Experimental design of a “Snap-on” and standalone single-bed oxygen concentrator for medical applications

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Abstract

A novel single-bed, “Snap-on” and standalone, medical oxygen concentrator design based on a rapid pressure swing adsorption process was investigated for continuous oxygen supply. The Snap-on concentrator design is easy to hook up to an existing compressed air source, and the unit can then be readily used to produce oxygen for medical applications. It is easily transportable and compared to a traditional oxygen concentrator with its dedicated compressor, the Snap-on concentrator is particularly relevant for the oxygen therapy needs of a larger number of patients in situations such as COVID-19. A commercially available LiLSX zeolite was used for the separation of oxygen from compressed ambient air. The experiments were performed at different feed air pressures using a constant supply of house air in the lab. Further, the device performance was also analyzed using a standalone medium size air compressor. The minimum bed size factor obtained with compressed house air was 100 lb/tons per day contained (TPD_c) O₂ at a cycle time of 7 s, whereas the minimum bed size factor obtained with a medium size air compressor weighing about 12 lbs was 210 lb/TPD_c O₂ at a cycle time of 14.5 s under the same feed pressures of 3.1 bar at an oxygen product purity of 90%. The product oxygen flow rate was nearly double for the same amount of adsorbent when using house air for the Snap-on design. The primary reason for this significantly higher oxygen production was the substantially higher and stable air throughput capacity of a typical house air compressor that enabled rapid cycling of the process at near-constant feed pressure compared to a medium size compressor used in a medical oxygen concentrator. The oxygen recovery was approximately 34% for both cases. Thus, the Snap-on oxygen concentrator was found to be easier to build and it delivered more oxygen for medical use compared to standalone units in locations where a constant supply of compressed feed air is available. This is typically the case in facilities such as hospitals, military medical camps and cruise ships. Further, the Snap-on design offers other benefits such as ease of transportation, higher reliability and lower weight.

Keywords Snap-on oxygen concentrator · Air separation · Rapid pressure swing adsorption · LiLSX · COVID-19 · COPD

1 Introduction

Recent demand for medical oxygen has grown exponentially due to the recent COVID-19 pandemic. The World Health Organization (WHO) has recommended oxygen therapy for all severe and critical COVID patients with doses ranging from 1 to 10 L/min based on patient age and severity of disease [1]. Additionally, the WHO has also predicted that 6.2×10^5 m³ oxygen is needed each day to treat the rapidly

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Dr. Shivaji Sircar fully contributed to the development of the ideas and results in this manuscript. If we had a choice, we would certainly include him as a co-author to posthumously recognize his novel idea of a Snap-on oxygen concentrator that he put forward in our early work in 2011.

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growing COVID-19 patients worldwide [2]. Clearly, medical oxygen has become a key component for the treatment of COVID-19. Chronic obstructive pulmonary disease (COPD) is another progressive life-threatening lung disease that causes shortness of breath. Globally, more than 3 million deaths were caused by COPD in 2015 alone [3]. Supplemental oxygen is needed to avail the breathing of COPD Patients. Oxygen therapy, i.e., the provision of medical grade oxygen, is commonly recommended for the treatment of COVID-19 and COPD. Common sources for administration of oxygen therapy are liquid oxygen in a bulk storage tank, high pressure oxygen cylinders, oxygen Pressure Swing Adsorption (PSA) plants and Medical Oxygen Concentrators (MOCs) [1]. Among all the sources for supplemental oxygen, MOCs can provide a continuous, safe, and cost-effective source of oxygen, but they require a continuous, reliable source of power supply [1].

MOCs are broadly categorized into stationary oxygen concentrators for long-term use at home and portable medical oxygen concentrators for travel, exercise and outdoor activities for a shorter period of time. Several MOC models are available in the market. A detailed summary on oxygen concentrators can be found in the review article published by Ackley [4]. Mainly, these units differ in their weight, flow rate of oxygen and the mode of oxygen delivery—continuous or pulse mode. Device weight, oxygen flow rate and power consumption are the key factors considered in the design of commercial oxygen concentrators.

One of the earliest reported design of a single-bed Ultra Rapid Pressure Swing Adsorption (URPSA) medical oxygen concentrator can be found in Kopaygorodsky et al. [5] for the miniaturization of the MOC device based on scaling analysis technique developed by Krantz [6]. They proposed a 2-step high frequency pressure cycle between 1 and 1.5 atm using 1-micron adsorbent particles. Later, Vemula et al. [7] proposed a two-step Pulsed Pressure Swing Adsorption (PPSA) process using a single adsorption column for the design of a MOC based on a detailed modeling and simulation of the process. The authors found out that the adsorbent particle size needs to be below 20 μm to minimize the weight of PPSA processes at a feed pressure of 3.5 atm. Chai et al. [8] published an experimental study of a single-bed, 4-step, Skarstrom-type PSA process for the design of an oxygen concentrator with 10 g of adsorbent using synthetic feed air and purge gases at a cycle time of 3–4 s. The authors showed that the bed size factor (BSF) can be significantly lowered between 28 and 70 lbs/Tons per day contained (TPDc) O_2 using their design. However, a synthetic purge gas at a fixed purity was used and the product delivery was not continuous in this study. These specific issues for the implementation of the single-bed design were addressed in a subsequent paper from the same group [9]. In this study, a single-bed MOC design integrated with a product tank based on Rapid

Pressure Swing Adsorption (RPSA) was designed to implement the product purge and continuous product delivery from the product tank around the column. The BSF was around 100 lbs/TPDc O_2 at a cycle time between 5 and 6 s and feed pressure of 4 bar. This unit was designed to continuously produce 1–2 standard liters per minute (SLPM) of 90% O_2 from the product tank. It was also reported that the process performance improved with simultaneous feed and product pressurization compared to feed pressurization alone. Later, Vemula et al. [10] reported the results of the effect of feed air pressure on performance of the single-bed RPSA process. The minimum BSF was obtained nearly at the same cycle time irrespective of feed pressure.

In the present paper, we evaluate the “Snap-on”, and standalone concepts for the design of a MOC using a single-bed adsorption column integrated with product oxygen storage tank. The Snap-on unit can be connected to a constant feed supply source of house air from a large compressor or storage tank outside a facility. It can be operated at a faster cycle time by controlling the feed air supply at a fixed pressure using a regulator. The standalone unit generally have a dedicated air compressor for feed air supply. The typical cycle times for these units are longer due a medium size feed air compressor used to minimize the weight, noise, and power consumption.

The concept of Snap-on oxygen concentrator was first proposed by Sircar et al. in the I&EC paper published by Chai et al. [8]. The Snap-on design does not require a standalone compressor, but it requires a high-pressure feed air supply source from a big size compressor or storage tank typically available in facilities such as hospitals, military camps, cruise ships, military aircrafts, etc. This allows a significant reduction in size and weight of the device by eliminating a dedicated compressor for the unit. Moreover, it is well-known that a dedicated small/medium size compressor in a standalone MOC cannot deliver a large flow rate of feed air in a short duration like in a Snap-on unit with a feed air supply at a constant feed pressure. A typical plot of bed inlet flow rates and pressures for both Snap-on and Standalone concepts are shown in Fig. 1 during a RPSA cycle at the same maximum feed pressure of 3 bara (30 PSIG) and product oxygen purity of 91% O_2 . The plot clearly shows that the stand-alone compressor is unable to rapidly deliver high flow rates during the short period of the pressurization and adsorption steps of the RPSA cycle, and this leads to a slow pressurization of the column in the standalone MOC. However, a higher capacity compressor or storage tank ensures that a substantially high flow rate of feed air is provided in a rapid burst during the critical pressurization and adsorption steps of the RPSA process at nearly a constant pressure. As we will show in our results, this allowed the rapid cycling of process and hence, it has a significant impact on the BSF of the resulting RPSA process, thereby making the Snap-on

Fig. 1 **a** Feed flow rates, and **b** feed pressures profiles with Snap-on design ($t_{cyc} = 7.5$ s) hooked to compressed house air source and Standalone design ($t_{cyc} = 13$ s) with a medium size dedicated compressor at a feed pressure of 30 PSIG (3.0 bar) and oxygen purity of 91%

design particularly attractive in specific situations where a large size compressor is readily available. Additionally, the simple design for a Snap-on oxygen concentrator is easy to build and transfer particularly for the treatment of COVID-19 patients in underdeveloped countries.

In this paper, we describe a single-bed rapid pressure swing adsorption-based Snap-on MOC to deliver 5–10 SLPM of 90% O_2 from compressed ambient house air. We compare the unit performance with that obtained when the Snap-on MOC is connected to a standalone medium size compressor. A detailed design methodology is proposed for the design of the single-bed oxygen concentrator. This unit can be hooked to a compressed air supply source and can be used as a Snap-on MOC or integrated with a compressor. The dynamics of feed air with high pressure house air supply and a stand-alone compressor are also analyzed.

2 Experimental design of a single-bed RPSA process

A single-bed medical oxygen concentrator was designed based on the RPSA cycle reported by Vemula et al. [9]. A nitrogen selective LiLSX zeolite adsorbent obtained from Zeochem Inc was used in these experiments to separate oxygen from air. The adsorbent physical properties, isotherms for O_2 , N_2 and Ar, and kinetic information can be found elsewhere [11–13]. The main components of an oxygen concentrator are: adsorption column, control instrumentation and a source of air supply such as a constant house-air supply at a fixed pressure or a standalone compressor. The single bed RPSA process has a custom-made adsorption column and a separate product storage tank for storing the product gas,

back purging the column and providing continuous supply of product oxygen gas.

The schematic of the experimental setup is shown in Fig. 2. The adsorption column is 18.52 in long and has an inner diameter of 2.37 in. The product and feed storage tank volumes are 5.22 L and 0.71 L, respectively. The photograph of the adsorption and storage tank assembly is shown in Fig. 3. The adsorption column is equipped with custom-made gas distribution plates at the inlet and exit of the column to improve the gas distribution across the column diameter. The inlet distribution plate is fixed rigidly between the inlet hemispherical head and inlet section of the straight column, and the exit distribution plate is removable at the top end of the bed. A spring load was used to hold the exit distribution plate on top of the adsorbent material. This spring-loaded design helps to prevent the movement and attrition of adsorbent particles in the bed during adsorption and desorption steps of the RPSA cycle.

The inlet and exit gas lines, and solenoid valves have a diameter of 0.75 in to facilitate the rapid pressurization and depressurization of the adsorption column. The product end tubing between the adsorption column and product storage tank has a diameter of $\frac{1}{2}$ in. The adsorption column was packed with 862.7 g of LiLSX zeolite adsorbent obtained from Zeochem LLC. The adsorbent material has a particle size range between 400 and 800 μm . It was regenerated at 380 $^{\circ}C$ for 6 h in an external column before loading into the adsorption column. During the regeneration process, a constant helium flow of 0.5 LPM was maintained throughout the regeneration process. The regenerated adsorbent was packed into the adsorption column in a glove bag filled with helium to avoid moisture contamination of the adsorbent. The adsorption column was constantly tapped on the wall,

Fig. 2 Schematic of experimental setup

Fig. 3 Photograph of experimental setup

while packing the column to improve the packing density, and minimize channeling in the adsorption column. The adsorbent was packed between the top and bottom distributor plate in the adsorption column. A back-pressure regulator at the end of the adsorption column was used to control the column pressure and regulate the product flow rate going into the product storage tank. A metering valve was used in the purge line to control the purge gas flow rate. The product gas delivery pressure was set at 7 psig, and a fixed product flow rate was maintained by using a flow control valve. The feed, purge and desorption gas flow rates were measured using SMC flow meters. The bed inlet and exit pressures, and tank pressures were measured using Honeywell pressure sensors. An oxygen analyzer (Model 905P, Quantek Instruments, range 0–100%) was used to measure the product and exhaust gas oxygen purity. A Raspberry Pi Platform with MCC DAQ cards was used for controlling the solenoid valves and the compressor, and for data acquisition from the flowmeters, pressure sensors and oxygen analyzer. A Python based graphical user interface (GUI) was developed for data acquisition and control of the RPSA process and compressor. Detailed information about the Raspberry Pi Platform can be found in Urich et al. [14].

The single-bed RPSA process has four cyclic steps similar to a typical Skarstrom cycle: (1) *Pressurization* In this step, column pressure increases from atmospheric pressure to super atmospheric pressure (P_H) using the compressed feed air supplied at the inlet end, and product oxygen from the tank at the product (exit) end during a feed and product pressurization step; (2) *Adsorption* In this step, high purity oxygen enters the product storage tank while adsorption column receives the feed; (3) *Depressurization* Desorption of gases is accomplished by lowering the column inlet pressure to atmosphere at the feed end; and (4) *Purge* In this step, a small amount of product gas from the product tank is used to back purge the column. The oxygen product is delivered at a constant flow rate from the product oxygen tank throughout the cycle. A back-pressure regulator shown at the end of the column was used to maintain the column pressure.

The process experiments were performed with two sources of feed air supply:

- A Snap-on design connected to the compressed house air supply with a feed pressure controller to maintain a constant feed air supply pressure. Commonly, compressed house air supply is available in facilities like hospitals, COVID-19 treatment centers, military base camps, emergency evacuation facilities, remote and military hospitals, high-altitude base camps, fighter jets and cruise ships.
- A standalone design equipped with a Gardner Denver Thomas compressor model number 2380Z to supply the compressed feed air to the device. This is mainly use-

ful for personal use at homes, for recreational activities and other portable needs of patients in situations where compressed air is not readily available.

A detailed evaluation of the experimental results obtained for both the Snap-on and Standalone designs of the single-bed RPSA process for MOC are discussed below. Further, methods to improve the device performance for a stand-alone unit with a dedicated compressor are also discussed.

3 Results and discussion

3.1 Experimental study on Snap-on concept connected to a constant house-air supply

Experiments were conducted with the compressed house air supply available in the lab, and the feed air supply pressure to the device was controlled with a feed pressure regulator in the upstream feed to the solenoid valve. The effect of cycle time was investigated on process performance indicators, Bed Size Factor (BSF, lb/TPDc O_2) and Oxygen Recovery (%R, % oxygen recovered in feed), over a range of total cycle time of 5–10 s at different feed air pressures. The effect of cycle time and feed air pressure on BSF and R is shown in Fig. 4 at a constant oxygen product purity of 90%.

BSF has a minimum at an optimum cycle time range between 6 and 7 s for all three feed pressures as reported in our earlier studies [9, 10]. R increased with increase of cycle time at a constant feed pressure. Further, BSF decreased with increase of feed air pressure and R increased with increase of feed pressure. The lowest BSF of 98 lbs/TPDc O_2 and the highest recovery of 34% were obtained at the highest feed

Fig. 4 Effect of cycle time on BSF and R% at three different feed pressures and a constant oxygen product purity of 90%. Pressurization time (t_p)=s, adsorption time (t_a)=2–6 s, depressurization time (t_d)=2 s and Purge time (t_{pu})=1 s

pressure of 3.1 bar (31 PSIG). Low BSF and high R are the preferred design parameters for miniaturization of a medical oxygen concentrator. On the other hand, the high feed pressure increases the compressor size in standalone design, and overall size and weight of an oxygen concentrator.

The effect of cycle time and feed pressure on product flow rate is shown in Fig. 5. The product flow rate increased with increase of column pressure and a maximum product flow rate of 10 SLPM was obtained at a short cycle time of 6 s and feed pressure of 3.1 bar. Oxygen product purity was maintained nearly constant at 90% for all experimental runs at every feed pressure. However, the product flow rate was decreased with increase of cycle time at a constant feed pressure as shown in Fig. 5. When the pressurization, depressurization and purge step durations were constant, the increase of adsorption time or cycle time leads to deeper penetration of nitrogen front towards the product end of adsorption column at a constant feed pressure. Thus, the bed requires more purge gas to clean the product end and maintain the oxygen product purity around 90%. The purge gas flowrate was increased by adjusting the purge needle valve to maintain the product oxygen purity. Therefore, this leads to a decrease in product flowrate with increase in cycle time at a fixed feed air pressure. From Fig. 5, it is evident that the product oxygen flow rate can be increased simply by increasing the supply feed air pressure using the “Snap-on” design with the same adsorption column.

The feed and exhaust flow rates, column inlet and exit pressures, oxygen product flowrate and purity were plotted for all the steps in a single cycle in Fig. 6 at a cycle time of 7.5 s and a feed pressure of 3.1 bar. As shown in Fig. 6a, a maximum feed flow rate of 400 SLPM was observed at the beginning of adsorption step and it was linearly decreased

because of linear increase in column inlet pressure during the adsorption step as shown in Fig. 6b. Similarly, a maximum peak flow of exhaust gas was observed at the beginning of the desorption step due to the exponential decrease in column inlet pressure. The maximum column inlet pressure at the end of adsorption step was nearly 3.1 bar (30.5 PSIG). The tank pressure varied between 2.18 and 3.08 bar (17–30 PSIG) during the cycle. The higher tank pressure is helpful to deliver oxygen to a patient at a longer distance (with longer tubing) from the device and it is also helpful for efficient purging of the column. The oxygen product purity and flow rates for the same cycle time are shown in Fig. 5c. The oxygen product purity is nearly constant at 91% during the cycle and product flow rate fluctuates between 8.8 to 9.2 SLPM. It is evident that the Snap-on design of a single-bed RPSA process can continuously supply an average product oxygen flow rate of 9.1 SLPM@91% O₂ as shown in Fig. 6c.

The above experiments show that this Snap-on design can deliver a product flow rate of nearly 10 SLPM if a compressed air supply is available at a fixed feed pressure of 3.1 bar. The oxygen product flow can be increased further by increasing the feed air supply pressure. The adsorption column assembly can be easily snapped on to an existing air supply source and it provides high purity oxygen for medical use. If a patient needs a high amount of oxygen flow for the treatment, the product flow can be simply increased by increasing the feed air supply pressure within the feed pressure range reported in this study. Therefore, this design is more flexible for use in facilities like hospitals and COVID-19 treatment centers, where compressed air supply is available at a constant high pressure from a feed air supply source like a large air compressor.

3.2 Experimental study on standalone design with a medium size air compressor for feed air supply

The design of a standalone oxygen concentrator for personal use of a COPD or lung disease patient requires a dedicated air compressor to supply the feed air to the unit. We have integrated the prototype unit with a customized Gardner Denver Thomas air compressor model no 2380 for this study. The standalone device performance with a dedicated compressor is a function of compressor size, speed of operation of the compressor (revolutions per minute, RPM), feed air temperature, pressurization time and adsorption times of the RPSA cycle. Therefore, a bigger compressor reduces the pressurization and adsorption time and improves the device performance, but the device weight increases significantly with the additional weight of the bigger compressor. Further, the compressed air is normally at high temperature, and adding a cooler or radiator to partially cool the compressed air improves the device performance.

Fig. 5 Effect of cycle time on product gas flow rate and oxygen product purity at different cycle times and feed pressure. Pressurization time (t_p)=s, adsorption time (t_a)=2–6 s, depressurization (t_d)=2 s and Purge time (t_{pu})=1 s

Fig. 6 **a** Feed and exhaust gas flow rate profile, **b** column inlet and exit pressure and tank pressure profiles, and **c** product purity and flow rates for all the steps in a single cycle at a total cycle time of 7.5 s and a column feed pressure of 3.1 bar

In addition, ramping of compressor speed during the critical pressurization and adsorption steps of the cycle also reduces the duration of these steps and improves the unit performance. All these options were explored in this study to maximize the performance of the unit with a medium size compressor.

A set of experiments was performed at different cycle times, (a) at a fixed RPM of the feed air compressor; (b) by adding a tank between the adsorption column and compressor to facilitate the fast pressurization for the process in case (a); and (c) by adding a radiator to cool down the feed air temperature and ramping-up the compressor RPM during the pressurization and adsorption steps of the cycle in case (a). In all these experiments, the compressor was continuously operated throughout the cycle. When the compressor is not feeding the column, the compressed air is either bypassed or used to pressurize the feed tank and/or radiator.

In case of a standalone unit with a medium size compressor, the device performance is mainly influenced by the adsorption step time of the cycle due to change in feed air moles supplied to the column. In all the above experiments, the adsorption step durations were changed, while maintaining the same step durations for pressurization, depressurization, and purge steps. Based on the experiments with compressed air line in Sect. 3.1, the optimum step durations for pressurization, desorption and purge steps are 0.5 s, 2 s and 1 s respectively. The same step durations were used to test the effect of compressor dynamics.

The effect of cycle time on process performance for all the above cases is shown in Fig. 7. For case (a), the BSF was exponentially increased with a decrease of cycle time below 10 s due to decrease in feed pressure with decrease of adsorption time, whereas, R increases with increase of total cycle time. A broad minimum in BSF was observed between 11 and 14 s, and corresponding recovery, R, is > 31%. The

Fig. 7 Effect of cycle time on BSF and R% using air compressor alone (square), air compressor and storage tank (triangle) and air compressor with ramp in feed steps and a radiator to cool the feed air (circles). Pressurization time (t_p)=0.5 s, adsorption time (t_a)=3.5–12.5 s, depressurization (t_d)=2 s and Purge time (t_{pu})=1 s

Fig. 8 Effect of cycle time on product flowrate and column pressure using air compressor alone (square), air compressor and storage tank (triangle) and air compressor with ramp in feed steps and a radiator to cool the feed air (circles). Pressurization time (t_p)=0.5 s, adsorption time (t_a)=3.5–12.5 s, depressurization (t_d)=2 s and Purge time (t_{pu})=1 s

decrease in product flow rate due to decrease in feed air pressure with decrease of cycle time is shown in Fig. 8.

In case (b), the BSF was increased with decrease of cycle time like case (a). But, a lower BSF was obtained at short cycle times below 10 s compared to case (a) due to the fast pressurization and adsorption of column with the excess feed air available in the feed air storage tank. The added feed air storage tank provided additional air to pressurize the column in a shorter duration for short cycle times below 10 s, resulting in a lower BSF than in case (a). A minimum

in BSF was observed between 10 and 12 s compared to case (a). A slight shift in minimum BSF towards a shorter cycle time was observed by adding the feed air storage tank. R was slightly higher compared to case (a) at short cycle times below 11 s. In summary, a slightly lower minimum BSF and higher R were obtained by adding a feed air storage tank to the stand-alone unit.

In case (c), a radiator was added to the standalone unit to partially cool the compressed air before entering the adsorption column, and the compressor was operated at maximum RPM in critical feed steps of the cycle. The BSF was decreased further for all cycle times compared to cases (a) and (b). The radiator can also serve as a feed storage tank for rapid pressurization of the column. The minimum in bed size factor was observed over a broad range of cycle times between 10 and 14 s for case (c) as in case (b). R experienced a trend similar to the other cases, i.e., as cycle time increased, R increased then reached a maximum value at and above a 14 s total cycle time. The oxygen recovery was higher for case (c) for cycle times below 14 s compared to cases (a) and (b) because of higher feed pressure with ramping of compressor RPM in the critical feed steps.

In all cases, the BSF reaches a minimum value at an optimal cycle time and increases above and below that optimal cycle time. The maximum recovery obtained in all the above three cases is around 34% at a cycle time of > 13 s. In all three cases, the lower R was obtained at short cycle times due to the lower feed pressure and higher purge gas volume to maintain a fixed product purity of 90% O_2 .

Figure 8 shows the relationship between feed air pressure and product flow rate with cycle time. The feed pressure was increased with increase of cycle time for all three cases with standalone design. As a result, the product flow rate was increased up to a cycle time of 12 s and was nearly constant with further increase of cycle time. The maximum product flow rates of 4.9 SLPM and 5.8 SLPM were obtained for cases (a) and (c) at a total cycle time of 13 s, and 5.2 SLPM was obtained at 11 s for case (b), respectively.

Therefore, the standalone device performance can be improved by adding a feed storage tank, which helps the fast pressurization of the column. The process performance can be further improved, as shown in Figs. 7 and 8, by adding a radiator to cool the compressed feed air and ramping the compressor speed in feed steps of the cycle.

These results indicate that the product delivery rate of a standalone oxygen concentrator can be controlled by operating the RPSA process at different cycle times below 14 s using an air compressor. The single bed standalone design integrated with a product storage tank can deliver nearly 5.8 SLPM of 90% pure oxygen from ambient air using a medium size compressor that weighs about 12 lbs. It is, therefore, feasible to design a transportable, standalone oxygen concentrator that can deliver nearly 5 SLPM of 90%

pure oxygen by limiting the overall device weight below 20 lbs. This is a 50% reduction in weight when compared to commercial oxygen concentrators used for home medical applications with the same product flow rate specifications.

Finally, the maximum oxygen delivery rate is below 5.8 SLPM at an optimum cycle time of 13 s even with the addition of a radiator and ramping the compressor RPM in critical feed steps of the cycle. It is nearly 40% lower compared to a Snap-on unit at the same feed air supply pressure of 30 PSIG and its corresponding optimum cycle times of 6.5 s. Further, the radiator or storage tank increases the weight and footprint of the unit, and ramping of the compressor RPM needs additional electronics and increases the power consumption of the device.

3.3 Performance comparison of Snap-on and standalone oxygen concentrator designs

The experimental results for Snap-on and Standalone concepts for the design of MOC using a single-bed RPSA process are compared in Table 1 at a feed air pressure of 2.1 bar. From this comparison, there is a clear trade-off between device performance and weight between the two designs. For the Standalone unit, adding a feed tank, or using a cooler and a ramped-RPM compressor was shown to reduce the BSF by nearly 3.4% and 12.5%, respectively, but adding those components significantly increases the device size and weight. The reduction in BSF is nearly 36.4% using a Snap-on design compared to the Standalone design. In addition, the overall weight of Snap-on design is lighter than the standalone design because no compressor is required for this design. Oxygen recovery varied between 28.2 to 31% for these cases. In conclusion, it is possible to reduce the adsorber size by 36.4% using Snap-on design compared to the standalone design at a feed pressure of 2.5 bar. Particularly, the same size adsorber can produce 55.7% more oxygen flow rate at the same feed pressure.

In the case of Snap-on design, the fast cycling of the device is feasible with a constant supply of feed air at a fixed feed pressure from a large compressor compared to a

standalone unit with a medium size dedicated compressor. Further, the Snap-on design allows easy transportation and more flexible use at the point of treatment because of the relatively lower weight and smaller device footprint without a compressor. In addition, the product flow rate can be marginally increased by increasing the feed air pressure based on the patient's needs within the pressure range studied in this paper. This design is easy to build, less noisy, requires relatively low maintenance and less power. Therefore, the Snap-on design is more efficient compared to standalone design in places where compressed air is available.

4 Design heuristics for Snap-on oxygen concentrator

Considering the current COVID-19 pandemic, a set of heuristics for the simple design of Snap-on MOC based on a single-bed, 4-step, RPSA process is listed below to deliver 90% O₂ from compressed air.

1. Select an optimum cycle time range between 6 and 8 s for the Snap-on MOC design at which the BSF is minimum as shown in Fig. 4.
2. Select a design oxygen product flow rate between 1 to 10 SLPM
3. Choose the design feed pressure from Fig. 4 at the design oxygen flow rate chosen in step 2.
4. Estimate the BSF at the selected cycle time chosen in step 1 and the selected design feed pressure chosen in step 3.
5. The compressed feed air supply is needed at the design feed pressure chosen in step 3

The above listed heuristics are helpful for quick design of a Snap-on oxygen concentrator for the treatment of COVID-19 and COPD patients.

Table 1 Performance comparison of Snap-on and standalone oxygen concentrators designed based on a single-bed RPSA process at a feed pressure of 2.5 bar (0.5, 3, 2, 1)

Feed supply	Cycle time (s)	Bed size factor (lbs/TPDc O ₂)	% Reduction in BSF	Oxygen recovery (%)	Oxygen product rate (SLPM)	% increase product rate with same amount of adsorbent
Air compressor	11	205.75	0	30.12	4.853	0
Air compressor with feed tank	9	198.62	3.5%	28.27	5.011	3.3%
Air compressor with radiator and ramping of compressor RPM in feed steps	9	180.0	12.5%	30.74	5.507	13.5%
Snap-on	6.5	131	36.3%	30.61	7.556	55.7%

5 Conclusions

The following conclusions can be drawn from the experimental study reported in this work:

1. A Snap-on, single bed design of an oxygen concentrator integrated with a separate product storage tank can deliver 10 SLPM of oxygen at a product purity of > 90% and feed pressure of 3.1 bar from compressed air. This concept offers a higher product oxygen flow rate at the same pressure using the same amount of adsorbent due to fast cycling of the process, which is not feasible with a standalone unit integrated with a medium size compressor. It is a simple, easily transportable, low maintenance design, and with less weight compared to a standalone MOC design. By integrating the Snap-on unit with an existing supply of compressed air, it can readily produce oxygen for medical treatment in remote hospitals, COVID-19 treatment centers, military base camps and military operations, combat fighter jets, recreation bars, cruise liners, etc. Further, the product oxygen flow rate can be increased based on demand by increasing the feed air supply pressure.
2. The BSF is optimum at a cycle time between 6 and 8 s using the Snap-on concept at all feed pressures.
3. The BSF of Snap-on design is nearly 36.3% lower compared to the Standalone design at the same feed pressure. In other words, the product oxygen delivery rate is nearly 55.7% more with the same amount of adsorbent. Further, the Snap-on Oxygen concentrator weighs less and is easily transportable because no compressor is attached to the unit.
4. The maximum product rate obtained with a standalone design is nearly 5.8 SLPM by addition of a radiator to cool the feed air and ramping the compressor speed in critical feed steps. The product flow rate is even lower without the radiator and feed storage tank.

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competing interests to declare. Data reported in the manuscript is available upon request.

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