Improving The Energy Efficiency of Oxygen Concentrators

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Abbreviations:

DC - direct current
LMIC - low- and middle-income country
LRS - low resource settings
MOF - metal organic frameworks
PSA - pressure swing adsorption
PWM - pulse width modulator
VPSA - vacuum pressure swing adsorption

VSA - vacuum swing adsorption

1. Introduction

This document is a summary of the ‘Energy Workshop’ conducted by the *Oxygen CoLab* via webinar on the 18th of March, 2021. The workshop sought to explore the challenges and potential solutions to improving the energy efficiency of oxygen concentrators. The Oxygen CoLab is a global network that enables, supports and connects those working to design oxygen concentrators that are fit for LMICs and LRS around the world.

2. Why Do We Need Energy Efficient Oxygen Concentrators?

Existing commercial oxygen concentrators consume a lot of energy, with a typical 10 l/min unit requiring around 600W. With nearly a quarter of primary health centers in Sub-Saharan Africa having no access to electricity, and many with very poor reliability, high performing, energy efficient concentrators could increase the viability of producing oxygen in remote health facilities using solar energy. Improved energy efficiency would allow for the use of smaller batteries and solar panels which not only enables appliances to run for longer but also reduces the cost of capital investment. Unlocking a remote clinic’s ability to generate their own oxygen would have very significant improvements on health outcomes.

So how can we improve the energy efficiency of concentrators that have been on the market for over twenty years? Since the first concentrators were designed there have been a number of innovations and advancements in different different fields which might make this possible. A recent publication by Gizicki et al., ‘Performance Optimisation of the Low-Capacity Adsorption Oxygen Generator’,[1] suggests that many oxygen concentrators for sale are not optimised in terms of energy efficiency and that a reduction of greater than 40% was possible. This is corroborated by other publications, suggesting that some big gains in reducing the energy required to produce the same amount of oxygen are possible.

So how can this be achieved? Before we discuss that we need to understand what we mean by energy efficiency in relation to oxygen concentrators.

2.1 Two Main Approaches to Improving Energy Efficiency

Improving the energy efficiency of an oxygen concentrator would result in being able to produce the same flow of oxygen with less unit energy input. With an oxygen concentrator this can be achieved via two main approaches:

[1] Gizicki, W.; Banaszkiewicz, T. Performance Optimization of the Low-Capacity Adsorption Oxygen Generator. *Appl. Sci.* **2020**, *10*, 7495. https://doi.org/10.3390/app10217495

(1) Improving Oxygen Recovery
This means increasing the amount of oxygen you get for a given energy input. It might come from innovations and improvements in the oxygen generation process (for example the timings and sequence of the cycling) or it might come from innovation in the adsorption capacity of the sorbent material, such as zeolite, which is currently used in commercially available units.

(2) Improving the power efficiency of the compressor or improving efficient use through energy recovery
Unit power efficiency gains can be achieved, for instance, through innovations in compressor design. Further energy recovery might be gained through new innovative equalisation sequences between sieve bed, or there might be creative ways of extracting energy from the exhausted nitrogen, for example, and using this to offset compression energy. Approaches of this sort could have an impact on the overall efficiency of the process.

We'll now look at what was discussed during the workshop and then look at the areas of research that appear to merit further collaborative exploration as part of the CoLab.

2.2 Maximum Theoretical Efficiency of Oxygen Concentrators

One of the key questions we need to answer is 'what is the maximum theoretical efficiency of an oxygen concentrator'? For example if we used the most efficient air compressor possible, optimised the process, made gains through innovations in sorbent technology and found ways to recover some of the energy lost (e.g. heat of compression, energy in the compressed exhaust gas), how efficient could we make the device? Once we know this, we can start to work out what is feasible and viable, what can be done and what makes commercial sense for bringing oxygen to off-grid health clinics in low resource settings.

3. Ways to Improve the Energy Efficiency of Oxygen Concentrators

3.1 Saving Oxygen

Before we actually talk about how we might improve the energy efficiency of an oxygen concentrator it is important to consider how we might **prevent wastage** and make the best use of the oxygen that we do generate. We breathe in for less than half the time that we breathe out, yet oxygen is delivered to a patient continuously. If oxygen were only delivered when the patient breathed in, a significant amount could be saved.

Two ways to achieve this were discussed (see below) but there are likely to be other approaches.

Pulse Flow	Firstly, some oxygen concentrators have a system called ‘pulse flow’, where the oxygen outflow is triggered by the patient breathing. Currently these are typically designed to work with adults, however, it was suggested in the discussion that a version could be designed to work for babies.
Nasal Reservoir	The other simpler approach discussed was the use of a nasal reservoir. This is known as a non-rebreather mask, where the mask is connected to a plastic reservoir bag which fills with oxygen from the concentrator. The mask has a one-way valve system that prevents exhaled oxygen from mixing with the oxygen in the reservoir bag. (This is different from a partial rebreather mask, which looks similar to a non-rebreather mask but contains a two-way valve between the mask and reservoir bag). The concentrator fills the reservoir bag at a constant rate, inflating as the person breathes out, therefore requiring a lower flow rate than is required with a nasal cannula.

3.2 Process Innovations

There were a number of innovations highlighted during the workshop that could improve the efficiency of concentrators by improving the process of pressurising and regenerating the sieve beds. These include:

Tuning the time of individual stages of the Pressure Swing Adsorption (PSA) process	e.g. to ensure you are making best use of the full volume of the available oxygenating layer bed (for example, by dynamically adapting the timing of the cycles to optimise the ‘transfer times’ of the air through the sieve bed). The timing and location of pressure equalisation is another example of a parameter that can be tuned to improve energy efficiency.
Adapting timings and the process to specific environments	Most commercial concentrators are not optimised for specific environments (e.g. altitude, temperature, humidity levels), rather a concentrator is designed for world markets, and not optimised for specific regions and environments. Manufacturers who do have ‘adaptive’ concentrators that do this retain the proprietary knowledge.
Having more than two beds carrying out multiple pressure equalisation steps	This has been shown to be a way to increase the percentage recovery and therefore the overall energy efficiency. There are various different equalisation sequences that can be considered depending on the number of bed. It was suggested that an equalisation tank could also be used.
Finding ways to reduce the	For example through the use of structured beds, which maximise the adsorption surface area of the zeolite while minimising the pressure drop.

pressure drop across the system	
Switching to VSA or VPSA instead of PSA	It has been shown that considerable efficiency gains are possible by using VSA or VPSA. However, there are many challenges associated with vacuum systems to overcome including the risk of leaks (air being sucked in by the vacuum and causing moisture contamination of the zeolite) and manufacturing challenges around the seals. There are also potentially increased costs due to the increased complexity of vacuum pumps and that they are not as readily available as traditional pumps. Despite this, there was however a general sense during the workshop that VSA should continue to be further explored, especially when the goal was reducing energy consumption.
Cycling based on a pressure cycle, rather than based on time	This has been explored by FREO2 and would mean the concentrator is more adaptive to changes in compressor performance.

It was noted that there is a considerable energy budget required to increase the concentration from 85% to 95%, and a concentrator designed to run continuously at 85% would use less energy compared to one designed to run at 95%.

It can be concluded that there are a number of key areas in optimising the cycle process where gains in efficiency can be made.

3.3 Compressor Innovations

The compressors used in existing concentrators tend to be WOB-L compressors (e.g. see https://www.gardnerdenver.com/en-gb/thomas/wob-l-piston-pumps-compressors), as these are the most cost effective. There have, however, been considerable innovations in compressor technology in other industries such as scroll compressors, which typically have a higher efficiency compared to reciprocating compressors. CLASP, for example, highlighted work they have been involved in relating to improving the efficiency of fridge compressors through the use of **brushless DC motors** driving the compressor. An improvement of 22-40% in energy efficiency was cited as being achieved across a wide range of products. Furthermore, there has also been other innovation in compressors for industrial air compression (e.g. hydro-based compressors) used in other industries, and development of innovative ideas which might be applicable to oxygen concentrators.

There are, therefore, potential efficiency gains to be made by adopting more efficient compressors and this is an area which warrants further research. One area of discussion was around the value of **variable DC compressors** (e.g. a DC compressor with a Pulse Width Modulation (PWM) controller), which would allow you to adapt the power input according to the flow output required. However, it was suggested that to achieve this it would require a more advanced ‘brain’ within the concentrator, to adapt cycle timings and other parameters in order to maintain high concentration levels and high efficiency. The general consensus was that nobody has spent enough time looking into compressors in relation to oxygen concentrators and that this was a missed opportunity.

3.4 Sieve bed Innovations

There is scope for innovation of the sieve bed materials and structure.

Enhancing Zeolite	Zeolite molecular sieves have been used in industrial applications for over 65 years, mainly for gas separation. There has been considerable innovation in **enhancing zeolite** in this period, including enhancing nitrogen capacity, selectivity and mechanical durability. Further innovation is possible, however, with *existing zeolite materials* (e.g. lithium, sodium enhanced 13X type zeolites). This is more likely to be an incremental improvement rather than a significant step change in performance.
Structured Beds	Zeolite molecular sieves in oxygen concentrators are typically used in a bead form. However, potential improvementsDieved through forming compact structures such as honey combs, and multi-channel or foam type structures. By choosing appropriate geometries, the packing density can be increased without increasing the pressure drop. Furthermore, structures can be designed to guide the gas flow through the structure to ensure adsorption is optimised.
Metal Organic Frameworks (MOF)	Step change improvements, however, might be expected from advancements in **metal organic frameworks (MOFs)**. These consist of metal ions connected with organic ligands that are arranged in a structure framework. MOFs are more tunable than zeolites in terms of designing them to have desired adsorption properties: e.g. strong binding forces between MOF structure and N_2 compared to O_2, while ensuring easy desorption of the nitrogen from the material. Furthermore, higher uptake capacity means less cycles for the same amount of oxygen and will subsequently reduce the required energy for the concentrator.

3.5 Potentially Disruptive Technologies

There are a number of emerging technologies, which might in the future be more appropriate for generating oxygen in remote health care centres. They are all at different degrees of maturity. They include:

Paramagnetic oxygen separation	This is where a strong magnetic field is used to do the gas separation. There is good physics that suggest this should work and some early experimental work by a group in Colorado has demonstrated this in practice. This is potentially game changing, as the energy budget would be drastically reduced, and there would be less parts (such as the sieve bed) which would be so susceptible to the kind of damage that caused existing concentrators to fail. See https://netl.doe.gov/sites/default/files/event-proceedings/2015/gas-ccbtl-proceedings/DOE-workshop.pdf for more information.
Using algae to generate oxygen	It is possible to produce large volumes of oxygen from algae through photosynthesis, a process which can be run directly from sunlight or from LED light sources. Algae consumes CO_2 and releases oxygen so it is ideal if it can be linked with a process that is producing CO_2, such as brewing, or combustion. It was also mentioned that algae could be used to scrub CO_2, e.g. scrubbing CO_2 from the exhaled air of a patient, and recycling this to reduce the oxygen concentration demand. This leads to a massive overall gain in system efficiency - because overall less oxygen has to be produced to provide to the patient. This technology is well developed and NASA has an algae bioreactor on the International Space Station which is scrubbing CO_2 and providing O_2 for crew. As a LMIC oxygen supply, it could run directly from sunlight during the day, with nighttime O_2 being supplied by O_2 storage or solar/battery storage running LEDs in the bioreactor.
Four Stroke Direct Compression VPSA	The PSA process could be enhanced through a four stroke direct compression VPSA based design. The energy of the compressed nitrogen is lost in most 'two stroke' compressors. 4-stroke compressors synchronize adsorption and desorption so that the system captures the energy of expansion of the waste N_2.
Free Piston Stirling Engine	Running an oxygen concentrator on a free piston stirling engine, either using the heat direct from sunlight or another waste heat source. This is already done for camping fridges, for example, by a company called 'Stirling Ultra Cold' (https://www.stirlingultracold.com/stirling-engine/). Stirling engines are also used in satellite power generation and submarine propulsion. This approach seeks to run the compression cycle without electricity. There is currently nothing off the shelf that would fulfill the requirements to run an oxygen concentrator, however, there is good potential in this technology. The piston-free stirling engine has only one moving part and no seals to wear. Night storage could be provided through thermal storage solutions, which are well established such as molten salt storage.

4. Conclusion

Improving the energy efficiency of oxygen concentrators is an important step towards creating concentrators that are fit for low resource settings. Benefits include the ability to power the concentrator with smaller and more affordable batteries, solar panels or other renewable sources allowing remote off-grid (or weak grid) clinics to generate their own oxygen; enabling concentrators to run for longer on a given size of battery (which may be vital for continuous production of oxygen throughout the night); and lowering the cost of providing oxygen and freeing up energy budgets or financial resources to be allocated to other important purposes.

The task of improving energy efficiency may follow two approaches: improving the efficiency of the process and improving the power consumption or energy recovery of the compressor. There are also a number of new technologies that have the potential to revolutionize the process of oxygen generation altogether.