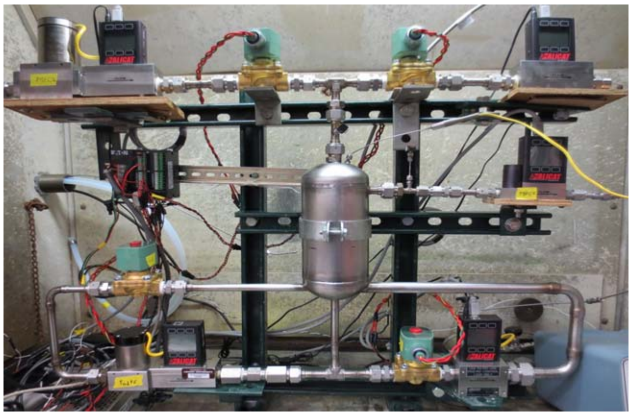

**Figure 3. Photograph of assembled RPSA unit.**

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The following cyclic steady-state performance data were studied:

a. BSF and $O_2$ recovery as functions of total cycle time
b. Transient cyclic adsorber inlet and outlet, and product buffer tank pressures
c. Transient cyclic adsorbent temperature at the center of the column
d. Transient cyclic product $O_2$ concentration and flow rate
e. Effect of argon in feed air on RPSA process performance

One example of the BSF and $R$ vs. $t_c$ plot measured using the scaled-up RPSA unit producing a continuous stream of ~90% $O_2$ from compressed air (21% $O_2 + 79\%$ $N_2$) is given in Figure 4. The conditions of operation are given in the figure. Performances for both modes (a) and (b) of column pressurization are shown. Mode (b) (product pressurization) of operation provides superior performance (lower BSF and higher $R$) than mode (a) (feed pressurization) at all cycle times. The functional dependences of BSF and $R$ on $t_c$ are qualitatively similar to those measured by the mini-adsorber unit. The BSF—$t_c$ plots exhibit a minimum validating the observation of Figure 1 that the cycle time cannot be

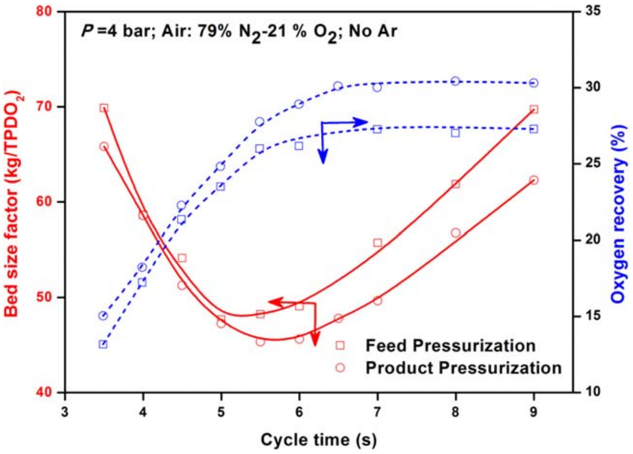

**Figure 4. Plots of BSF and $O_2$ recovery vs. total cycle time at $P_A$= 4 bar, $P_D$ ~ 1 bar, $d_p$= 200–600 μm, measured using the scaled-up single column unit of Figure 3.**

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decreased indefinitely to lower BSF. However, the minimum values of BSF and their locations differ from those shown in Figure 1. The net $O_2$ production rate at the minimum was 1.6 sl/m, and its purity was 90.5% $O_2$. The corresponding $O_2$ recovery was ~27 %.

There are a few possible reasons for these performance differences. The operation of the small diameter mini system was close to isothermal due to a large specific heat sink provided by the vessel body per unit amount of adsorbent in the column and a small effective adsorbent to wall heat transfer path. Conversely, the operation of the scaled-up unit was nearly adiabatic because of nearly 13 fold larger column diameter which significantly increased the effective adsorbent to wall heat transfer path and decreased the size of the specific heat sink provided by the vessel. Second, the mini-adsorber was packed with a nearly uniform sized adsorbent particle of ~350 μm diameter while the adsorbent particle diameters in the scaled-up unit ranged between 200 and 600 μm. This decreases the effective mass-transfer coefficient for adsorption in the scaled-up unit. The impacts of column pressure drop in the two cases are also different due to differences in adsorbent particle sizes and distribution. Lower adsorbate mass-transfer coefficient, higher column pressure drop during desorption steps, and nonisothermal column operation have detrimental effects on the efficiency of $N_2$ desorption steps of a RPSA process which increases BSF.[8, 9] In addition, the optimum BSF occurs at a longer cycle time (~6 s) in the scaled-up unit than that for the mini-adsorber (~3.5 s) which is also responsible for higher BSF for the former system. Differences in flow hydrodynamics inside the mini-adsorber and the scaled-up unit may also contribute to differences in process performance.

Nevertheless, Figure 4 shows that the scaled-up RPSA unit using the novel design and operating under mode (b) could deliver a BSF of ~45.34 kgs/TPD $O_2$ and a $R$ of ~27% when the total cycle time is ~5–6 s and adsorption pressure was 4 bar. The unit was capable of continuously producing ~1.6 sl/m of 90% $O_2$. These performance numbers indicate that the novel concept can potentially reduce the adsorbent inventory of an MOC by a factor of ~2–3 while offering similar or ~10% higher $O_2$ recovery (proportional decrease in air compressor size and power) *vis a vis* a conventional MOC system. It should also be noted from Figure 4 that a higher $O_2$ recovery of ~30% can be achieved by the present design, if desired, with a somewhat higher BSF (~57 kgs/TPDO$_2$), which is still a factor of ~2 less than that of a commercial unit. Thus, there is a large flexibility in the operation of the RPSA unit of Figure 3. These improved process performances and previously mentioned process control advantages are high points of the proposed RPSA MOC design *vis a vis* the existing MOC designs in the literature.[4]

It should be noted that superior performance of a PSA process using product pressurization *vis a vis* feed pressurization was reported earlier by Knaebel et al. who carried out a limited numerical PSA model analysis of this issue for binary $CH_4$—$H_2$ separation using conventional, long PSA cycle-time formats [total cycle time ~80 s (feed pressurization), ~180 s (product pressurization)] and activated carbon as an adsorbent.[10] This article experimentally demonstrates a similar behavior for a RPSA cycle using total cycle times of 3–8 s for the first time.

Figure 5 reports the cyclic, steady-state product tank and purge gas inlet pressures as functions of time ($t$) during two consecutive cycles when the BSF was at minimum (product pressurization case) and the total cycle time ($t_c$) was 5.5 s (see Figure 4). The times for the individual steps of the process (pressurization = $t_p$, adsorption = $t_a$, depressurization = $t_d$, product purge = $t_{pu}$) are also marked in the figure. The tank pressure remains substantially super-atmospheric (>2.3 bar) during the entire cycle which guarantees that the product can be continuously withdrawn above ambient pressure and delivered to an user located at a reasonable distance. Conversely, higher tank pressure translates to larger purge gas inlet pressure which is also cause of lower recovery and larger BSF. Consequently, there is room for further improving the performance of the present RPSA system by fine tuning the mechanical designs (valve, piping, etc).

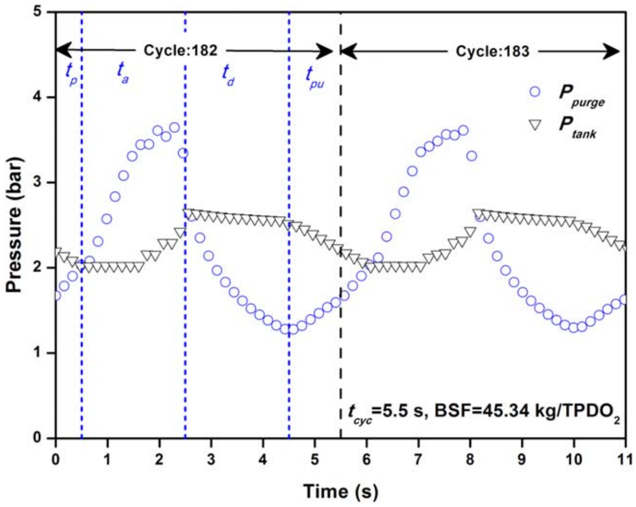

**Figure 5. Purge inlet ($P_{purge}$), and product storage tank ($P_{tank}$) pressure profiles for two consecutive cycles during steady-state operation at the minimum BSF condition (product pressurization) of Figure 4.**

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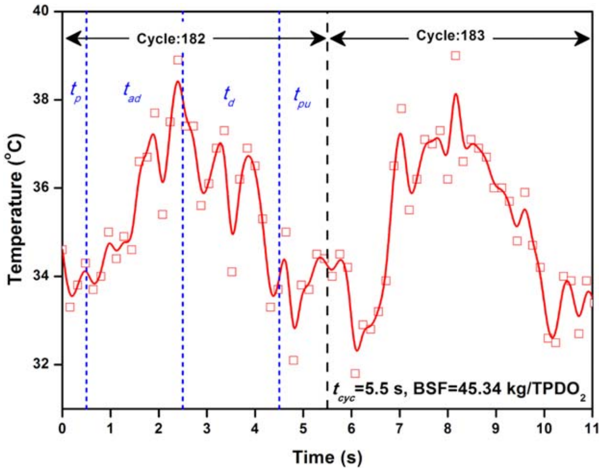

**Figure 6. Column midpoint temperature changes for two consecutive cycles during steady-state operation at the minimum BSF condition (product pressurization) of Figure 4.**

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The cyclic, steady-state adsorber temperature at the column midpoint as functions of time ($t$) during two consecutive cycles corresponding to the data reported in Figure 5 are plotted in Figure 6. The times for the individual steps of the process are marked in the figure. The temperature increases during the product purge, product pressurization and adsorption steps, reach a maximum, and drops during depressurization step to the lowest temperature of the cycle at the end of that step. The column temperature cycles between 32 and 39°C. This clearly shows that the operation is not isothermal.

Figure 7 shows the net $O_2$ product flow rate (sl/m) and composition (%) for two consecutive cycles during steady-state operation of the unit corresponding to the data reported in Figure 5. It demonstrates the constancy of continuous product withdrawal rate and its purity during the entire cycle from the unit of Figure 3. This can be a major advantage *vis a vis* a portable MOC unit which supplies the $O_2$ product discontinuously (pulsed delivery).[3]

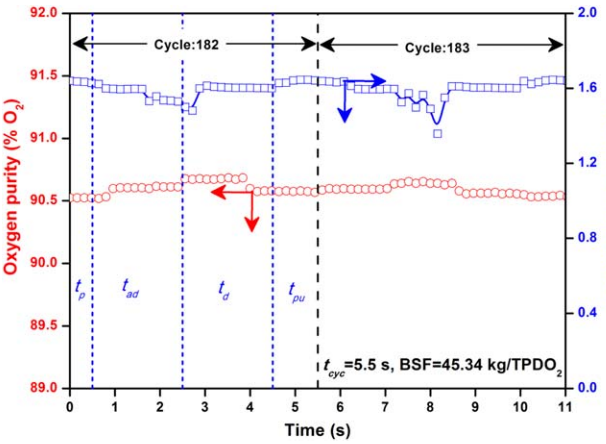

**Figure 7. Product oxygen purity and flow rate profiles for two consecutive cycles during steady-state operation at the minimum BSF condition (product pressurization) of Figure 4.**

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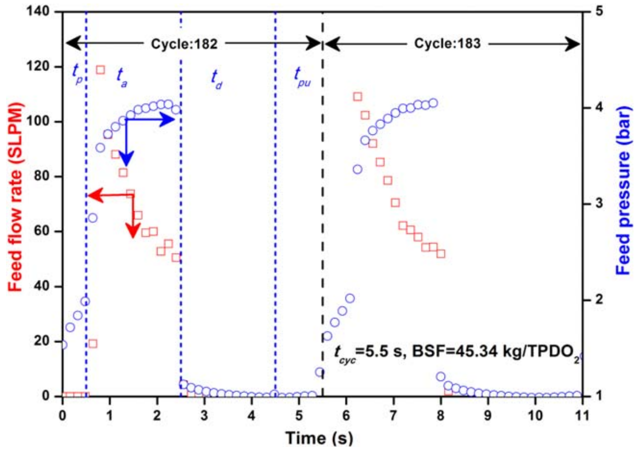

**Figure 8. Air feed flow rate and pressure profiles at the column inlet for two consecutive cycles during steady-state operation at the minimum BSF condition (product pressurization) of Figure 4.**

**[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]**

The net feed air flow rate and pressure as functions of time corresponding to the data reported in Figure 5 are shown by Figure 8. It may be seen that the feed air flow rate is high at the start of the adsorption step, and then, it gradually decreases by about a factor of 3 at the end of the adsorption step. The feed air pressure progressively increases to the final adsorption pressure during that step. Thus, the compressor duty changes with time during the adsorption step.

Figure 9 reports the effect of argon (~1%) in the feed air (21% $O_2 + 78\%$ $N_2$) on the RPSA process performance using identical conditions of operation as used in the data of Figure 4. Only the product pressurization case is described. It shows that the location of the minimum of BSF vs. $t_c$ plot is practically unchanged. However, the minimum value of BSF is increased from 45 to 50 kgs/TPDO$_2$ and the corresponding $R$ is reduced from ~27 to 26%. In other words, the detrimental effects of presence of Ar in feed air on the process performance are rather small. The substantial performance advantages of the present system discussed earlier remains practically unchanged.

## Performance Test Using Compressed Ambient Air

A key remaining factor in comprehensive evaluation of performance of the proposed novel MOC design is to carry out a continuous long duration process performance test using compressed ambient air containing moisture and $CO_2$ as the feed gas. This will be undertaken in our laboratory by modifying the present adsorber packing with a layer of a desiccant (such as a mesoporous activated alumina) in the feed air end of the column. This is traditionally practiced in design of conventional PSA air separation processes for removal of $H_2O$ and $CO_2$ from feed air prior to air separation.[11] Most commercially available RPSA MOC units adapt

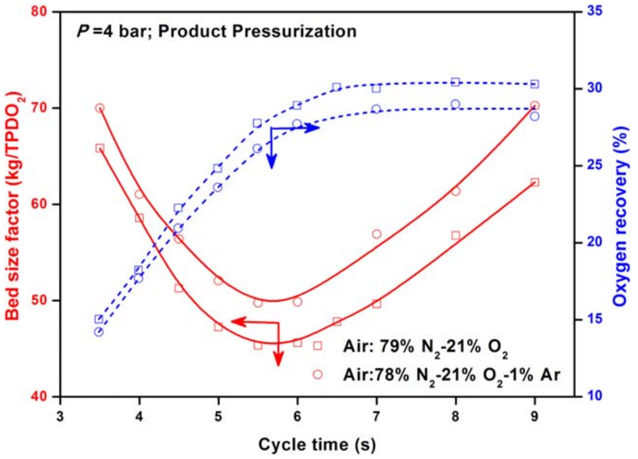

**Figure 9. Effect of Ar in feed air on performance of RPSA process with product pressurization.**

**[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]**

this procedure. Thus, pretreatment of compressed air feed ($H_2O$ and $CO_2$ removal) using a RPSA concept is well proven. The kinetics of ad (de)sorption of $H_2O$ on small particles of mesoporous alumina is fast.[11] Consequently, adsorption equilibrium primarily dominates the ad(de) sorption process. Nevertheless, the efficiency of integration of this procedure in our MOC design needs to be experimentally tested.

## "Snap On" MOC

One interesting application of the novel design of RPSA MOC concept described in Figure 3 (after a compact and potable repackaging of the design using miniature valves, and removing the control instruments) can be as a "Snap On" MOC unit where the portable unit is connected to an existing compressed air line and product $O_2$ is delivered to the user on site. Such an application may be suitable for use in a hospital (civil or military), remote site, cruise ship, aqua culture and so forth, where compressed air line may exist. This eliminates the requirement of a dedicated air compressor for the MOC unit.

## Conclusions

A compact, RPSA system based on a novel design concept consisting of a single adsorber enclosed inside a gas storage vessel was constructed and successfully tested for continuous production of 1–3 Slpm of 90 + % $O_2$ for medical use using a commercial sample of pelletized LiLSX zeolite (~0.15 kg) as the air separation sorbent and a total cycle time ($t_c$) of only 3–9 s. It was demonstrated that (a) the process BSF cannot be indefinitely reduced by lowering $t_c$, (b) adsorber pressurization using a part of the product gas provides a superior process performance (lower BSF and higher $R$) than feed air pressurization, and (c) presence of Ar in feed air increases BSF and lowers $R$, albeit by a small amount. The optimum process performance(BSF ~ 45.34 kgs/TPDO$_2$ and $R$ ~ 27 %) were achieved using a $t_c$ of 5–6 s, which indicate that the designed unit is potentially capable of reducing the adsorbent inventory by a factor of 2–3 and improving the $O_2$ recovery by ~10% compared with the performance of a commercial MOC unit. Testing the performance of the unit using compressed ambient air remains to be carried out.

An attractive application of the proposed MOC concept is a "Snap On" approach where the portable RPSA unit is connected to an existing compressed air line for on-site production of medical $O_2$, thereby, eliminating the need for a dedicated air compressor.

## Acknowledgment

The authors are grateful to University Science Centre, Philadelphia for their 2011 QED grant to support a part of this research work.

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*Manuscript received Dec. 28, 2013, and revision received Apr. 2, 2014.*