Supporting Information A

Manual – DIY Oxygen Concentrator

Knowledge Transfer in Support of the Development of Oxygen Concentrators in Emergency Settings During the COVID-19 Pandemic

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A1. Introduction

The aim of this document is enabling the reader to build an oxygen concentrator. This manual explains how such a device works and which materials are used. The basis of this is a prototype developed at the Functional Materials Laboratory (FML) of ETH Zürich. To successfully operate the concentrator please refer to the optimization report, which will provide you with the needed settings.

The idea of the oxygen concentrator is to produce a steady and concentrated flow of oxygen enriched air by using pressure swing adsorption (PSA). This is a technology where pressure and zeolite, which is a material that can trap specific molecules, are used to separate gases from each other. Under pressure, this material tends to adsorb certain molecules more, while letting others through. Once the pressure is released again, the adsorbed molecules leave the system. This way, two gases can be separated in repeated cycles of pressurization and depressurization as shown in Figure S.A1. Additionally, to achieve a more constant flow two containers are operated in an antiparallel manner.

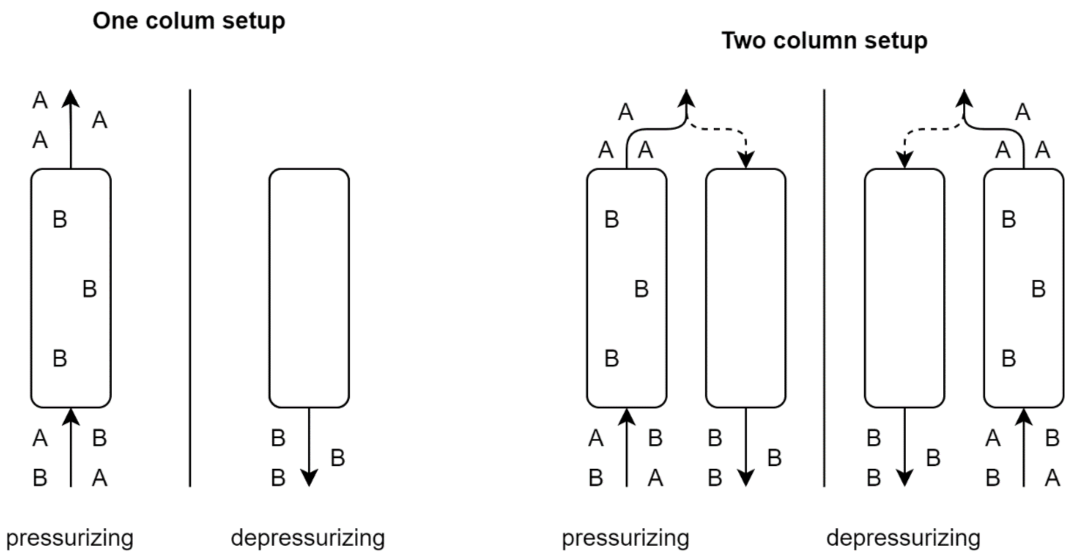

Figure S.A1: Left: Separation of two kinds of molecules by PSA. Right: The antiparallel operation of two column allows to produce a steadier flow of output gases.

A2. Setup

Material

To build the DIY oxygenator you´ll need the following material:

Table S.A1: Items and estimated costs for a DIY oxygen concentrator.

ITEM	ESTIMATED COST (US$)
- A compressor	- 250
- 2 drying containers	- 20
- Silica gel (2.6 kg)	- 15
- A 5-2 solenoid valve (alternative valve set-ups are shown in the appendix)	- 65
- 2 zeolite columns	- 25
- A heavy-duty spring, perforated metal sheet and abrasive cleaning sponge to line the zeolite column	- 5
- Zeolite ZEOX Z12-49 Li-LSX (0.7 kg)	- 30
- A storage container	- 10
- 2 check needle valves	- 50
- 1 needle valve	- 30
- A timer	- 5
- A power supply	- 5

-	Cables	-	5
-	Cable connectors (as needed)	-	5
-	Tubing (2m)	-	10
-	Tubing connectors	-	35

Above are links to the websites where most components are from. Besides providing an opportunity to order from, the websites might assist in further explaining the components or in evaluating costs or alternatives. Note that these links were last updated March 23rd, 2022, so some items might not be available, but we suggest considering other providers, as they can be cheaper or more accessible.

The cost of our prototype, not taking the compressor or shipping costs into consideration, amounts to 285 CHF (305 US$), but bear in mind, that some things can be acquired more cheaply with other providers.

Column Packing

In a first step, the zeolite columns must be filled. Therefore, the columns should be washed with water and well dried (no water left!). Next cut out 2 disks of perforated metal sheet and the abrasive fabric each to neatly fit into each end of the column. Drop the first disk into the cylinder followed by the fabric. Then fill the column with zeolite almost to the very edge and place the second disk of fabric. The next step is very important: While holding the fabric disk in place and pushing with your fingers onto it, knock the column vertically on a hard surface in order to tightly pack the zeolite. This will create a little extra space which can be filled with more zeolite (after having removed the fabric). Then give it a few final knocks to ensure tight packing (again, use the fabric disk in order to keep the zeolite in place). Then place the metal sheet on top, followed by the spring and close the column. Try using a broad spring and place it in the middle to assure evenly distributed pressure from both columns. When packing the second column, try to follow the exact same procedure, so that you have even oxygen production. After you´ve finished, the columns should not sound at all, when shaken, this means it is well packed. And during generation they should sound the same, which means they are packed the same and produce the same amount of oxygen.

For the drying columns the same procedure can be followed but using the silica gel instead of the zeolite.

Electronics

The valves are controlled by a timer, where you can set the switching time. Depending on which valve set-up you have the connection of the timer to the valve should look similar to the graphic on the left. In case you use only the one 5-2 valve, you can ignore the gray valve connection to the timer. Lastly, + and – go to the power source. Note that choosing a timer, power source and valves using the same voltage level simplifies the set-up a lot as you don't need a relay.

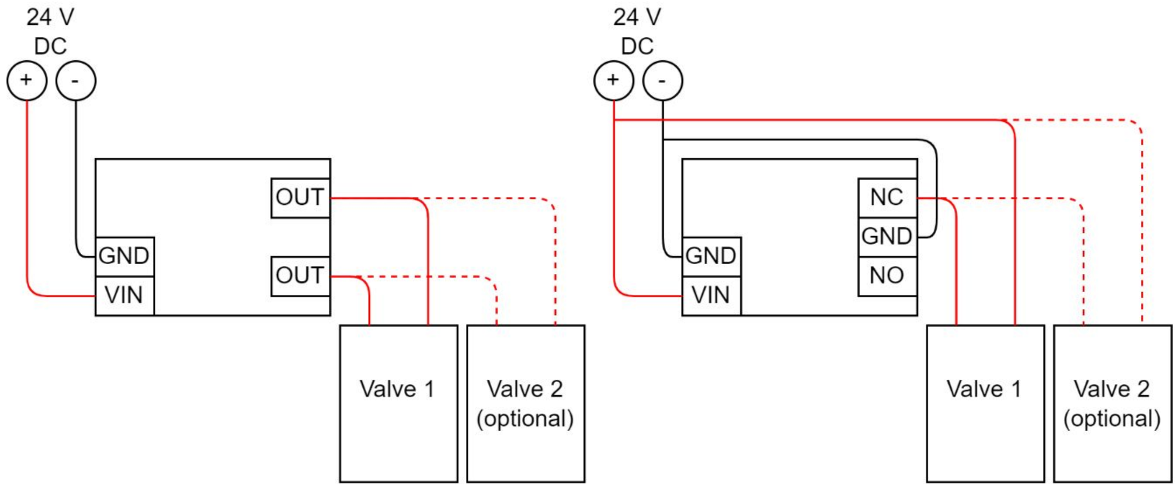

Figure S.A2: Electronic connections of 24 V power source, timer, and valves. Left: simple timer. Right: timer with relay. VIN = Voltage Input, GND = Ground, NC = Normally Closed, and NO = Normally Open.

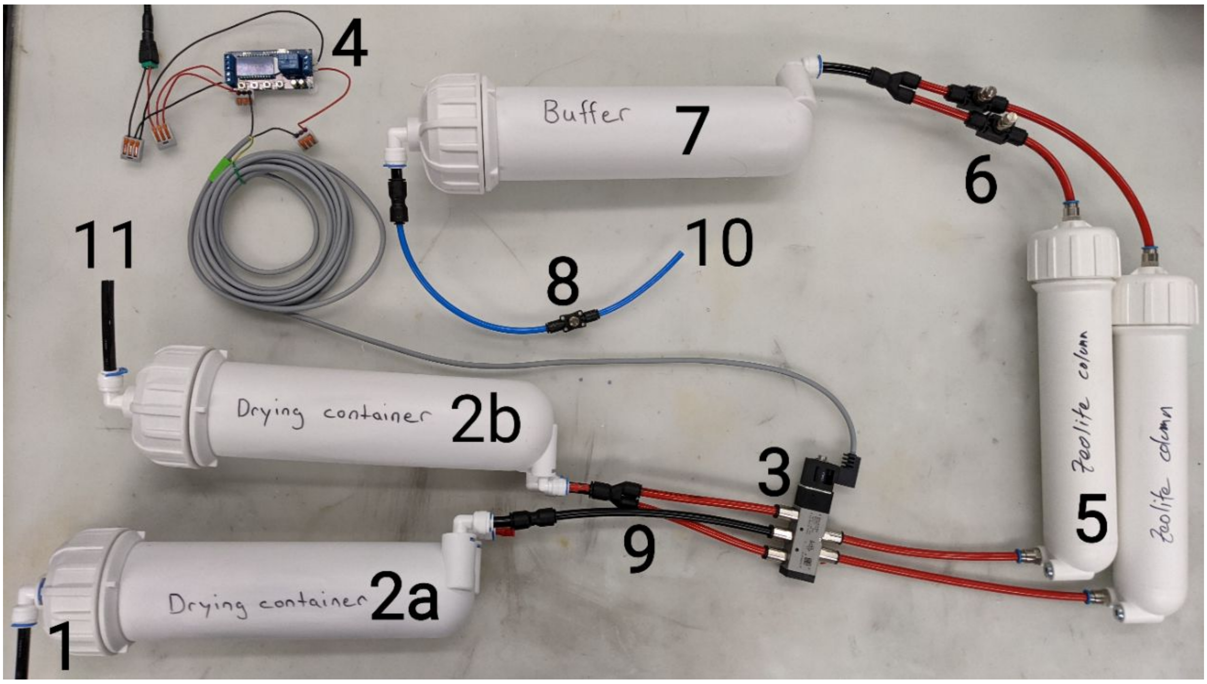

Figure S.A3: Picture of the full two-column oxygen concentrator.

Final Setup

Figure S.A3 shows the full setup of a two-column oxygen concentrator. Every element is labeled and named. Further information about most elements, e.g. about their function, requirements or alternative options, can be found at the respective page. It is important to note, that the device can be separated into three parts: air drying, oxygen production, where PSA is applied and oxygen supply, so that the gas can be easily accessed.

The set-up is very straight forward if you follow Figure S.A4. Connect the containers filled with silica gel (2a&b) to the solenoid valve (3), making sure there is one port to pressurize, connected to the inlet (1) and one port to release the pressure (11) for each cycle. The pneumatic valve (3) is connected to the timer (5) as described above. Connect the outlets of the valve to a zeolite column (5) each. The columns in turn should be connected to the check needle valves (6), check the direction of these valves to assure smooth operation. Both check needle valves are connected to the storage tank (7), which in turn is connected to the needle valve (8). The oxygen can be released through the outlet (10). In general, there is no specification how long and which thickness the tubing should be or how many different connectors should be used. Use as much and the kind as needed or available, but try not keep the distances between the individual parts short.

Note 1: There are two drying containers in two modes. 2a dries the inlet air and 2b is regenerated by returning the water to the dry air going out.

Note 2: In case the oxygen is for medical use, you will also need a rehumidifier/bubbler and a filter to treat the oxygen.

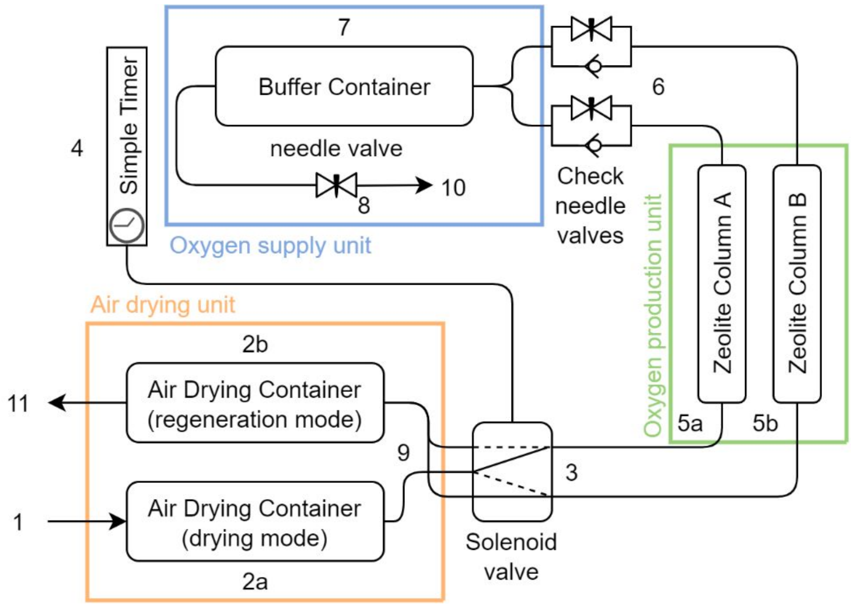

Figure S.A4: Schematic representation of the full two-column oxygen concentrator.

A3. Process

In the following paragraphs all the different phases and steps, which happen when the concentrator is running, are explained. It is crucial to understand how the concentrator works if changes or alternations should be made, or when there is a malfunction. With the help of the legend on the right, the illustrations should give a handy visual explanation of the process. Disclaimer: If certain elements or their function are unclear it is advised to read the dedicated text on them, referenced in "Setup".

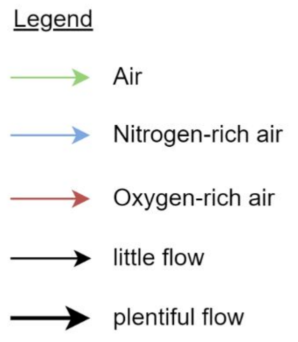

Figure S.A5: Legend for the following schematics.

When the concentrator is started, air flows through the drying container where most of its humidity is removed. After that, the air flows through the solenoid valve into a zeolite column.

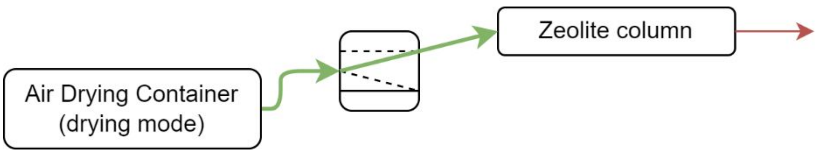

Figure S.A6: Flow of air from drying container to zeolite column.

Nitrogen is adsorbed while oxygen continues to flow through the column, through the check needle valve, and into the buffer container. Since the pressure in the buffer container is still atmospheric pressure, the incoming oxygen starts building up pressure, only then the output flow rate starts rising.

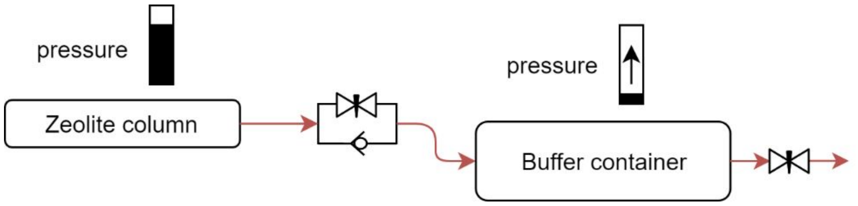

Figure S.A7: Flow of oxygen from zeolite column to outlet.

As soon as the valve switches positions, the column, which was just being filled, now empties itself from the nitrogen, which flows backwards through the solenoid valve and drying container out of the system. (The drying container here does not dry the air, but rather the dry air becomes humid again. The nitrogen waste air regenerates the silica gel in the drying container.)

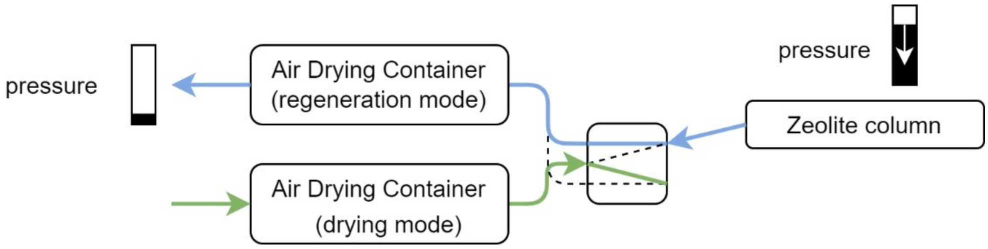

Figure S.A8. Flow of nitrogen from zeolite column to waste outlet

Since the buffer tank further down has reached the pressure of the feed air, the nitrogen flows backwards out the system because there, outside, the pressure is much lower (atmospheric pressure). When the nitrogen leaves the zeolite column, some oxygen from the buffer tank flows into the column, pressing out more nitrogen to clean the column. The check needle valve is only open a little since not much oxygen is required to clean the column.

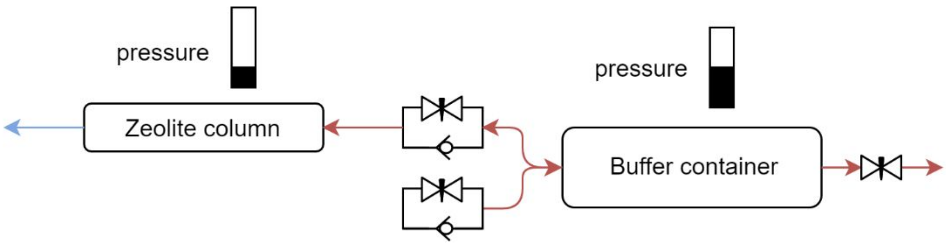

Figure S.A9: Purging of zeolite column using oxygen being produced by the other column.

At the same time when one column is emptied of its nitrogen, the other column is being pressurized with air again. Therefore, the whole process at that moment would look as following.

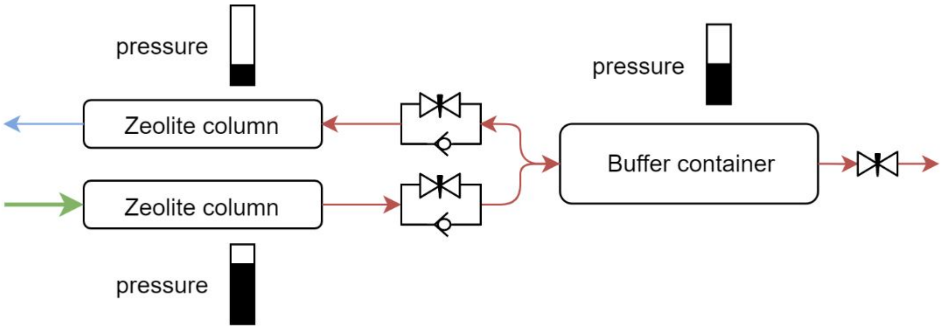

Figure S.A10: Flow of all gases through the air separation section during the first half cycle.

By switching the valve every few seconds, the zeolite columns are pressurized antiparallelly (Figure S.A10 and Figure S.A11) enabling a continuous output of oxygen enriched air.

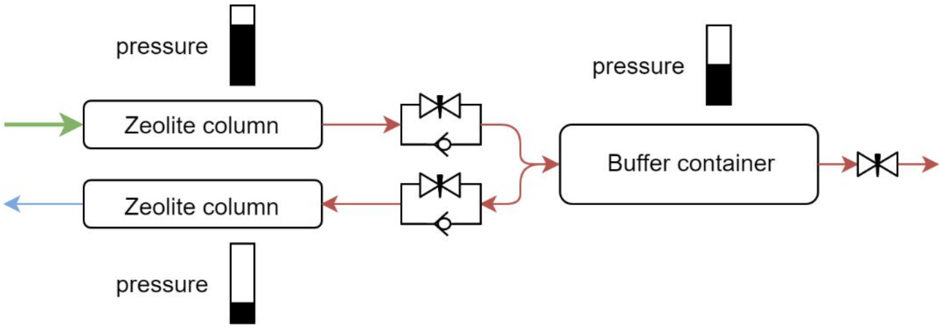

Figure S.A11: Flow of all gases through the air separation section during the second half cycle.

A4. Components

A4.1 Input air

What is important about the source of compressed air is that it provides a constant flow of air. The compressor should be able to run for a long time without overheating. Additionally, the air should be compressed to a minimum of 2.5 bar overpressure, as only upwards of this pressure, good results can be achieved. It should also be a clean compressor; oil should be avoided.

A4.2 Air Drying Unit

Exposure of the zeolite to humid air may lead to a decrease in performance over time. To prevent this the inlet air should be dry.

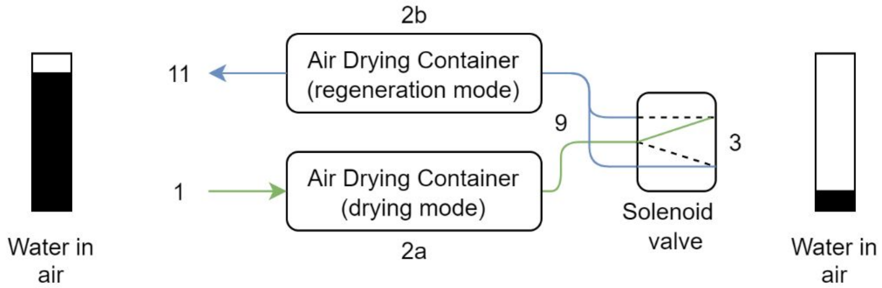

Figure S.A12. The two drying containers control the humidity of the entering and leaving air.

There are two drying containers filled with silica gel beads. They operate in anti-parallel manner, one in drying mode and one in regeneration mode.

The humid and compressed inlet air (1) flows through the container in drying mode (2a). In the container, the silica gel binds water and thereby dries the air. The dried air leaves the column and is passed to the solenoid valve (3).

The oxygen depleted air from the zeolite columns passes the solenoid valve and is fed to the container in regeneration mode (2b). The silica gel in this container is itself wet. Since the entering air is dry, it takes up water from the silica gel, which dries the silica gel.

After a while, the silica gel at the inlet becomes too wet, thus the two containers should be switched manually.

For the prototype around 1.3 kg of silica gel in each container were used. The containers are reverse osmosis tubing with an inside length of 31 cm and an inside diameter of 7.8 cm.

There are of course alternatives to silica gel as a drying agent, zeolites for example. However, silica gel is the easiest and cheapest to use. When using silica gel though, a non-toxic kind should be chosen.

A4.3 Solenoid valve

The valve before the zeolite columns has to direct the airflow into and out of these columns. This must happen in such a way that, while one column is being filled with pressurized air, the other column releases its air. Not only that, but the valve should also make it possible to switch which column is filled and which is emptied. For the presented prototype this problem has been solved with a 5-2 solenoid valve.

The notation 5-2 refers to the number of ports and states. Therefore, a 5-2 valve has 5 ports and two states. It has three ports on one side and two on the other. In each state two ports from one side are connected to two ports from the other side as shown in Figure S.A13 and Figure S.A14. Figure S.A15 shows the 5-2 valve connected to the drying and zeolite columns.

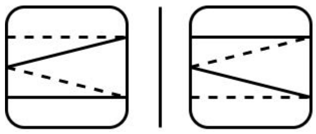

Figure S.A13. States of a 5-2 valve.

Figure S.A14. Picture of a 5-2 valve.

A solenoid valve is a valve that creates a magnetic field when energized, which is used for changing the valves state. This has the advantage of being fast and not requiring any mechanical force.

Another attribute to consider is the stability of the valve. It can be mono- or bi-stable, which refers to the states in which it can rest without the need for energy. A mono-stable valve will be either normally open or normally closed. When energy is added, the valve will change states but fall back into its original state as soon as power is withdrawn. A bi-stable valve will also change states with the use of energy but can stay in all its states without energy. Both types of valves can be used. However, in combination with the timer it is important to know which it is. In our case it is a mono-stable valve.

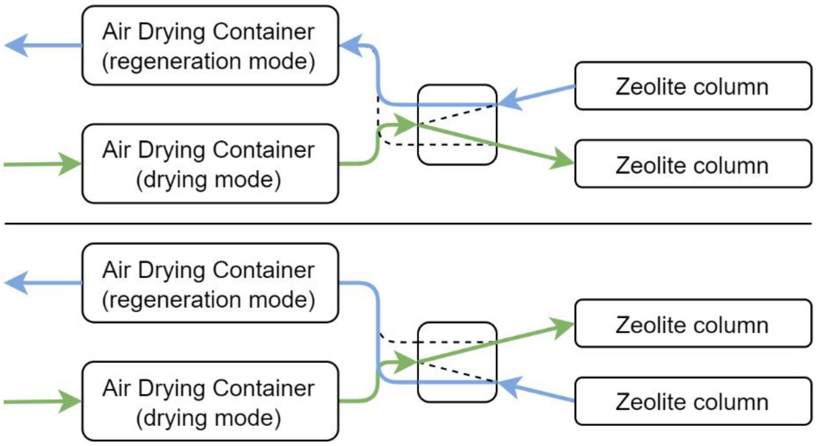

Figure S.A15: States of the 5-2 valve in the oxygen concentrator.

There are alternatives to the 5-2 valve as well. It is possible to have the same mechanic with a 4-2 valve, or, with the help of several valves, it is possible to use two 3-2 or four 2-2 valves. Diagrams to these can be found in the appendix.

A4.4 Timer

The timer controls the state of the solenoid valve. For a mono-stable valve, the timer opens or closes the electric circuit that powers the valve. For a bi-stable valve, the timer gives an impulse whenever the valve should switch. For further information on connecting the timer to the valve, please refer to the section Electronics in Setup.

It is favorable if both the timer and valves operate on the same voltage level (e.g. 24 V). Otherwise, a converter or an additional power supply will also be needed. In our case both timer and valve were running on 12 V, so a converter was redundant.

A4.5 Zeolite columns

The zeolite in the columns is what makes this concentrator work in the first place. It is the sieve material which was mentioned in the introduction. A zeolite is a mineral which, due to its crystalline microstructure, has an enormous number of microscopically small pores, with a width through which only small molecules fit. Additionally, zeolites contain cations, positively charged atoms, which help adsorbing molecules. So, when certain molecules pass through the zeolite they will be adsorbed to the surface. And since the surface is so huge, a large amount of substance can be adsorbed in the zeolite. Not all molecules are adsorbed with the same force though, which makes it possible to filter out certain types. In the case of the zeolite used for the oxygen concentrator nitrogen is adsorbed much more strongly than oxygen.

The zeolite in the column has to be tightly packed. If it is not, it results in friction which creates dust which in turn is bad for the valves. The zeolite was packaged by putting a metal sheet with holes, as well as some stiff fabric, on the bottom of the tubing. The tubing was then filled to the very top with the zeolite. Some stiff fabric and another perforated metal sheet were put on top, together with a spring, which would press everything together when the lid was screwed on.

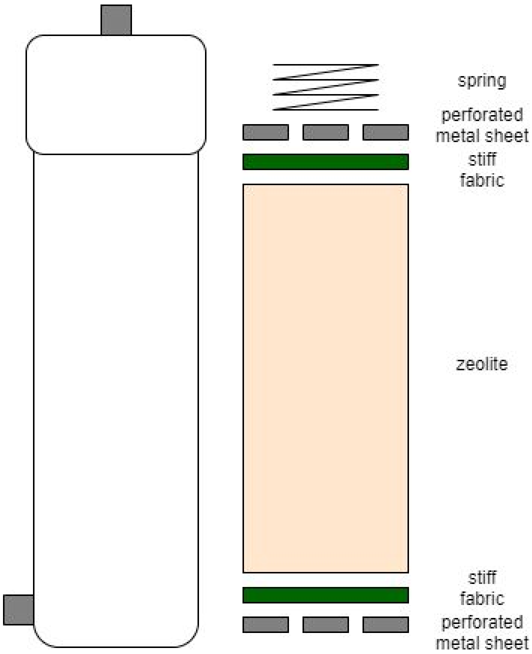

Figure S.A16: Diagram and image of the way the zeolite should be packaged into the column.

For the prototype around 340 grams of zeolite with a bead size of 0.4 - 0.8 mm were used in each column. The columns have a diameter of 5 cm, and an inner length of 28 cm and reverse osmosis tubing was used for them as well. An important aspect is the length to diameter ratio. Although no optimal value has been determined it can be generally said that a high L/D ratio is advantageous, read more on this in the optimization document.

The zeolite used was LiX. It has the advantage of very strongly adsorbing nitrogen but letting through oxygen easily. There are alternatives like 5A or 13X (similarly efficient, deactivates quickly though), both also used for oxygen concentrators. LiX has proven to be overall more efficient.

A4.6 Check needle valves

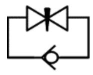

Figure S.A17: Icon representing a check needle valve.

The check needle valve is a parallel combination of a check valve (flow is only possible in one direction) and a needle valve (flow is bidirectional and can be restricted). Therefore, it works in such a way that it lets air through in one direction but restricts air flow into the other direction. The check needle valve has a pin which can be turned to determine how much the air flow should be restricted.

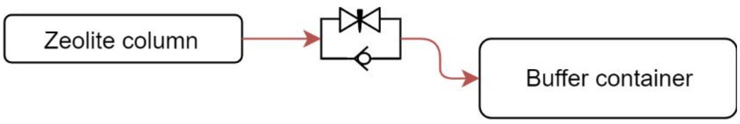

Figure S.A18: The check needle valve allows unrestricted flow from the zeolite column to the buffer tank.

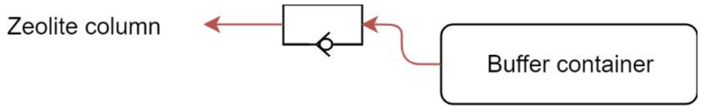

Figure S.A19. The check needle valve restricts flow from the buffer tank into the zeolite column.

The purpose of the check needle valves right after every zeolite column is to let a small amount of oxygen from the buffer container back into the zeolite column while depressurizing to push out more nitrogen and thereby clean the column. If the pin fully restricts flow back to the zeolite column, nitrogen stays in the zeolite column as soon as it reaches atmospheric pressure. If the pin allows too much flow back to the column, the produced oxygen of the other column would just leave the system via the column that is being emptied.

It is possible to replace the check needle valves by solenoid valves, which would increase the control over the airflow more. However, this setup with two check needle valves is simple and inexpensive.

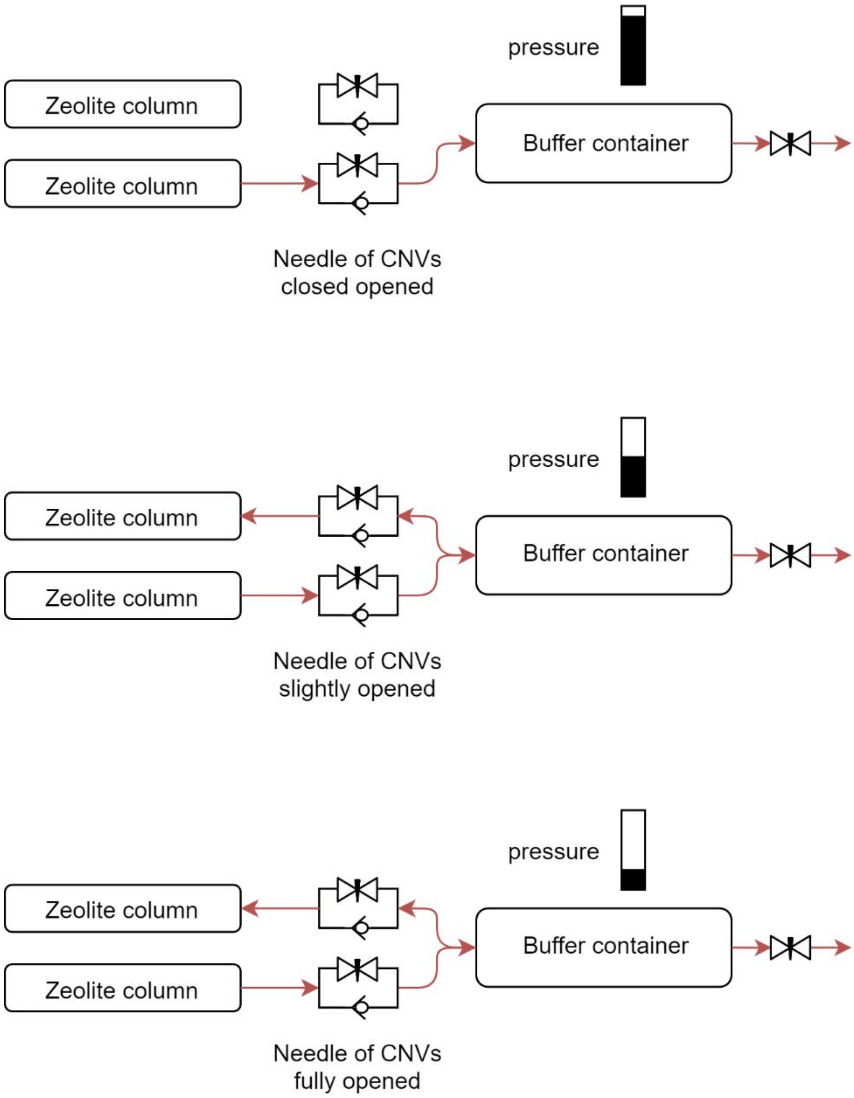

Figure S.A20: Effect of the check needle valve on the gas flow in the system.

A4.7 Buffer container

The buffer container at the end is important because it stabilizes the production of oxygen rich air. Without it, at the beginning of a cycle when the pressure is low, the output flow rate would drop. By having a big buffer container, which can hold the pressure up during the low-pressure phases in the columns, the output flow rate stays more or less constant.

The bigger this container is, the better the oxygen enriched air flow can be stabilized. However, a bigger container also means that is takes much longer to build up pressure and a high oxygen concentration and therefore the concentrator would need longer to become operational once started.

A4.8 Needle valve

The needle valve at the end of the system is responsible for a (relatively) constant flow of air. A needle valve does this by having a pin, that can be screwed into the tube beneath, which reduces the space for the air to flow through. Not only does it make the air flow more constant, but without it, the nitrogen would exit the zeolite from both sides, because the buffer container would not be under pressure.

A4.9 Plastic tubing and connective elements

The prototype uses plastic tubing and plastic connective elements, which are very advantageous as it makes the contraption very flexible and easy to modify. Other methods of connecting all the components can of course also be used.

Generally, it is preferable if all the tubes, connective elements and components of the concentrator have a uniform size, so that they all connect to each other easily without the requirement of additional adapters. This is not the case in the prototype since this was not possible with the available materials.

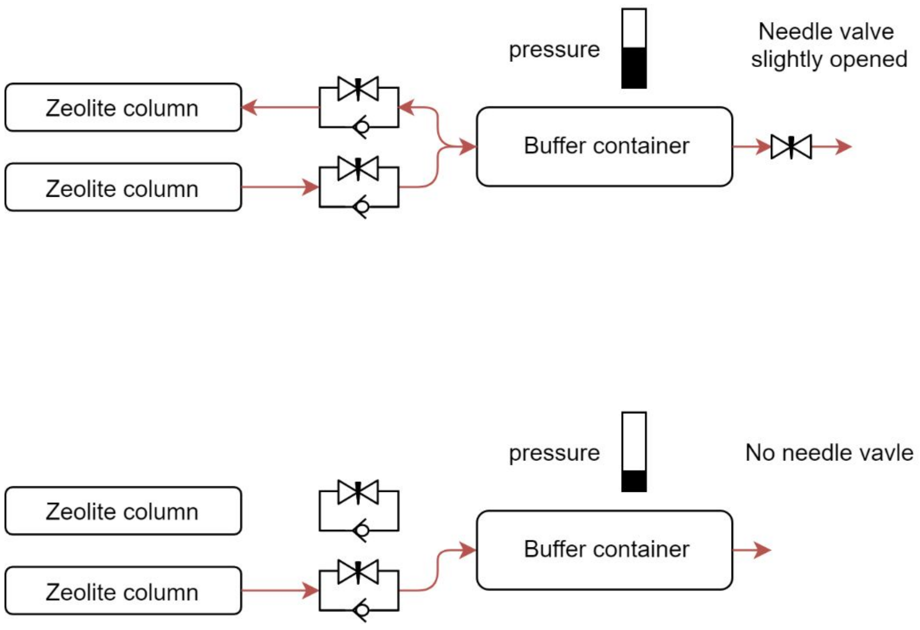

Figure S.A21: Effect of needle valve on the flow of the gases in the system.

A5. Safety Considerations

The generated oxygen is not guaranteed to be of medical grade, as this device is rather seen as a supplemental aid. Also, oxygen accelerates combustion tremendously, so the devise must be operated far away from any open flame or other heat sources. Don´t use oil or grease with the oxygen concentrator either, as the mixture of these substances with oxygen may lead to fire hazards. While it should be taken care to use a non-toxic zeolite, these particles are very small and must not be inhaled, as this may lead to respiratory problems. Hence it is suggested to wear a mask and protective goggles, during the assembly of the device.

A6. Appendix

A6.1 Alternative valve setups

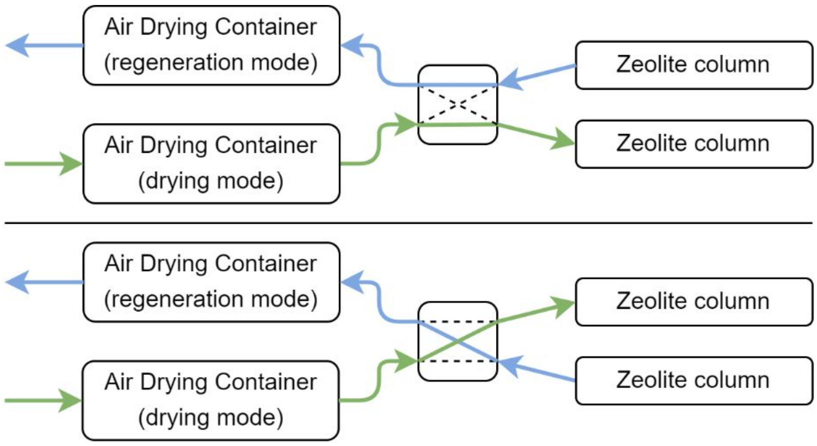

Figure S.A22: One 4-2 valve for the concentrator.

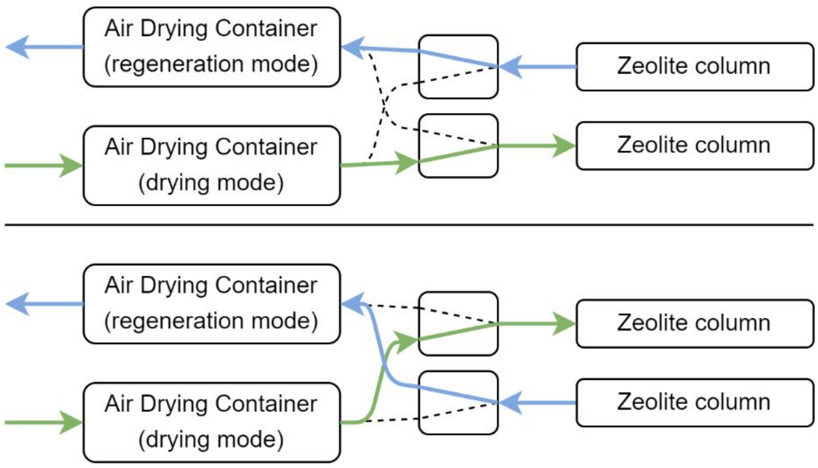

Figure S.A23: Two 3-2 valves for the concentrator.

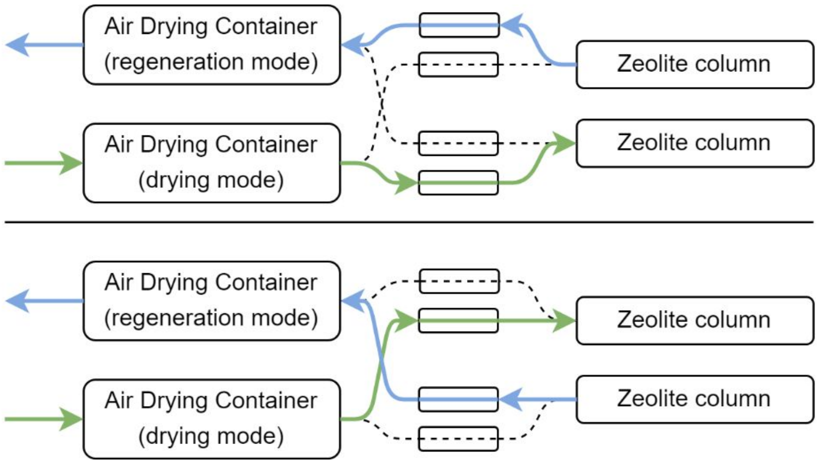

Figure S.A24: Four 2-2 valves for the concentrator.