Transformative Design of Medical Oxygen Concentrator by Rapid Pressure Swing Adsorption

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ABSTRACT

A novel, single-bed, 4-step, Rapid Pressure Swing Adsorption (RPSA) process is designed for producing 90% O_2 from compressed air for medical use by patients with Chronic Obstructive Pulmonary Disease (COPD) and other lung disorders. The proprietary design integrated with product storage tank is capable of continuously producing 1 - 3 LPM of ~90±% O_2 by employing a commercial sample of LiLSX zeolite as an adsorbent for air separation. An optimum cycle time of 4-6 s was identified from the experimental results at which a lower Bed Size factor (BSF) of ~ 41 kgs/TPDO2 and corresponding oxygen recovery (R) of ~29 % were obtained. An optimum adsorbent particle size range was also identified by simulating the RPSA process. Thus, the transformative design of medical oxygen concentrator (MOC) using RPSA Technology has a potential to reduce the adsorber size by a factor of 2 to 3 while offering similar or ~10% higher O_2 recovery.

Keywords: medical oxygen concentrator, rapid pressure swing adsorption, charonic obstructive pulmonary disease, air separation, litheium exhanged zeolite

1 INTRODUCTION

Medical oxygen concentrators(MOC) directly produce 1-10 SLPM of ~ 90 % O_2 from ambient air by employing a rapid pressure swing adsorption (RPSA) technology using a N_2 selective zeolitic adsorbent. The O_2 is used to help breathing of patients suffering from non-curable lung disorders like COPD, fibrosis, etc. Nearly 5 % of world population suffer from these conditions which are one of the leading causes of deaths [1-2]. Several MOCs designs have been marketed by various manufacturers during the past five to ten years. The potential U.S and Global market for MOCs is growing rapidly and it is estimated to reach $ 2 billion by 2017 from $ 0.4 billion in 2014 [3].

The commercial stationary MOCs are bulky and heavy, whereas the portable MOCs deliver oxygen in a pulse mode. The battery life is also an issue for the portable units. Consequently, A light-weight and compact MOC delivering a continuous supply of O_2 is a very highly desirable product for this market.

Therefore, the objective of this research work was the design of next generation MOC, which is a smaller, lighter, more energy efficient unit that can deliver continuous (as opposed to pulsed boluses of) ~90% oxygen at 1-3 slpm using a novel rapid pressure swing adsorption. Furthermore, the critical resistances effecting the RPSA process performance were identified from the modeling and simulation study.

2 MODELING AND SIMULATION OF RPSA PROCESS

The Cyclic Skarastrom type rapid pressure swing adsorption (RPSA) technology is commonly used for the design of a commercial MOC unit [4]. The cycles consist of various combinations of adsorption, desorption and complimentary steps and a nitrogen selective lithium exchanged X zeolite is employed for the air separation. The key performance variables for an MOC are bed size factor (BSF = kg adsorbent / ton of product/ day), and oxygen recovery (R = amount of product produced/ amount of oxygen in feed air). The perfomance of RPSA process is primanrly governed by the individal step durations, feed pressure, purchage rate and adsorbent particle size. In addition, the nonidealities like momentum, heat and mass transfer resistance impadiment the performance. A mathematical model of RPSA process was developed and simulated to study the cyclic adsorption and desorption of N_2 from a zeolite bed. The effect of individual process variables and non-idealities were thoroughly investigated in the simulation study. A similar situation exisits in air separation. A N_2- He was selected as adsorbates for this study. The mathamatical model equations and boundary conditions were reported elsewhere[5]. The Comsol Multiphysics software with MATLAB, which uses finitite element method for discritizing the model equations, was used to solve the model equatins. All the nonidelaities present in the RPSA process were considered in these simulations.

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The effect of RPSA cycle time (t_c) on Bed Size Factor (BSF) and He Recovery (R) is shown in Figure 1 at cyclic steady state conditions. The BSF decreases with decreasing t_c up to 5 s and then increase with further drease in t_c. Thus, a minimum of BSF was observed for an optimum cycle time (t_c) of ~3- 4 s. The increase in BSF with increasing of t_c for longer cycle times is due to lower frequency of operation of the RPSA process and it lowers the specific productivity of helium from the PSA system. However, the derecease in BSF for shorter cycle times (t_c< 3s) is due to the detrimental effects of the mass, heat and momentum transfer resistances in the system. The He recovery (R) from the feed gas is nearly constant for longer t_c and it derecses with decrease of tc below 5 s as shown in Figure 1.

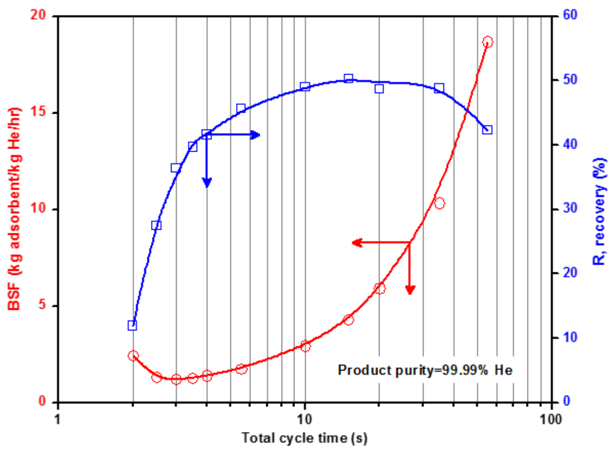

Figure 1: Effect of cycle time on BSF and R for 99.99% He product purity

In another study, the effect of adsorbent particle size (d_p) on rapid pressurization and depressurization of RPSA process was studied by simulating the individual pressurization and depressurization steps of the RPSA cycle [6]. The N_2 was selected as an adsorent and 5A zeolite material was chosen as an adsorbent. An optimum adsorbent particle size (d_p) range between 200- 350 µm was identified to lower the pressurization and de-pressurization times below 1s from the simulation study as shown in Figure 2. The decrease in adsorbent particle size below the optimum size range leads to increase in column pressure drop and also increases the mass transfer coefficicent. On the other hand, the increase of particle size leads to drease in mass transfer coefficient and lowers the column pressure drop. Thus, an optimum particle size range exists as shown in Figure 2 with in which both the resistances are counter balanced, and the pressurization and depressrization step durations were less than 1 s.

Therefore, it is evident from the above simulation results that the BSF of a RPSA process cannot be reduced indefinitely by lowering the process cycle time due to impediments created by finite the mass and heat transfer resistances whose detrimental effects on the process performance become pronounced at smaller cycle times, which was also experimentally demonstated in our study reported below [7].

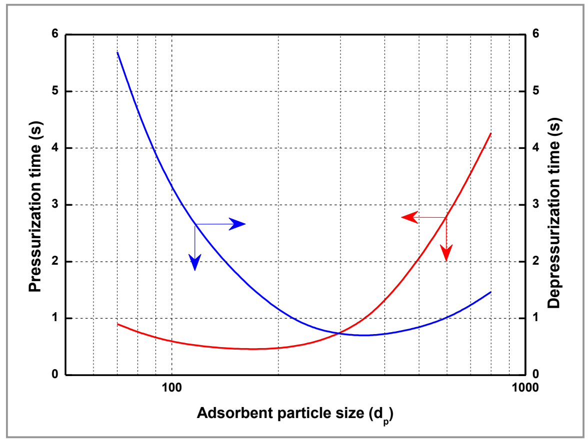

Figure 2: Simulated base case pressurization-depressurization times as functions of adsorbent particle size.

3 ACTUAL EXPERIMENTAL OPERATION OF A RPSA-MOC PROCESS

A bench scale unit consisted of a single adsorber vessel (diameter = 0.0498 m, Length = 0.127 m) was designed and constucted to study the miniaturization of MOC using RPSA Technology. The novel design has an intergated-coaxial product storage tank for continuous supply of product O_2 as well as to back purge the oxygen in purge step of RPSA cycle. The schematic and photograph of experimental set is shown elsewhere in our earlier publication[10]. It is capable of producing a continuous stream of 90 % O_2 at a flow rate of 1 – 3 SLPM from a compressed air gas as feed employing a total cycle time of 2.5 seconds or more.

The cyclic steady performance of the RPSA process using a commercial sample of LiLSX zeolite obtained from Zeochem Corporation was extensively studied. The synthetic air (21% O_2 + 78% N_2+ 1% Ar) was used as feed gas for the continuous production of 90 ± 1.0% O_2. The adsorbent sample was used as-received after thermal regeneration at ~ 350° C under dry N_2 flow for 8 hrs. A modified four-step Skarstrom-like PSA cycle was employed, which consisted of (i) column pressurization using a part of the O_2 enriched product gas from storage tank, (ii). Adsorption by flowing compressed air into the adsorber and collecting the product O2 in the tank, (iii) blowdown to ambient pressure for partial desorption of N_2 and (iv) back purge with a part of enriched O_2 from the tank for further desorption of N_2. The effect of cyclic time (tc) on RPSA process was extensively studied in the bench experimental unit. 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 effect of cycle time on BSF and R was shown in figure 3. A minimum BSF of is ~ 40.8 kgs/TPDO2 was observed at a total cycle time of ~ 5.5s from the experimental results and the correspond oxygen recovert is 24%.

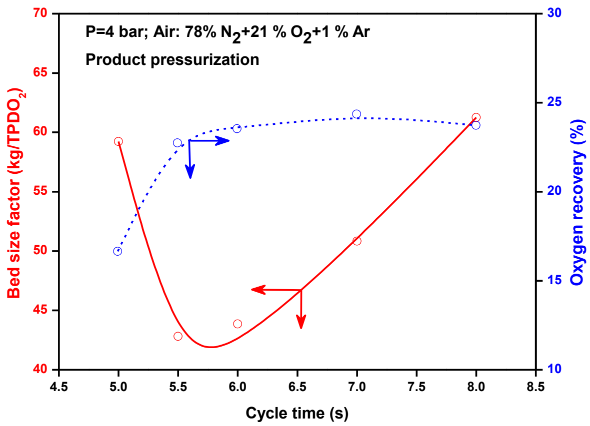

Figure 3: Experimental plots of BSF and O_2 recovery vs total cycle time at P_A=4 bar, P_D ~ 1 bar. Adsorbent particle size (dp)=400-800 µm.

Therefore, our propritory design of RPSA can potentially lower the adsorbent inventory of a RPSA-MOC by a factor of 2–3 and improving the O2 recovery by ~10% compared with the performance of a commercial MOC unit.

Salient Features of Lehigh Patented RPSA Design for MOC.

- The RPSA MOC design delivers a continuous stream of product O_2, which is preferred by 80% of the patient suffers with COPD and other lung diseases.
- It can be used to design both portable and stationary units of various sizes because of its ease of scalability.
- A unique single-bed adsorber enclosed in a product gas storage tank allows compact, light - weight design.
- The single adsorber RPSA permits easy process control vis a vis a conventional two or multi-adsorber RPSA design.
- The optimum total and individual -step cycle times of RPSA to obtain minimum adsorbent inventory and the maximum O_2 recovery were identified through our R& D efforts.
- The R & D led to the use of an optimum adsorbent particle size to maximize the RPSA performance, which was also previously unknown.

4 CONCLUSIONS

A novel, RPSA system based MOC design was constructed and successfully tested for continuous production of 1–3 lpm of 90% O_2 for medical use of COPD patients using a commercial sample of pelletized LiLSX zeolite (0.15 kg) as the air separation sorbent and a total cycle time (tc) of only 3–9 s. A lower BSF of 41 kgs/TPDO2 and at a corresponding recovery of 24 % were achieved using LiLSX zeolite at cycle time of 5–6 s with the current design. An optimum adsorbent particle size range of 200- 350 µm was identified by modeling and simulation of RPSA cycle. Thus, our transformative RPSA design of MOC is 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.

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