Improving The Resilience of Oxygen Concentrators Against Humidity

Contents

Abbreviations:
LMIC - low- and middle-income country
LRS - low resource setting
PSA - pressure swing adsorption
VSA - vacuum swing adsorption

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1. Introduction

This document is a summary of the ‘Humidity Workshop’ conducted by the *Oxygen CoLab* via webinar on the 11th of March, 2021. The workshop sought to explore the challenges and potential solutions to improving the performance and longevity of oxygen concentrators in humid environments. The Oxygen CoLab is a global network that enables, supports and connects those working to design oxygen concentrators that are fit for low and middle-income countries (LMICs) and low resource settings (LRS) around the world.

2. The Humidity Challenge

Zeolite, which is commonly used as a sorbent material for oxygen concentrators, has a strong affinity for water. Moisture is strongly adsorbed onto the surface and is difficult to remove, greatly affecting the efficiency of the oxygen separation process - both impacting the capacity as well as the selectivity. Even a small amount of moisture (~1% by weight) prevents nitrogen from being adsorbed. Consequently, if zeolite is left exposed to the air, moisture is adsorbed and the material is ‘poisoned’.

Many existing commercial oxygen concentrators have been found to perform poorly under conditions of high heat and high humidity and ultimately fail more quickly. This can be compounded by poor user practices when operating the unit, which we will discuss later.

Another challenge that was raised during the workshop related to moisture penetration in zeolite beds during the storage or warehousing of oxygen concentrators. This might be done, for example, when oxygen concentrators need to be stored for long periods in case required for an emergency. It was found by UNICEF, that stored oxygen concentrators do not perform well after an extended period of warehousing.

Regeneration of the zeolite bed is possible but requires a high level of energy. It is often not very practical for users to carry this out themselves (e.g. it requires some specialist equipment). Therefore, innovations which protect and even make sieve beds more resilient to moisture can play a significant role in making oxygen concentrators more resilient in tropical, hot and humid environments common to many low resource settings.

2.1 Background to Zeolite Used in Oxygen Concentrators

The zeolites most commonly used in oxygen concentration are what are know as type Z and A. These are made of silica (SiO_2) and tetrahedral shaped alumina $(AlO_2)^-$ connected in an octahedral structure. The $(AlO_2)^-$ groups introduce a negative charge, which is compensated by the presence of cations (e.g. Na^+, Li^+). Zeolites can be produced with a greater amount of SiO_2, which improves their hydrothermal stability. However, lower amounts of SiO_2 gives higher cation exchange capabilities and a high capacity to adsorb polar molecules - meaning it performs better for oxygen concentration.

The majority of research into zeolites for oxygen concentration has focused on improving the adsorption capacity of zeolite and optimising the adsorption isotherm in order to create, for example, smaller sieve beds. Improving its hydrophobic properties has not been the focus of significant research. However, an air stream into an oxygen concentrator does not only contain nitrogen and oxygen, but also contains other components including water vapour, which is in high concentration in tropical climates. Therefore, because existing high performing zeolites for oxygen concentrators strongly adsorb water vapour, research and development in this area is paramount to designing a more resilient oxygen concentrator for low resource settings.

3. Current Approach: Multi-Layer Beds

Typically, pressure swing adsorption PSA concentrators use multi-layer beds, for example, using silicon gel, activated alumina or 13X before a more adsorbent lithium based zeolite. This is supported by the work of Rege et al.[1]. In their study they conclude that activated alumina (a-Al2O3) adsorbents appear to be the best for water removal and 13X zeolite is the best choice for carbon dioxide, also an important contaminant to remove. They suggest using an initial layer of activated alumina, followed by 13X.

There have been various studies on the effects of water adsorption in oxygen separation in a vacuum swing adsorption process e.g [2]. They discuss that even when using a vacuum, most molecular sieves do not completely reversibly desorb water and therefore a prelayer of activated alumina or NaX is required to protect the main adsorbent layer, e.g. of a lithium or calcium based adsorbent. They conclude that a pre-treatment layer is essential and that two pretreatment layers could be considered (e.g. activated alumina as a first layer, followed by NaX as a second layer before the oxygenating zeolite). Using multi-layer beds has become common practice among manufacturers. What is not widely published is the proportion of each of the adsorbents required in different parts of the bed for different conditions.

It was commented in the discussion that one of the disadvantages of using the multi-layered bed approach results in a decrease in the energy efficiency of the concentrator. This is especially true when using zeolites such as activated alumina, as these take up volume but do not contribute to oxygen concentration.

[1] Air-prepurification by pressure swing adsorption using single/layered beds, Salil U. Rege, Ralph T. Yang, Kangyi Qian, Mark A. Buzanowski, Chemical Engineering Science, Volume 56, Issue 8, 2001, https://doi.org/10.1016/S0009-2509(00)00531-5.

[2] High-Purity Oxygen Production by VPSA, Daniel Antonio Santos Silva Ferreira, thesis, 2016, https://core.ac.uk/download/pdf/185616093.pdf

4. Making Oxygen Concentrators More Resilient

Different ways of making the concentrator more resilient to moisture were suggested during the workshop. These are summarized below.

Selection of zeolite	Different zeolites behave very differently to the presence of moisture and other gas contaminants in the system. Therefore, in designing a system for LRS, careful selection of the most appropriate zeolite is required. For example, LiLSX and AgLiLSX type zeolites are low-silica type zeolites, and have a strong affinity towards water vapour. Therefore, concentrators using these types of zeolites are more likely to suffer from a loss of capacity in tropical climates more quickly. In a study by Santos et al.[3] different zeolites were found to be affected by water vapour/carbon dioxide to different degrees. The choice of zeolite used in a concentrator should therefore be carefully considered. Further work in optimising zeolite for a high humidity environment would be beneficial.
Pre-treatment of incoming air	Another approach is to find ways to pre-treat the incoming air to ensure that the moisture content is at tolerable levels. For example, it was discussed that membrane drier technology could be used. However, there were questions around the pressure requirements for this to be effective. Further research and experimentation is required. Another suggestion was to explore new materials to replace activated alumina that are even better tuned to moisture removal and regeneration. Another suggestion was simply separating out the drying and oxygenating parts into separate columns since the lower cost drying columns would likely require to be replaced more frequently than the (often) more expensive oxygenating zeolite column. Further exploration and experimentation is required in order to identify other novel approaches and analysis as to the cost/benefit of these new methods.

[3] *Contamination of Zeolites Used in Oxygen Production by PSA: Effects of Water and Carbon Dioxide*, J. C. Santos, F. D. Magalhães, and A. Mendes*
https://pubs.acs.org/doi/abs/10.1021/ie800024c#

Dynamic adaption of the concentrator	One suggestion for increasing the life of sieve beds in high humidity environments was to monitor or dynamically model the moisture front in the beds and then dynamically adjust the cycle timings in order to prolong the life of the sieve bed and reduce the advance of the moisture front. Monitors/alarms/remote notifications could be used to tell local staff or repair & maintenance teams when a service is predicted to be needed. Predictive maintenance of oxygen concentrators could be of great benefit to a fee for service model and ultimately allow companies to offer a better service and save money in the process.
Replaceable zeolite columns and affordable regeneration machines	One approach to solving the problem around humidity is not to make drastic changes to the design of the concentrator, but rather to make it simple to recondition/restore sieve beds locally. This might mean designing an affordable machine to regenerate sieve beds and making sieve bed connectors standardised. It might mean designing the unit in such a way that sieve beds are expected to be removed and regenerated by users (e.g. every 6 months or as required).
Over-engineering the bed	Some products appear to get around the issue of moisture by over-engineering the bed, making it far larger than required in order to ensure an extended concentrator life. However, the bed will still eventually fail and need to be regenerated or replaced.
Vacuum Swing Adsorption (VSA) vs Pressure Swing Adsorption (PSA)	VSA draws moisture off the bed and supports the regeneration of the sieve beds (even if it does not do this completely). VSA systems tend to perform better in high humidity environments and in addition use less energy. There have been commercial challenges to implementing this at the small scale of a 10 litre/min oxygen concentrator. It was seen as valuable to explore this further - perhaps there is an innovative way of making this more available for oxygen concentrators.
Warehousing oxygen concentrators	The challenge of warehousing oxygen concentrators for extended periods was raised. There are situations where it is required to store a

	concentrator for over a 12 month period. Experience on the field has shown that after this period many concentrators fail to function effectively. A number of the suggested simpler solutions, such as vacuum packing the entire concentrator during storage have been tried but do not work effectively in practice. This is due to the difference in temperature between the environment where the concentrator was made, and where it is transported and then stored. The adsorption capacity of zeolite changes (fairly strongly) as a function of temperature and this can lead to seals breaking when this occurs. Other approaches to solving this challenge that were suggested: ● Using a disposable/replaceable silica gel filter module at the inlet and outlet, so that any air has to pass through this before entering the concentrator. This way the concentrator can 'breathe' easily during transport, while keeping the inside of the concentrator safe from humid air until it is required for use. These moisture filters could then be removed before use. ● Using a small accumulator, which stores dry product O2 and exposes both ends of the columns to this during storage and transportation. This allows a change in the volumes of air as the temperature changes. ● Filling the columns with completely dried compressed air at the production phase, and then having a way to release. ● Periodically automatically running the concentrators for a short time while in storage. Units would of course need to be stored connected to the mains/have a battery to enable it to run. ● Using a moisture membrane at the inlet of the columns and a check valve at the end in order to reduce the amount of moisture entering.

5. Conclusion

Improving the performance and longevity of oxygen concentrators in hot and humid environments is a vital step towards designing concentrators that are able to withstand the conditions often experienced in low resource settings and LMICs around the world. There are a number of ways in which current zeolite based oxygen concentrators could potentially be improved to withstand humidity, which include: improvements to sieve beds (e.g the selection and ratios of adsorbent materials used in multi-layered beds, or dynamic adaptation of cycle times to prolong life of sieve beds); improvements to columns (e.g. independent columns for drying and oxygen concentration that can be easily replaced or regenerated); improvements to the concentration process (e.g employing VSA to assist in the removal of moisture from the sieve bed); and pre-treatment of incoming air to make it as dry as possible before it enters the sieve bed. Any solution however, must take into consideration not only the operational environment of the concentrator but also protecting the sieve bed from moisture during the transport and storage phases as well.