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Full Dissertation

Design and Development of a Portable Multi-user Medical Grade Oxygen Concentrator

In fulfilment of the requirements for the degree:

MSc. Biomedical Engineering Dissertation

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Declaration

I, **Vongani Cliff Lowan**, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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Dedication

To my beloved wife, **Azola Lowan**,

In the pages of this thesis, I find not only a record of my academic journey but also a testament to the profound love and unwavering support you have showered upon me throughout this endeavour. Your presence has been a constant source of strength and inspiration, guiding me through the challenges and triumphs of this pursuit.

Your boundless encouragement and belief in me have been the beacon that lit my path, especially in moments of self-doubt or exhaustion. Your patience, kindness, and deep understanding have been the sanctuary I needed, offering solace and rejuvenation.

Together, we have weathered late nights of study and rejoiced in every milestone achieved. This dissertation is as much a product of your unwavering faith and support as it is of my academic effort. It stands as a symbol of our resilient partnership, which has nurtured and sustained my aspirations.

This accomplishment, while mine in name, is ours in spirit. With heartfelt gratitude and immeasurable love, I dedicate this thesis to you, my dearest Azola.

Table of Contents

List of Figures

Figure **Page**

List of Tables

Table **Page**

List of Abbreviations

Abbreviation	Full Form
ACHE	Air-cooled heat exchanger
CAD	Computer Aid Designs
CDC	Centers for Disease Control and Prevention
CNC	Computer Numerical Control
COPD	Chronic obstructive pulmonary disease
COVID	Coronavirus Disease
CPU	Computer processing unit
dB	Decibel
HEPA	High-Efficiency Particulate Air
HP	Horse power
ISO	International Standard Organisation
LCD	Liquid Crystal Display
LMICs	Low and Middle-Income Countries
LPM	Litres Per Minute
LRS	Low Resource Settings
LTOT	Long-Term Oxygen Therapy
ORI	Oxygen Reserve Index
PC	Personal Computer
PLC	Programmable Logic Controller
POC	Portable Oxygen Concentrator
PPU	Pre-purifier Unit
PSA	Pressure Swing Adsorption
PVC	Polyvinyl Chloride
PU	Purifying Unit
SANS	South African National Standards
SARS	Severe Acute Respiratory Syndrome
SDG	Sustainable Development Goals
UN	United Nations
UNICEF	United Nations International Children's Emergency Fund
WHO	World Health Organization

List of Graphs

Table **Page**

Abstract

Introduction: The COVID-19 pandemic has increased the demand for high-flow oxygen concentrators, particularly in resource-limited areas. There is a pressing need for an innovative, high-flow, multi-user oxygen concentrator using local materials to address this healthcare challenge.

Methods: The study focused on creating a portable, medical-grade oxygen concentrator using the Skarstrom pressure swing adsorption cycle, incorporating a silica gel drying tank and 13X Zeolite adsorption beds. Critical parameters such as compressor output pressure, heat exchanger efficiency, systemic pressure losses, air separation duration, and peak flow rate of oxygen-enriched air were extensively analysed through experiments and simulations.

Results: The concentrator achieved a 21 litres per minute flow rate with over 85% oxygen purity at 100kPa. Cost efficiency was ensured using local components. Enhancements included an orifice in the sieve beds to increase back pressure and equalisation valves to reduce cyclic duration, thus improving efficiency. An internal spacer in the sieve bed was designed to optimise airflow and oxygen production.

Discussion: This device addresses the scarcity of oxygen in resource-constrained regions like sub-Saharan Africa. It aims to reduce the cost of oxygen therapy (currently R20.00-R40.00 per patient per day) and should be expanded and implemented in similar settings. Future efforts should focus on integrating advanced functionalities such as remote monitoring for operational efficacy and safety.

Conclusion: This multi-user oxygen concentrator represents a significant advancement in medical technology, especially for resource-limited settings. It provides a high oxygen flow rate and concentration at an optimised cost, addressing the oxygen shortage exacerbated by the pandemic. Its innovative design utilises local materials and features that enhance efficiency, offering a cost-effective solution and a model for future healthcare technologies. Future developments should aim to extend this technology's reach, ensure adaptability, and continuously improve its features for enhanced efficacy and safety. This contributes to more equitable medical resource distribution in areas with significant resource constraints.

CHAPTER 1

1. Introduction and Background of the Study

1.1 Background To Study

Oxygen, recognised as an essential medicine, is crucial for treating various diseases, including heart failure, asthma, pneumonia, and chronic obstructive pulmonary disease (COPD), and is vital in surgical operations and ambulatory care. Continuous blood oxygen saturation measurement is essential for patients with these conditions (Haque, 2021). The World Health Organization has highlighted pneumonia as a leading cause of death in Low- and Middle-Income Countries (LMICs), accounting for 800,000 fatalities annually, with a significant portion potentially preventable through adequate oxygen therapy (WHO, 2020).

The COVID-19 pandemic has significantly exacerbated the oxygen crisis, especially in LMICs. It has strained oxygen delivery infrastructure in health facilities, with many hospitals facing acute shortages and increased demand (Audley, 2020). For instance, hospitals in South Africa's Gauteng province have faced severe shortages, requiring patients to be treated in makeshift facilities (Isilow, 2021).

This project proposes a solution to the challenge faced in LMICs by developing a high-flow, multi-user oxygen concentrator designed for underprivileged healthcare institutions. This innovation aims to meet the heightened oxygen needs in these regions, which are burdened with a high prevalence of global surgery, infectious diseases, and respiratory complications, especially in the aftermath of the COVID-19 pandemic. Such oxygen concentrators have been shown to lead to marked improvements in general well-being, breathing, mobility, and sleep patterns for patients, making them a critical component in healthcare settings (Khor, 2017). Such development in oxygen therapy could transform accessibility, offering a sustainable solution to a problem exacerbated by the pandemic and currently underserved in existing healthcare models.

1.1.1 Challenges Facing LMICs In Delivering Oxygen Therapy

In low- and middle-income countries (LMICs), the delivery of oxygen therapy presents significant challenges, primarily due to resource constraints and healthcare system priorities. Inadequate oxygen therapy in these settings can lead to increased mortality rates in emergency and surgical settings due to significant blood flow reduction and potential toxicity (Sjöberg, 2013). Hospitals in LMICs often report high death rates for conditions where oxygen therapy is critical, underscoring a dire consequence of resource scarcity. Furthermore, the healthcare focus in LMICs, as documented by the World Health Organization, tends to prioritise infectious diseases and maternal health. This results in an overlooked importance of oxygen therapy, particularly in surgical and emergency care.

The prioritisation within healthcare systems in LMICs impacts the availability and effectiveness of oxygen therapy. These systems are primarily geared towards managing infectious diseases and maternal-child health, leading to underinvestment in areas like oxygen therapy. Consequently, the

infrastructure in these regions is often inadequate to meet the surgical and oxygen therapy needs (WHO, 2020).

Regarding the technology of oxygen concentrators, which is vital in addressing oxygen scarcity, Harris et al. (1987) describe them as devices that concentrate oxygen from ambient air using Zeolite, a synthetic microporous material. This process involves adsorbing nitrogen, producing an oxygen-rich output essential for generating medical-grade oxygen in resource-limited settings.

The adaptability and challenges of oxygen concentrators in LMICs are noteworthy. These devices offer a cost-effective and adaptable solution for oxygen delivery. WHO (2020) emphasises their importance even when other oxygen sources are available. However, implementing oxygen concentrators in LMICs faces hurdles, including the need for reliable electricity, trained personnel, and appropriate infrastructure. Moreover, the current market models of oxygen concentrators, often expensive and not designed for easy transportation, pose additional challenges in resource-limited settings like rural South Africa (WHO, 2015).

Addressing the challenges of oxygen therapy in LMICs requires a multifaceted approach that involves reassessing healthcare priorities, improving infrastructure, and leveraging appropriate technologies such as oxygen concentrators. Tailoring these solutions to the unique needs and constraints of LMICs is crucial for enhancing healthcare delivery in these regions.

1.1.2. Existing Techniques Used to Process Oxygen

Oxygen production techniques offer unique benefits, including fractional distillation, electrolysis, and pressure swing adsorption (PSA). Fractional distillation, a prevalent method, involves separating different air components at various boiling points. Though effective, it requires significant energy and infrastructure, posing challenges in LMICs. This method is economically feasible for producing pure oxygen and nitrogen but involves high energy consumption in the compression and distillation units (Ebrahimi, 2015). Electrolysis, another method, splits water into oxygen and hydrogen. While efficient for producing high-purity hydrogen and oxygen, its high energy requirements make it less suitable for large-scale operations, particularly in LMICs (Sapountzi, 2017).

In contrast, PSA, initially proposed by Skarström (1966), has gained prominence, particularly in LMICs, due to its lower infrastructure demands and adaptability in various settings. This method involves adsorbents like zeolites to separate oxygen from air, which is suitable for producing 10–60 l/min of oxygen and is optimal for patient care scenarios (Banerjee,1990). The PSA process operates dynamically, contrasting with the continuous nature of other chemical processes. It requires precise control to maintain efficiency significantly as flow rates increase (Xu,2018). Using zeolites enhances the system's energy efficiency, throughput, and overall environmental impact.

In PSA, pressurised air is injected into a column filled with Zeolite, which selectively absorbs nitrogen, allowing oxygen-enriched air to be collected. When the Zeolite becomes saturated with nitrogen, it is vented, preparing the system for another cycle. This process results in a quasi-continuous stream of oxygen-enriched air, with oxygen content exceeding 90% at flow rates up to $10\ l/min$, depending on the operation mode, system size, and zeolite selection (Ferreira, 2015).

PSA's simplicity, cost-effectiveness, and adaptability make it an optimal choice for oxygen production in LMICs, addressing the limitations of fractional distillation and electrolysis.

1.1.3. Challenges Of Using Oxygen Concentrators In Southern African LMICs

In Southern African LMICs, particularly South Africa, healthcare facilities face formidable challenges in using oxygen concentrators, chiefly due to frequent power outages. These outages critically hamper the functionality of traditional oxygen generators and cylinders, which are non-portable and singular in their usage, rendering them impractical in scenarios where continuous oxygen supply is vital (Madzimbamuto, 2020). Moreover, maintaining oxygen cylinders is costly and often unfeasible in settings with limited financial resources (WHO,2021).

The proposed solution in this study, a portable, multi-user oxygen concentrator, is tailored to address these unique challenges. Designed to focus on affordability, user-friendliness, and cost-effectiveness, it seeks to ensure a consistent supply of medical oxygen even in power-limited settings(Howie, 2009a). This concentrator is particularly suited for underprivileged areas with a high incidence of infectious diseases, limited electricity infrastructure, and a population of low-income earners. By integrating features that allow for uninterrupted operation during power outages, the design aligns closely with the specific needs of Southern African healthcare facilities, thereby offering a practical and sustainable solution in low-resource settings (Bradley, 2011).

1.2. Clinical Problem Description

In LMICs, the burden of surgical and infectious diseases necessitates a substantial need for oxygen therapy. Despite hosting only a fraction of the world's surgical procedures, these regions are plagued by a shortage of medical oxygen, a situation that the COVID-19 pandemic has severely aggravated. The World Health Organization reported a staggering gap of 1.1 million oxygen cylinders needed to manage patients effectively as of February 2021 (Sikder, 2022). This gap is not solely a matter of production but also involves issues related to distribution, maintenance, and the cost of oxygen supplies, creating a multifaceted challenge for healthcare systems in these countries(Flesher, 2016)

The reliance on single-use, bulky oxygen cylinders in LMICs' healthcare facilities presents a logistical and economic challenge. While commonly used, these cylinders are impractical for broader applications due to their limited portability and single-patient usage (Greif, 2000). In contrast, oxygen concentrators, known for their efficiency and cost-effectiveness, are unfortunately represented in the market by models that predominantly cater to single-user needs and are ill-suited for continuous operation in challenging environmental conditions (Navuluri, 2021).

This project aims to design a portable, high-flow, multi-user oxygen concentrator that is both user-friendly and cost-effective, specifically for LMICs. The proposed solution addresses the critical challenges of reliability and versatility, ensuring effective operation in varied climatic conditions and meeting the needs of diverse patient groups, including children. This innovation is intended to bridge the significant gap in oxygen delivery systems in LMICs, offering a practical solution to a critical global health issue (Howie, 2009b)

1.3. Significance of Study

Through the development of a portable, multi-user oxygen concentrator, this research addresses a crucial gap in healthcare provision within LMICs. Oxygen therapy, essential in diverse medical contexts from surgery to ambulatory care, has been notably limited in these regions, a deficiency further highlighted by the COVID-19 pandemic. The need for oxygen therapy in managing COVID-19 patients, particularly those with severe respiratory failure, has emphasised the importance of uninterrupted oxygen supply and rational use during the pandemic (Hanidziar, 2020). The introduction of this technology aims to provide a sustainable and adaptable solution for a wide range of healthcare needs, including infectious diseases and complications related to pregnancy and childbirth, as highlighted by recent studies (Pierce-Williams, 2020).

Beyond direct healthcare benefits, the broader implications of this study lie in its potential to influence healthcare policies and practices in LMICs. The study's findings could improve patient outcomes by enabling consistent access to medical oxygen, particularly in regions with scarce healthcare resources, notably in treating respiratory diseases and supporting surgical procedures (Johnson, 2021). This innovation is poised to significantly enhance the quality of medical care in LMICs, reducing mortality rates associated with respiratory illnesses and supporting global health equity (Navuluri, 2021b).

1.4. Research Approach

In this research, spanning six chapters, we begin with a literature review that lays the groundwork for the subsequent development of the oxygen concentrator. Adhering to the engineering design paradigm, as Khandani (2005) outlined, the study meticulously follows a systematic methodology that includes analysis, design, implementation, testing, and deployment. This approach incorporates data from the literature review, providing insights into previous and current research and practical, hands-on experimentation. Crucial data such as compressor pressure output, temperature variations in heat exchangers, dew points before air separation, and pressure fluctuations across sieve beds are integral to the design process. These factors are essential in ensuring the final product is technically robust and tailored to meet the specific requirements of oxygen therapy in various healthcare settings. For example, optimising the heat exchanger surface area, flow, and pressure of incoming air is critical to minimise capital and operating costs (Singla, 2021). Furthermore, the operating temperature impacts oxygen recovery and bed size factor in oxygen concentrators, with ideal temperatures ranging between 20°C and 30°C for favourable performance (Zhu, 2021).

1.5. Study Aim

This research aims to design and validate a high-flow and multi-user oxygen concentrator for healthcare institutions in under-resourced areas. The 'high-flow' aspect refers to the concentrator’s capacity to deliver a larger volume of oxygen per minute, essential for treating multiple patients simultaneously or those with severe respiratory conditions. High-flow oxygen therapy has been shown to significantly reduce the need for escalation of care in patients with acute respiratory failure (Frat, 2019). The 'multi-user' feature signifies the concentrator's design to support multiple patients simultaneously, distinguishing it from conventional single-user systems. This dual capability is central

to the solution's effectiveness in resource-limited healthcare settings where such technologies are critically needed(Weatherson, 2021). High-flow and multi-user oxygen concentrators offer updated knowledge to multidisciplinary teams, allowing an appropriate selection of devices and delivery systems tailored to patient needs (Hardavella, 2019).

1.6. Research Question

This research project addresses the following question: 'How can the development of a locally-produced, multi-user, medical-grade oxygen concentrator specifically contribute to enhancing the effectiveness and efficiency of oxygen therapy in low-resource clinical settings?' This question explores the specific design, production, and application aspects, focusing on the unique challenges and needs of under-resourced healthcare environments. Locally-produced oxygen concentrators can provide satisfactory oxygen concentrations, flows, pressures, and reliability for various medical applications, particularly in remote areas and situations where resources are constrained (Easy, 1988). Furthermore, developing compact, lightweight concentrators with high oxygen permeability and selectivity significantly improves the effectiveness and efficiency of oxygen therapy in these settings (Akutsu,1990). These advancements are central to addressing the pressing healthcare needs in low-resource clinical settings, where technologies like these are critically required.

1.7. Research Objectives

The research aims to meticulously develop a portable, multi-user medical-grade oxygen concentrator capable of exceeding flow rates of 20 litres per min (LPM), particularly for low-resource settings. The objectives are detailed as follows:

1) Design a molecular sieve-based oxygen concentrator capable of delivering oxygen-enriched gas at flow rates surpassing 20 Lpm.
    a) Design a compression module incorporating thermoregulation and moisture control systems to counteract the diminished efficacy of Zeolite adsorbent under elevated thermal and humidity conditions following ISO specifications (Fenton, 2013).
    b) Design the air separation system featuring various sizes of adsorbent/sieve beds, optimising operational parameters to meet medical-grade requirements (Pan, 2017).
    c) Design a robust oxygen tank and an efficient gas delivery system, considering safety standards and current trends in concentrator technology (Harris,1987b).
    d) Design an electronic control unit and system for operational management and regulation of the medical device.
2) Assemble the designed sub-systems to construct the oxygen concentrator prototype, utilising techniques that ensure mechanical reliability and patient compliance (Howard, 1983).
3) Conduct rigorous testing to assess the efficiency and performance of the Multi-user Medical Grade Oxygen Concentrator, ensuring adherence to ISO 80601-2-69 standards and WHO Technical specifications for Oxygen Concentrators(WHO, 2015b).

1.8. Key Study Parameters

This study's critical parameters for developing portable oxygen concentrators, particularly for LMICs, include air pressure, cycle time, tank capacity, and the equalisation step. Each of these parameters plays a crucial role:

1. **Air Pressure**: Determines the efficiency of oxygen concentration. High-pressure swing adsorption processes, such as those in oxygen concentrators, ensure efficient oxygen production (Li, 2014a).
2. **Cycle Time**: Affects the rate at which oxygen is produced and delivered. Optimal cycle times are necessary for efficient oxygen production, with some studies suggesting an optimum total cycle time for a medical oxygen concentrator to be around 5-6 seconds (Rao, 2014).
3. **Tank Capacity**: Impacts the duration for which oxygen can be supplied continuously. The capacity should be determined based on demand and usage patterns in LMICs, considering the need for a longer supply duration (Gurkin, 2021).
4. **Equalisation Step**: Crucial for maintaining consistent oxygen purity. Incomplete pressure equalisation in oxygen concentrators can affect process performance; hence, optimising specific purge and extent of equalisation is essential for productivity and light-component recovery (Shin, 2000).

1.9. Scope of Study

The study's emphasis on developing multi-user oxygen concentrators with a flow rate of 20 litres per minute, specifically for deployment in LMICs, is driven by the acute need for improved oxygen delivery systems in these regions. This need arises from various factors:

1. **Hospital Settings**: In hospital environments, particularly in LMICs, there is an urgent requirement for reliable oxygen delivery systems to improve survival rates, reduce hospitalisations, and enhance exercise tolerance for patients with severe chronic obstructive pulmonary disease (COPD) and other respiratory conditions (Dunne, 2009).
2. **Home Settings**: The need for improved oxygen systems in home settings is equally critical, particularly for patients with advanced COPD or other chronic respiratory illnesses. The goal is to prolong life, reduce hospitalisations, and potentially lower costs by enabling home-based care (Petty, 1990).
3. **Global Health Equity**: Addressing the gaps in healthcare infrastructure in LMICs and providing sustainable solutions to enhance oxygen therapy contribute to global health equity. The focus on hospital and home environments ensures the developed concentrator meets a broad spectrum of needs, from clinical to private care, thereby supporting a range of patient demographics and conditions (Flesher, 2016b).

1.10. Dissertation Overview

The proposed structure of the dissertation, detailed in six chapters, was systematically aligned with the progression of the study; see below Figure 1-1:

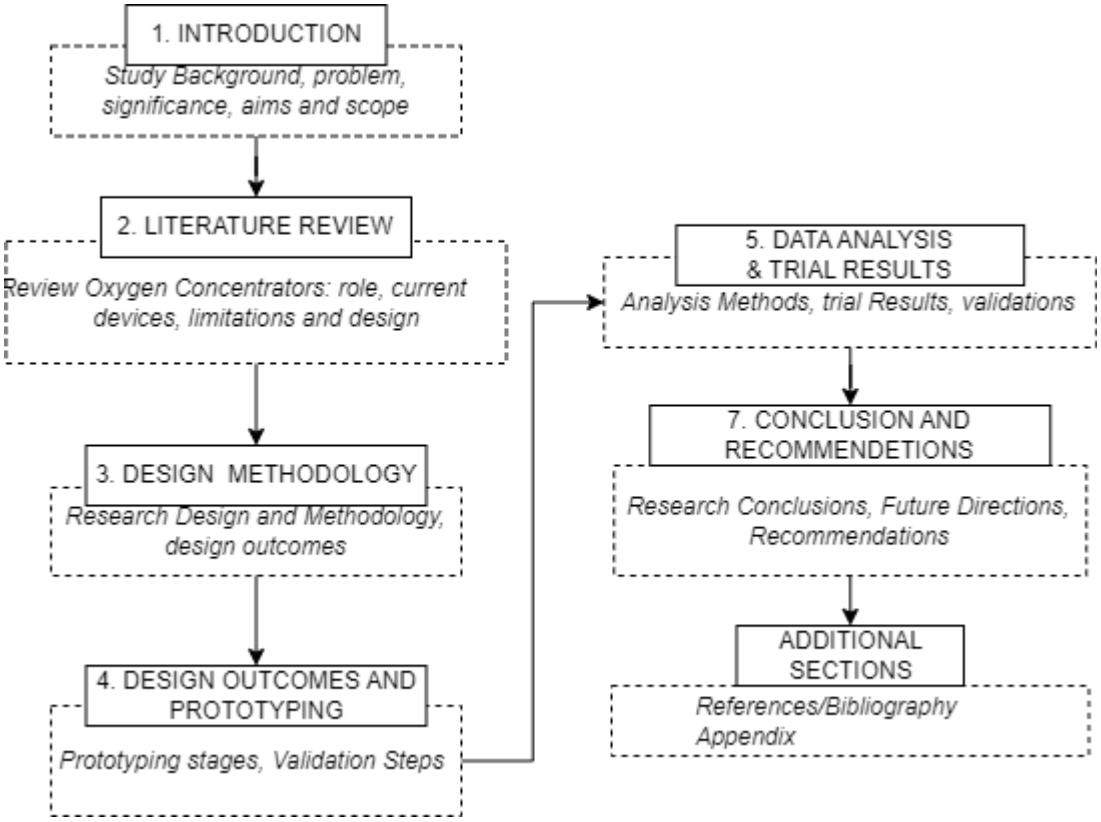


Figure 1-1: Research Project Overview

CHAPTER 2

2. Literature Review

Oxygen, an essential component of medicines, is crucial yet remains inaccessible in many developing countries and under-resourced healthcare facilities. According to the WHO (2015), even developed countries' healthcare institutions, such as nursing homes and clinics, face significant mortality risks among critically ill individuals due to insufficient oxygen supply. The high cost and lack of facilities to build and sustain oxygen production exacerbate this issue. Additionally, challenges like power outages and workforce shortages in certain regions hinder the effective implementation of oxygen therapy in Low- and Middle-Income Countries (LMICs), increasing mortality rates (Melani, Sestini & Rottoli, 2018). When piped or oxygen cylinders are unavailable, healthcare facilities often resort to oxygen concentrators as a last resort (Duke, 2010). These devices, increasingly popular for concentrating oxygen from the air, do not rely on compressed gas cylinders but draw air from the environment, separate oxygen from other gases, and deliver concentrated oxygen directly to patients (Rybak, 2017).

2.1. History of Oxygen Concentrators

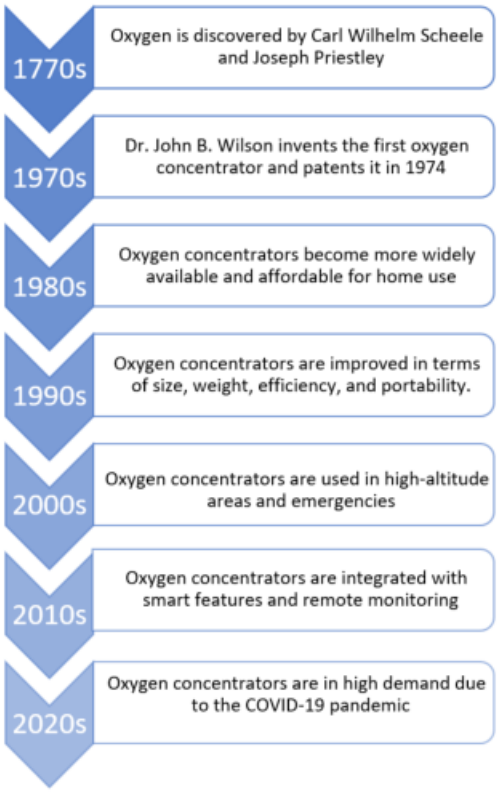


Figure 2-1: History Of Oxygen Concentrator

a) **Early History and Development:** The use of oxygen in medicine is traced back to the 19th century, with Dr. George E. Holtzapple first utilising it in 1885 to treat pneumonia (Shultz, 2005). The evolution of oxygen therapy included significant milestones, such as John Scott Haldane's development of the gas mask during World War I to treat soldiers exposed to chlorine gas (Warren, 2005). By the mid-1900s, oxygen masks had become common in hospitals and ambulances, treating various illnesses.

b) **Introduction of Oxygen Concentrators**:
Home oxygen therapy gained momentum by the 1970s, marking a shift from cumbersome oxygen cylinders to the first home oxygen concentrators (Zhang, 2007)). While still large and power-intensive, these early models laid the groundwork for future innovation. Oxygen concentrators drew in room air, separated oxygen from other gases, and delivered concentrated oxygen to patients, a technology that has evolved significantly over the years.

c) **Advancements and Portable Designs:** Over the next three decades, oxygen concentrators rapidly developed, becoming more user-friendly, energy-efficient, and portable (Inogen, 2017). By the early 2000s, portable oxygen concentrators entered the market, offering groundbreaking mobility and improved quality of life for respiratory patients. These devices

had become increasingly compact, with some models now small enough to fit in a purse, highlighting the technological advancements in oxygen therapy (Warren, 2005).

d) **Contemporary Significance and Challenges in LMICs:** Today, recognised by the WHO as an essential medicine, oxygen therapy, mainly through portable concentrators, has become vital for patients globally (WHO, 2015). However, operational challenges persist in LMICs due to factors like unreliable power and extreme environmental conditions(UNICEF, 2019). Initiatives like UNICEF's Oxygen Concentrator Innovation Project aimed to develop more resilient concentrators suitable for such challenging settings, emphasising the ongoing need to adapt and innovate in response to diverse global health needs (WHO, 2019).

2.2. Medical Oxygen Theory

Medical oxygen, designated as a compressed gas, is rigorously regulated under international standards led by the World Health Organization (WHO). These standards are critical for ensuring safety and effectiveness in cylinder usage, ownership, refilling, and transportation. In specific regions, like South Africa, national authorities, for example, the South African Health Products Regulatory Authority, implement these regulations. The COVID-19 pandemic particularly highlighted the importance of medical oxygen in LMICs, exposing significant distribution and availability challenges (Баула, 2022).

In terms of regulation, considerations for medical oxygen include its production sources, specifications, storage methods, and distribution protocols within healthcare facilities. These factors are pivotal in effectively managing and rationalising oxygen, especially during health emergencies like the pandemic. The British Thoracic Society's guidelines offer comprehensive recommendations for medical oxygen use, emphasising the importance of robust strategies and safety measures in healthcare environments (O'Driscoll et al., 2017).

2.3. The Principles of Oxygen Production

Oxygen production encompasses large-scale and small-scale methods. Commercially, oxygen production primarily utilises cryogenic liquefaction and fractional distillation of air (Björn, 2022). Initially introduced on a grand scale by Von Linde and Hampson in 1895, this method involves air filtration to remove impurities, followed by compression and cooling for liquefaction. Subsequent stages include carbon dioxide removal at $-80°C$ and further cooling to $-200°C$, crucial for separating nitrogen, which boils at $-195°C$, thus isolating liquid oxygen. The resulting high-purity, pale blue liquid oxygen, cooled to $-183°C$, necessitates specialised cryogenic tanks for transportation and storage, as illustrated in **Figure 2-2**.

Recent advancements in large-scale oxygen production have seen the development of efficient electrocatalysts for the Oxygen Evolution Reaction (OER) and the use of cobalt-based materials for hydrogen and oxygen production, enhancing the efficiency of traditional methods (Wang, 2016). Additionally, advances in non-noble bifunctional oxygen electrocatalysts have improved large-scale production activity, stability, and scalability (Zeng, 2020). This progression signifies a shift towards more sustainable and efficient oxygen production methodologies.

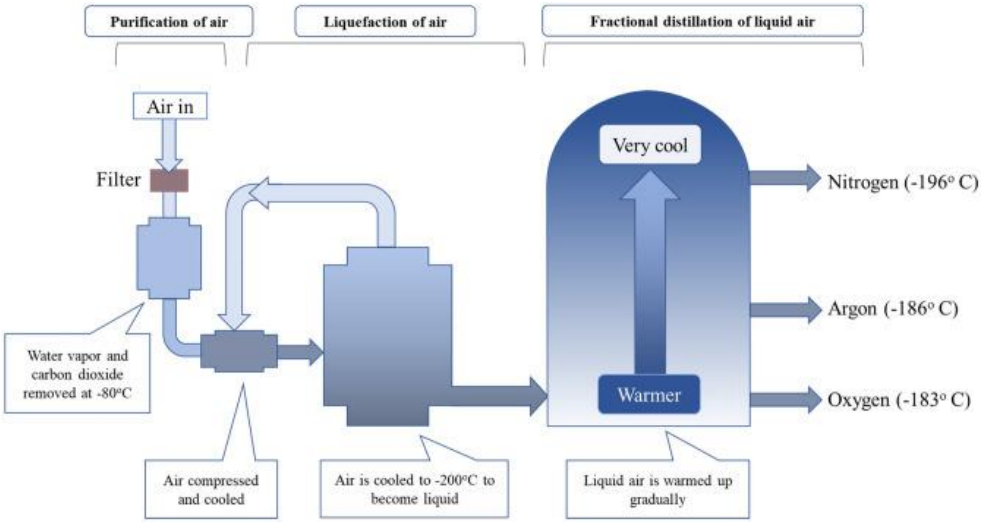


Figure 2-2: Oxygen Production Process Source (Ismail, 2022)

In healthcare settings, liquid oxygen is stored in cryogenic tanks and supplied through self-vaporisation to piped systems, requiring periodic refilling from commercial liquid oxygen plants. This ensures patients' consistent oxygen therapy supply (Баула, 2022b).

Two primary techniques for separating oxygen from air are Membrane Technology and Pressure Swing Adsorption (PSA). PSA, particularly suited for Portable Oxygen Concentrators (POCs), employs zeolite to filter out nitrogen and argon, achieving up to 99% oxygen concentration (Smith, 2001). Oxygen membranes, yielding about 40% concentration, require larger surface areas and are less desirable for portable applications (Williams, 2013).

In designing POCs for emergencies, selecting an efficient, compact method that does not require extreme temperatures, pressures, or additional materials like water is vital. PSA stands out in this regard. In a typical PSA-based POC, compressed air is passed through zeolite sieve beds, selectively absorbing nitrogen see Figure 2-3. This alternating process between two sieve beds continuously supplies oxygen-enriched air, with each bed releasing nitrogen and recharging in cycles (McAllister, 2021).

Such POCs are designed to be material-efficient and energy-saving, capable of providing over 90% oxygen concentration at various flow rates, making them highly suitable for medical use in diverse environments (Innoget,2019). This approach ensures the delivery of high-purity oxygen and minimises exposure to contaminants, safeguarding patient health.

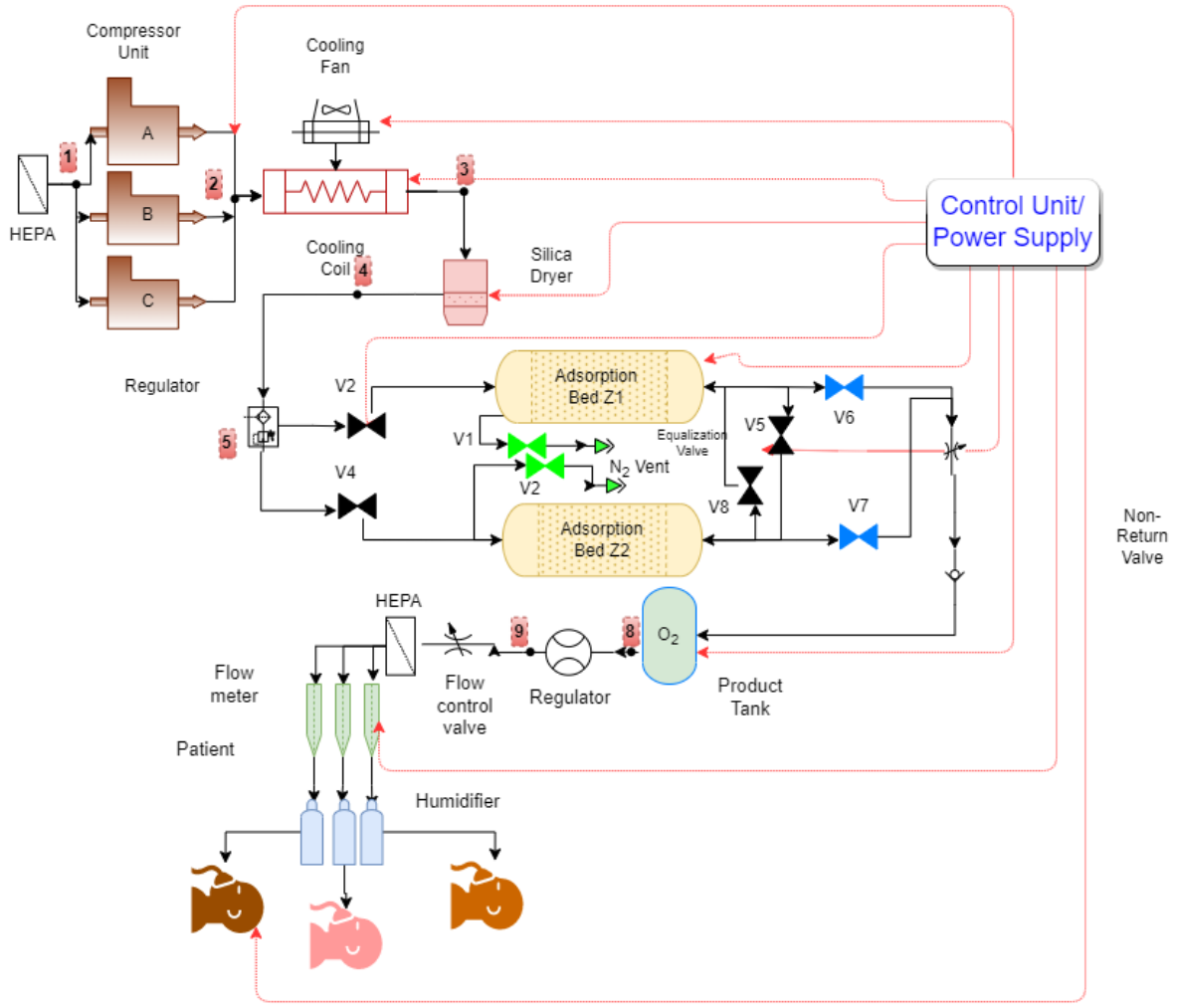


Figure 2-3: PSA flow diagram showing all components and 8 Solenoid valves (Note: Author's Illustration)

2.4. Existing Devices

Oxygen concentrators, crucial for medical oxygen delivery, are available in stationary and portable forms. Stationary concentrators, typically more significant, are used in settings like hospitals and homes where mobility is not a concern. In contrast, portable oxygen concentrators (POCs) offer mobility for patients on Long-Term Oxygen Therapy (LTOT), facilitating an active lifestyle. These devices incorporate oxygen cylinders of varying sizes and capacities, affecting the mobility and duration of the oxygen supply. The cylinders range from small, portable ones for ambulatory use to larger ones for stationary settings (Hardavella, 2019).

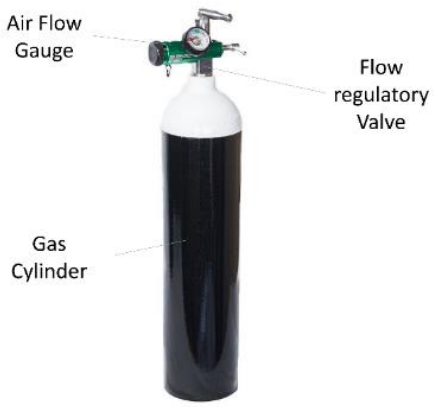


Figure 2-4: Oxygen Cylinder (Source: Masks for Africa, 2023.)

Compressed oxygen cylinders, despite their extensive use, have limitations, especially in capacity, requiring frequent replacement for continuous use. Portable compressed gas cylinders are commonly used in clinical settings for temporary oxygen support during diagnostic procedures outside intensive care units. Portable oxygen concentrators are often preferred for LTOT patients needing outdoor mobility for ease of use (Rassool, 2017). In regions with unstable power supplies, like some areas in South Africa, a reliable oxygen supply is crucial, and constant electricity is needed to operate medical devices, including oxygen concentrators (Peake, 2021).

The combination of compressed gas cylinders and oxygen concentrators demonstrates the medical field's adaptability to various patient needs. This approach varies globally, influenced by infrastructure, healthcare policies, and resource availability. However, it also exposes gaps in oxygen delivery systems, especially in efficiency and adaptability to different environments (Hardavella, 2019).

To address these gaps, innovation in the design of portable oxygen concentrators is crucial, especially in Low and Middle-Income Countries (LMICs) and areas with erratic power supplies. The goal is to develop oxygen delivery systems that are versatile, efficient, and capable of operating autonomously. This ensures a consistent and reliable oxygen supply for patients, irrespective of their geographical location or the stability of local infrastructure (Peake, 2021)

In light of this, a comparison of various oxygen concentrators available in the market is provided in table 2-1 below. This table offers a comprehensive overview, comparing models based on weight, flow rate, noise level, oxygen purity, warranty, price, and additional features. Each model caters to different requirements, ranging from high flow rates to compact designs, offering various options for different healthcare needs.

Table 2-1: Comparison of Various Oxygen Concentrators (Comparison Of Portable Oxygen Concentrators | Vitality Medical, 2024.)

Model	Weight (kg)	Flow Rate (LPM)	Noise Level (dB)	Oxygen Purity	Warranty	Price (ZAR)	Features	Pros	Cons	Global Access Issues
CAIRE AirSep Newlife Intensity 10	26.3	2 to 10	Not specified	Not specified	3 Years	~28,425	High flow rate, durable	High flow rate, durable, suitable for varying needs, no tank refills needed, continuous oxygen supply	Weight limits portability, specifics on noise and purity are not available, electricity is required, and there is a high upfront cost.	Cost prohibitive in LMICs
Respironics Millennium M10 with OPI	24	1 to 10	53	88-96%	3 Years	~29,925	Oxygen Percentage Indicator (OPI)	Features OPI, suitable for a range of LPM needs, low maintenance, environmentally friendly	potential unavailability in some regions	High cost, potential unavailability in some regions
Invacare Platinum 10	24	2 to 10	<58	93% (+/- 3%) at 10 LPM	3 Years	~22,425	Compact, ergonomic design	Compact design, good oxygen purity, quiet operation, variety in sizes and models	Weight may be a concern for portability, susceptible to power outages, and high upfront cost.	Costs and limited availability in LMICs
Respironics Millennium M10	24	1 to 10	About 49	92% (+/- 4%) at 8-10 LPM	3 Years	70,000	Standard model without OPI	Good oxygen purity, quiet, wide range of flow rates, portable and suitable for home use	Standard model without OPI, high cost, limited battery life for portable models	Expensive, not easily accessible globally

Invacare Platinum 10 with SensO2	24	2 to 10 with SensO2	58	93% (+/- 3%) at 10 LPM	3 Years	60,000	SensO2 Oxygen Purity Sensor	Includes SensO2 Oxygen Purity Sensor, good purity level, environmentally friendly, continuous oxygen supply	High cost and weight may impact mobility, and it is not suitable for all patients.	Price and availability issues in LMICs
Reconditioned Respironics Millennium 10LPM	24	Up to 10	About 49	92% (+/- 4%) at 8-10 LPM	Not specified	~14,925	Refurbished, durable, and built to standard	More affordable, durable, refurbished to standard, cost-effective over time	Lack of warranty, potential reliability concerns, dependent on proper functioning	Availability of refurbished models may vary.
Nidek Nuvo 8	24.5	Not Specified	<48	<96%	3 Years	50,000	Durable and quiet operation	Durable, quiet operation, good oxygen purity, reduces the risk of running out of oxygen.	Weight, lack of warranty and specific flow rate information, some models can be bulky.	Accessibility and cost concerns in LMICs

This detailed comparison is instrumental in aiding healthcare providers and patients in making informed decisions regarding procuring and using oxygen concentrators tailored to their specific healthcare settings and patient needs.

2.5. Limitations of Existing Devices

Oxygen therapy devices, including concentrators and cylinders, play a crucial role in treating respiratory illnesses but face significant limitations, especially in low- and middle-income countries (LMICs). While essential for oxygen storage, cylinders are cumbersome and not easily transportable without additional equipment like trolleys (Thomson, 2021). Shrestha et al. (2020) highlight the need for trolleys, wheeled carts, or backpacks to carry these cylinders, increasing costs and logistical challenges, particularly in LMICs (Zelasko, 2020). Furthermore, the frequent need to change cylinders due to their limited capacity can lead to extended hospital stays, thus escalating patient medical costs (Lam, 2020).

During emergencies such as the COVID-19 pandemic, the drawbacks of oxygen cylinders become more pronounced. Cylinders do not produce oxygen; they only serve as storage units (Górecka, 1997). This limitation poses challenges in managing oxygen supply during mass casualty events or pandemics, as experienced during the COVID-19 crisis (Crockett, 1996). Maintenance concerns, such as the risk of oxygen leakage due to cylinder gasket failure, further complicate their use in emergencies (Lazzerini, 2015).

Though beneficial due to their efficiency, oxygen concentrators are not without flaws. They require constant maintenance and a stable power source, which may not be readily available in many LMICs (Eastwood, 2009). As noted by the Center For Global Development (2020), power cuts in LMICs hospitals can disrupt oxygen therapy delivered via concentrators, endangering patient safety (Belle, 2010)

This research addresses these challenges by developing a portable, multi-user, medical-grade oxygen concentrator tailored for low-resource settings. The design includes a compression unit with integrated cooling and drying to mitigate performance decline due to heat and humidity, aligning with ISO standards (ISO, 2020) and adhering to WHO Technical specifications for Oxygen Concentrators (WHO, 2015). Table 2-2 compares the limitations of existing oxygen delivery systems and how the proposed device aims to overcome these challenges.

Table 2-2: Comparison of Limitations in Oxygen Delivery Systems

Feature	Oxygen Cylinders	Oxygen Concentrators	Proposed Device
Portability	Limited; requires trolleys	Good; self-contained	Highly portable
Maintenance	High; frequent cylinder changes	Regular technical upkeep	Low; simplified maintenance
Reliability	Limited capacity; leakage risks	Power dependent	High autonomous operation
Suitability for Emergencies	Limited supply; high maintenance	Disrupted by power cuts	Optimised for emergencies
Cost-Effectiveness	High operational costs	Efficient but needs power	Designed for cost-efficiency

2.6. Material Consideration

The development of portable oxygen concentrators for low- and middle-income countries (LMICs) demands careful material selection to overcome the limitations of traditional bulky oxygen tanks. The transition from using PVC materials to anodised aluminium for zeolite canisters exemplifies this need. Anodised aluminium, selected for its superior heat conduction, effectively cools the canisters, enhancing the overall performance and longevity of the concentrators (Duke, 2016). This choice reflects a strategic balance between functionality and cost-effectiveness, as supported by research indicating the advantages of anodised aluminium in improving performance and longevity in such applications (Koponen, 2007).

The selection process also considers materials' availability, cost, and practicality. Sheet metal is favoured due to its robustness, affordability, and adaptability in production, which is vital for supporting the weight and vibrations of components like zeolite canisters and large compressors (Hamilton, 2022). The efficacy of sheet metal, particularly anodised aluminium, in such applications is corroborated by its documented robustness and application characteristics (Zu-fan, 2000). The inclusion of push fittings in the design further exemplifies the need for materials that simplify the installation and maintenance of pneumatic circuits. Additionally, using high-flow axial fans encased in PU foam for thermal management showcases a balance between thermal efficiency and material cost-effectiveness, aligning with the advancements in material science that enhance such aspects in portable oxygen concentrators (Jani, 2013).

Table 2-3: Material Considerations for Portable Oxygen Concentrators

Material	Advantages	Suitability for LMICs
PVC	Cost-effective	Limited by thermal management
Anodised Aluminum	Efficient heat conduction, lightweight	Preferred for functional efficiency
Sheet Metal	Durable, cost-efficient, adaptable	Ideal for structural integrity
PU Foam	Insulation, effective cooling	Suitable for thermal management

Table 2-3 provides a clear overview of the materials chosen for portable oxygen concentrators, highlighting their advantages and appropriateness for LMIC settings. This table aids in understanding the rationale behind each material choice, demonstrating how they collectively contribute to creating a cost-effective, durable, and efficient oxygen concentrator suitable for LMICs.

2.7. Manufacturing Consideration

In medical device manufacturing, particularly for oxygen concentrators, stringent adherence to international standards and the incorporation of high-quality components are paramount. This section outlines our comprehensive approach towards manufacturing oxygen concentrators, explicitly tailored to the unique demands of LMICs. Our focus extends beyond mere compliance with standards; we aim to deliver effective but also durable, user-friendly, and suitable products for challenging healthcare environments. Adhering to international standards and using high-quality components ensures product safety, efficacy, and consistency under various conditions, particularly in manufacturing medical devices like oxygen concentrators (Milamed, 2013)

Given the critical role oxygen concentrators play in healthcare systems, especially during global health crises like the COVID-19 pandemic, ensuring these devices are reliable, efficient, and readily available is essential. The availability of reliable devices is critical in LMICs, where healthcare infrastructure may face resource limitations, technical expertise, and supply chain stability. Our manufacturing considerations, therefore, encompass a broad spectrum of aspects, including adherence to ISO standards, technical detailing adapted to LMIC conditions, quality of components, comprehensive technical support, compliance with global regulations, and cost-effectiveness. Ensuring these medical

devices' safety, security, and reliability under expected operating conditions is critical to adherence to international standards(Wassyng, 2015).

In the subsequent sections, we will explore these aspects in detail, supported by tables outlining the essential ISO standards **(Table 2-4**), compliance requirements for different regions **(Table 2-5),** and a cost-benefit analysis of using quality components **(Table 2-6).** This comprehensive approach is designed to meet the immediate needs of healthcare providers and patients and ensure oxygen concentrators' long-term sustainability and effectiveness in diverse healthcare settings. Utilising high-quality components and adherence to international standards in medical devices can lead to safer, more efficacious products that are more closely aligned with user needs (Dharavath, 2022).

2.7.1. Standards and Specifications

In our manufacturing process for oxygen concentrators in the UCT MedTech Lab, we look to international standards as essential guidelines, though we are not yet fully compliant. We draw a lot from ISO 13485:2003, which sets out the quality management systems for designing and manufacturing medical devices (Wu Jun-hua, 2002), and from ISO 14971:2007, which deals with risk management in medical devices—furthermore, following ISO 80601-2-69, which specifically addresses the design of an oxygen concentrator as detailed in Table 2-4.

This approach is fundamental in LMICs, where infrastructure conditions can vary greatly. The selection of these standards, as listed in Table 2.4, reflects our commitment to meeting the highest quality and safety benchmarks in our manufacturing process.

Alongside these ISO standards, we partially align with the WHO technical specifications for oxygen concentrators. While full compliance is our eventual goal, we currently use these guidelines to shape our manufacturing process. Our focus is on improving and ensuring the reliability and safety of our medical devices, using these globally recognized standards as benchmarks. ISO 13485:2003 emphasises the safety and efficacy of medical devices. It requires risk management in the quality management system (Razak, 2009), a key aspect also underlined in ISO 14971:2007, which helps manufacturers control the risk of their devices at an acceptable level (Wang Hui-fang, 2009).

Table 2-4: Key ISO Standards for Oxygen Concentrators

ISO Standard	Description
ISO 13485:2003	Medical devices - Quality management systems
ISO 14971:2007	Medical devices - Application of risk management
ISO 80601-2-69	Medical device- Oxygen Concentrator

By adhering to these standards, we ensure that our oxygen concentrators not only meet international quality criteria but also address the specific needs and conditions present in LMICs.

2.7.2. Technical Detailing Components

The manufacturing process is adapted explicitly for LMIC conditions, accounting for power instability and extreme climates (Kim, 2017). The devices are designed for durability and ease of repair, essential in remote or resource-limited areas (UNICEF, 2022).

2.7.3. Component Quality and Supply

High-grade components, including sieve beds and compressors, are sourced from top manufacturers (Vos, 2016). To ensure consistent supply in LMICs, we collaborate with local suppliers, reducing lead times and logistics costs (Cui, 2017).

2.7.4. Technical Support and Maintenance

Each unit includes a comprehensive troubleshooting manual, which is vital in LMICs where access to specialised technical training may be limited (PATH, 2019).

2.7.5. Compliance with Global Regulations

Our products comply with regional and international regulations, essential for their worldwide application (Mishra, 2021).

Table 2-5: Compliance Requirements for Different Regions

Region	Compliance Requirement
EU	Medical Device Directive 93/42/EEC
USA	21 CFR Part 820; 21 CFR Section 868.5440

2.7.6. Costs

Cost considerations are essential, especially in balancing quality and affordability in LMICs. Although initial costs may be higher for quality components, they offer long-term savings by reducing replacement and repair needs (Grimes, 2014).

Table 2-6: Cost-Benefit Analysis of Quality Components in Oxygen Concentrators

Component	Initial Cost	Long-Term Savings
High-grade Sieve Bed	Higher	Reduced replacement frequency
Durable Compressor	Higher	Longer lifespan, fewer repairs

2.8. The Role of Global Surgery in Design Consideration.

The imperative for safe and affordable surgery in Low and Middle-Income Countries (LMICs) is increasingly acknowledged, aligning with the Lancet Commission of Global Surgery targets for 2030, Universal Health Coverage, and the United Nations' Sustainable Development Goals. Neglecting surgical care can render UN SDG health-related goals unattainable and result in staggering economic losses, estimated at $12.3 trillion by 2030 (Citron, 2019). Investment in surgical services in LMICs drives economic growth and enhances overall well-being, benefiting all health sectors, demographics, and age groups (McQueen, 2016).

Capacity building in surgical care in LMICs yields extensive positive impacts, transcending surgery to strengthen entire health systems (Reddy, 2020). Reliable oxygen concentrators are pivotal, providing essential post-surgery oxygen therapy for stabilization and recovery. This need is highlighted by the limited access in LMICs, where only 10% of hospitals have access to pulse oximetry and oxygen therapy (Table 2-7: Metrics for Evaluating Oxygen Concentrator Design, Federation of American Scientists,

2023). The global rise in surgeries for medical conditions and injuries underscores the critical importance of oxygen in extended surgical procedures (Stein, 2020). Portable oxygen concentrators are life-saving in surgical departments, optimizing patient outcomes and addressing the inconsistent availability of oxygen sources in healthcare institutions (Ross, 2023).

The COVID-19 pandemic underscored the dire consequences of oxygen scarcity in LMICs, such as Nigeria, where oxygen affordability impacted mortality rates (George, 2021). Patients at secondary and tertiary healthcare levels face diverse payment methods for oxygen, with cylinder oxygen often imposing financial burdens (Hardavella, 2019). In contrast, concentrators offer cost-effective solutions, with electricity and consumables as primary expenses (Duke, 2010). Well-designed concentrators are life-saving alternatives for inaccessible cylinder oxygen, especially in emergencies, aligning with the need for devices suitable for varied environments and healthcare settings (Smith, 2020).

Table 2-7: Metrics for Evaluating Oxygen Concentrator Design

Metric	Qualitative Measurement	Context & Statistics
Accessibility	Improved access to surgical oxygen	Limited access in LMICs, with only 10% of hospitals having access to pulse oximetry and oxygen therapy, particularly affecting rural and low-income areas (Transforming On-Demand Medical Oxygen Infrastructure to Improve Access and Mortality Rates - Federation of American Scientists, 2023.)
Availability	Consistent oxygen supply during surgeries	Inconsistent availability, with less than half of healthcare institutions in 12 African countries having uninterrupted oxygen sources and less than a quarter equipped with an oxygen concentrator(Ross, 2023)
Affordability	Reduced costs for oxygen therapy	Affordability issues, such as the sustainable supply of medical oxygen, have been neglected, with concentrators requiring reliable power and maintenance for long-term sustainability(Smith, 2020).
Acceptability	High user satisfaction with concentrators	Positive patient feedback on well-being, breathing, mobility, and sleep patterns despite issues with noise and outlet availability (Dilworth, 1990)
Appropriateness	Alignment with healthcare needs and settings	Need for devices suitable for varied environments, including areas with frequent power cuts and limited healthcare infrastructure (Smith, 2020).

Impact Analysis: Our concentrators' design significantly enhances surgical care in LMICs, ensuring reliable oxygen supply during surgeries, improving patient outcomes, and minimizing complications. This aligns with Global Surgery's goals, facilitating safe and accessible surgery while mitigating oxygen shortages and reducing costs. The high user satisfaction with concentrators, as reported by patients regarding well-being, breathing, mobility, and sleep patterns (Dilworth, 1990), further underscores the importance of our design approach in addressing global surgery needs.

2.9. Barriers to Surgical Care in LMICs

The challenges in providing surgical care in low- and middle-income countries (LMICs) are multifaceted, especially in terms of ensuring access to high-quality and affordable surgical healthcare. These challenges are acutely felt by the poorest third of the world's population, who, despite bearing a significant burden of surgical diseases, receive only about 6% of the global surgical care volume. This situation is compounded by the need for an additional 2.2 million surgeons, obstetricians, and anesthesiologists, as estimated by Ma et al. (2020), alongside significant investments in surgical equipment and healthcare infrastructure.

Ologunde et al. (2014) identified critical barriers to surgical care in LMICs, which include issues of accessibility, availability, affordability, and acceptability. A specific challenge Dauncey et al. (2019) identified is the use of oxygen cylinders in surgical care. These cylinders, while common, pose several challenges due to their weight, transportation difficulties, high cost, and need for frequent refilling, limiting the ability of LMICs to provide adequate surgical care.

Table 2.8 ("Oxygen Supply Challenges in LMICs") elaborates on these issues. It details the challenges related to cylinder limitations, such as increased operational costs and logistical challenges. It contrasts them with the benefits of portable oxygen concentrators, which are more reliable and cost-effective. The table also highlights issues with electrical supply, training deficiencies, equipment breakdowns, and staff shortages, all of which impact the effective delivery of oxygen therapy.

Table 2-8: Oxygen Supply Challenges in LMICs

Challenge	Description	Impact on Healthcare
Cylinder Limitations	Heavy, costly, and requires regular refilling	Increases operational costs, logistical challenges, and patient access issues
Concentrator Benefits	Reliable oxygen supply, portability, cost-effectiveness	Enhances patient care, reduces costs, and improves accessibility
Electrical Supply Issues	Poor electrical infrastructure affects usage.	This leads to disruptions in oxygen therapy, affecting patient safety and treatment continuity.
Training Deficiencies	Lack of formal training in oxygen administration	Results in suboptimal use of equipment, risking patient safety and care quality
Equipment Breakdowns	Frequent breakdowns disrupt the oxygen supply.	Causes interruptions in patient care and increases the risk of adverse outcomes
Staff Shortages	Insufficient skilled personnel for administration	Compromises effective oxygen therapy delivery and patient management

Furthermore, McAllister et al. (2021) discussed the concerns of parents in LMICs whose children required surgery, emphasizing the impact of frequent breakdowns of oxygen concentrators, delays in repairs, and inadequate power supplies. This situation underscores the urgent need for a robust oxygen supply strategy in resource-limited settings, with the development of multi-user oxygen concentrators being a potential solution to address these shortages, as detailed in Table 2-9 ("Oxygen

Supply Challenges in Surgical Settings"). This table explicitly highlights issues like concentrator breakdowns, power supply problems, the economic factors influencing cylinder preference, and the benefits of new multi-user concentrator models.

Table 2-9: Oxygen Supply Challenges in Surgical Settings

Challenge	Description
Concentrator Breakdowns	Frequent breakdowns of oxygen concentrators notably impact patient care, with their effectiveness reduced to 28.6% in standard use conditions(Escarrabill, 1992).
Power Supply Issues	Inadequate power supply leads to significant performance issues in oxygen concentrators, causing overheating and breakdowns(Howie, 2008).
Cylinder Priority	Economic factors such as cost and convenience influence the preference for oxygen cylinders over concentrators, with cylinders being more expensive but less convenient(Lowson, 1981).
Multi-User Solutions	Advancements in multi-user oxygen concentrators, like the 'Permox' model, offer reliable and economical alternatives for long-term oxygen therapy, especially in emergencies and resource-limited settings(CARTER, 1985).

In addressing these barriers to surgical care in LMICs, our multifaceted approach encompasses patient-centric solutions, physician training, healthcare institution support, and structural enhancements. Additionally, adopting portable oxygen concentrators as an alternative to cylinders addresses critical oxygen supply challenges (as detailed in Table 2.8) while developing multi-user oxygen concentrators aims to mitigate barriers and facilitate surgical care in LMICs, which is further elaborated.

2.10. Conclusion

The analysis of various oxygen concentrator models reveals a range of features addressing diverse healthcare needs. These features include variable flow rates, typically between 1 and 10 LPM, noise levels ranging from below 48 dB to about 58 dB, and oxygen purity levels approximately between 88% and 96%. The models vary in weight, affecting their portability, and offer functionalities like the Oxygen Percentage Indicator (OPI) and the SensO2 Oxygen Purity Sensor. However, common limitations such as electricity dependence, high upfront costs, and challenges in global accessibility, particularly in LMICs, are prevalent (Lakshmi, 2021).

The literature review emphasizes the vital role of oxygen concentrators as frugal innovations in healthcare, providing cost-effective, efficient, and independent logistic solutions (Lakshmi, 2021). They are crucial for offering tailored therapies to patients with chronic pulmonary diseases (Hardavella, 2019b). Despite their long-standing market presence, gaps exist, especially in delivering uninterrupted oxygen for multiple users.

Innovations in concentrator design, such as the incorporation of high medical-grade PSA Processed Zeolite X Oxygen, are particularly significant for healthcare facilities in resource-limited regions.

Nonetheless, the adoption of these frugal innovations in low-resource settings is impeded by technological, financial, and sociocultural barriers (Nowadly, 2022).

Advocating for frugal innovations like multi-user portable oxygen concentrators is essential to tackle these challenges effectively. These innovations need to meet the "5 A's" criteria, Availability, Accessibility, Acceptability Appropriateness, and Affordability to significantly reduce mortality rates in LMICs (Arora, 2021).

In summary, this review highlights the existing gaps in current practices and paves the way for subsequent chapters that will focus on the design methodology and development of oxygen concentrators. It underscores the urgency for innovations that address the unique challenges in low-resource settings while strictly adhering to the 5 A's framework. The upcoming chapter will explore the design methodology, including the design flow chart, concentrator layout, and experimental hypotheses, building on the insights gained from this comprehensive review.

CHAPTER 3

3. Design and Methodology

3.1. Overview

This chapter details the design of a multi-user oxygen concentrator, explicitly targeting healthcare facilities in low and middle-income countries (LMICs), where resource scarcity poses a significant challenge. The design emphasises affordability and user-friendliness while ensuring a high oxygen flow, which is crucial for addressing the vital oxygen requirements in these regions.

The design tackles specific challenges faced in LMICs, including:

a) **Employing Molecular Sieve Technology**: The oxygen concentrator uses molecular sieve technology to generate over 20 litres per minute of oxygen-enriched gas, involving:

i. A compression unit, specifically designed to ensure adequate cooling and dehumidification, plays a crucial role in regions experiencing high temperatures and humidity. These conditions can potentially diminish the effectiveness of Zeolite adsorbents. The design and functionality of this unit align with the standards established by the International Organisation for Standardisation (ISO, 2020).

ii. An air separation device is designed to combine adsorbent or sieve beds of varying sizes, enabling efficient gas separation.

iii. The conceptual design includes an integrated oxygen storage tank and an effective gas distribution system for optimal performance.

iv. The design incorporates an electronic control system specifically developed for monitoring and managing the operations of the medical device. Recent advancements in molecular sieve technology for oxygen concentrators have led to significant improvements in the selective adsorption of air components, offering an alternative oxygen source for hospitals and medical facilities (Friesen, 1992).

b) **Design Methodology**: The design methodology, grounded in an engineering design prototype, was selected for its practicality in meeting these specific requirements. It highlights the role of IT-enabled technologies like virtual prototyping in the early-stage comprehensive analysis of products, encompassing performance, cost, reliability, and modifications. This approach, supported by TWI Global (2022), accelerates construction, enhances quality, and reduces costs by integrating electrical design principles. Recent developments in virtual prototyping for engineering design include collaborative simulation and component-based modelling, significantly enhancing product development (Li, 2004).

c) **Pressure Swing Adsorption (PSA) Technology**: The concentrator uses PSA technology, employing a dual-column system with selective zeolite to filter necessary gases from the air. Zeolites' unique crystalline structures play a crucial role in gas adsorption, a critical factor in the functionality of the concentrator. The latest advancements in PSA technology for oxygen

concentrators include new pressure equalisation steps and improved systems for oxygen recovery and purity (Li, 2014).

This chapter will further explore the systematic design process, material selection, and technical considerations underpinning this innovative medical device.

3.2. Flow chart illustrating the design methodology

The origin of the pressure swing adsorption (PSA) cycle, which is essential for modern oxygen concentrators, can be attributed to the innovations made by Skarstrom, as mentioned by Chai et al. (2011). The oxygen production system consists of several essential components, including a silica gel dryer tank for moisture removal, an activated alumina Zeolite for purification, and dual adsorption beds that use either 13X or Lithium X Zeolite(Baksh et al., 1992). The equipment is equipped with oil-free air compressor motors to guarantee a consistent and dependable air supply, an air-cooled heat exchanger (ACHE) for temperature control, and a network of PVC tubes and solenoid valves that manage the movement and direction of gases in the system. The critical component of the delivery system is a product tank, as shown in **Figure 3-1**, which stores the oxygen before being directed to patients via accurate flow regulators.

A HEPA inlet filter pulls The air into the system and then goes through a two-stage compression. After that, it undergoes a careful cooling and drying procedure. This preparation is crucial for the effective functioning of the Zeolite sieve beds, which perform the vital function of separating nitrogen from oxygen, assuring that the resulting product is a concentrated stream of oxygen ready for delivery to patients. The outlined procedure is depicted in **Figure 3-1**, labelled as 'PSA Block Diagram.'

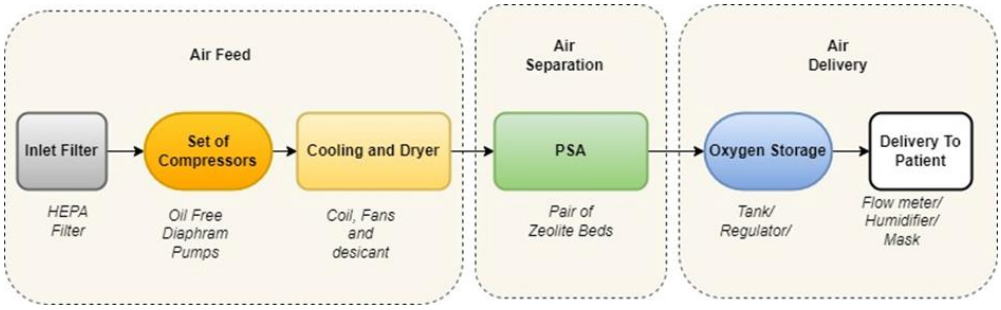


Figure 3-1:PSA Block Diagram

While developing and creating initial models, the researcher emphasised using materials derived from the local area. This sustainable method allowed for a trial period in which materials were thoroughly assessed for their conformity with the system's criteria. Initially, zeolite canisters were made using PVC to handle 16 bar pressure. However, later versions switched to anodised aluminium because of its better thermal conductivity, which helps remove heat from the canisters. Bunel, Shoukri, and Chopin (2016) elaborate on the reasoning behind the choice of materials, emphasising the importance of cost-effectiveness, accessibility, and the speeding up of production cycles as decisive aspects.

The system's design included a strong support structure that could endure substantial weight and vibrations in preparation for the mechanical pressures caused by the massive compressors and zeolite canisters. A significant advancement in this field was the implementation of colonial compression

springs, as Bunel et al. (2016) discovered, which are used to separate and reduce vibrational forces. Incorporating push fittings was crucial in streamlining the installation of pneumatic circuits, improving the system's maintainability. A high-low axial fan is used to reduce the heat produced by the compressors, and the containment unit is covered with PU foam for insulation. This is shown in **Figure 3-2**, 'Methodology Flowchart,' and explained in more detail in **Figure 3-3**, 'Methodology **Flowchart 3-3.**'

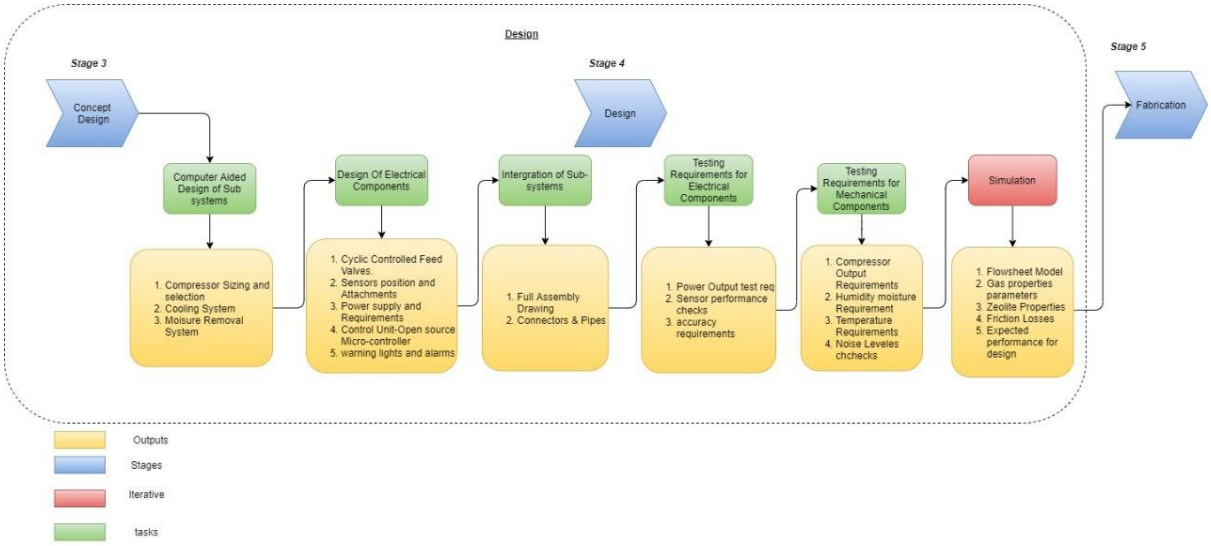


Figure 3-2: Methodology Flowchart

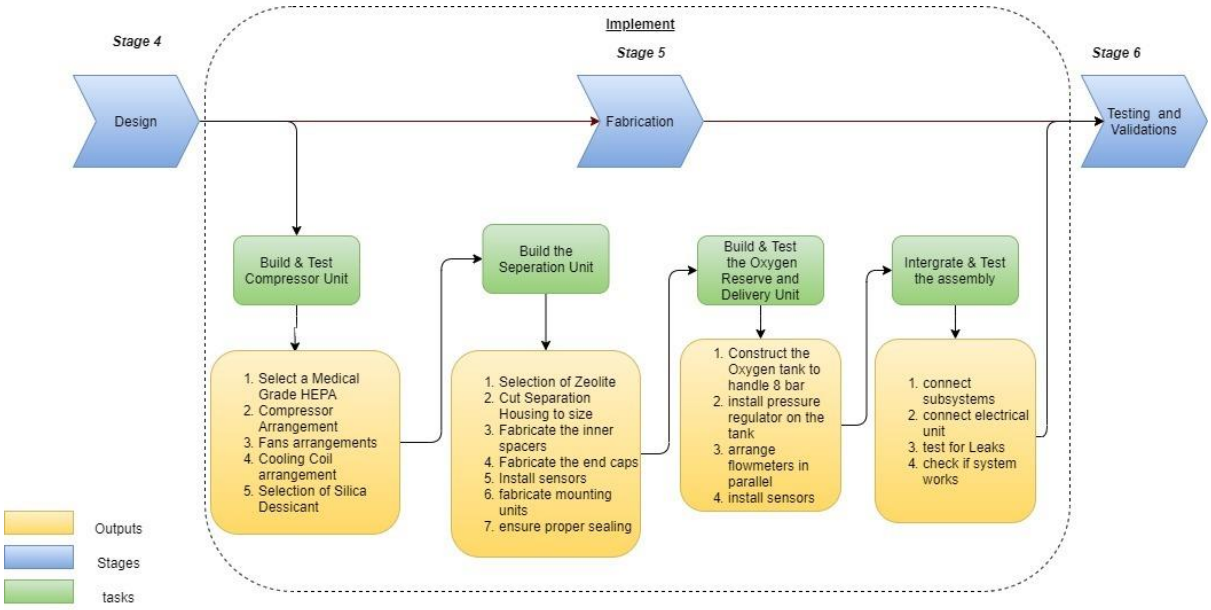


Figure 3-3: Methodology Flowchart 2

3.3. Design Subsystems

The design and functionality of portable oxygen concentrators are intricate, involving the integration of various subsystems critical for effective operation. These systems include efficient compressors, heat exchangers, gas storage tanks, precision controls, and advanced management systems, all vital for delivering medical-grade oxygen.

a) **Multi-Stage Compressors and Air-Cooled Heat Exchangers**: These components are fundamental for continuous compressed air provision and maintaining ideal operating temperatures, which is essential for the system's integrity and performance (Al-Mutairi, 2022).
b) **Secure Gas Storage and Pneumatic Controls**: Gas storage tanks are engineered to meet stringent safety standards(Gurkin et al., 2021), while pneumatic controls manage the pressure swing adsorption process crucially (Nowadly, 2022b).
c) **Flow Meters and Distribution Networks**: Accurate oxygen output measurement is ensured by flow meters for patient safety (Khor et al., 2017), and flow networks are designed to minimise resistance, ensuring even oxygen distribution (Cheng, 2014).
d) **Programmable Logic Controller (PLC)**: The PLC serves as the central control unit, coordinating activities and ensuring subsystem synchronisation, besides offering user interface capabilities (Sanchez-Morillo, 2020).
e) **Compliance with Standards**: Electrical components comply with international standards like IEC 60601 for safe operation (International Electrotechnical Commission, 2020), and mechanical components are designed for durability and easy maintenance, ensuring reliability and adherence to healthcare regulations (Brown, 2021).
f) **Application in Low-Resource Settings**: These concentrators are particularly beneficial in low-resource settings, offering a cost-effective and maintenance-friendly solution in areas with limited access to electricity and healthcare infrastructure (Nowadly, 2022).
g) **Challenges and Future Research**: Despite their utility, challenges in optimising these systems for various environments remain, necessitating further research to enhance efficiency, especially in low-resource settings (Nowadly, 2022).

In summary, the engineering of portable oxygen concentrators involves sophisticated integration of multiple subsystems. Each component is designed with specific functions.

3.3.1. Multi-compressor

Designing and selecting an appropriate multi-compressor system for a portable oxygen concentrator involves a comprehensive understanding of fluid dynamics, thermodynamics, and medical device standards. Here is an elaborate design and sizing of such a system, integrating thermodynamics and fluid mechanics concepts with equations and formulas.

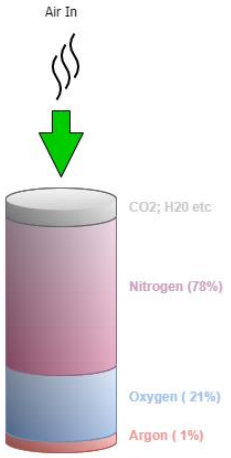
3.3.1.1. Calculations and Design of Multi-Compressor

The objective of the multi-compressor in an oxygen concentrator is to intake atmospheric air and compress it to a pressure where the PSA technology can effectively separate the oxygen from nitrogen

and other gases. The desired output for this project is a greater than 85% oxygen concentration at a flow rate greater than 20 L/min.

Air Intake Calculation

To calculate the amount of air needed to produce 20 L/min of oxygen:



$$Air = \frac{Oxygen}{0.21}$$

Equation 1

For 20 L/min of oxygen:

$$Air = \frac{20\,l/min}{0.2} = 95.24\,L/min$$

However, considering an 85% efficiency and losses:

$$Air_{in} = \frac{95.24\,l/min}{0.85} = 112.05\,l/min$$

Adding a 25% allowance for leakages:

$$Air_{required} = 112.05\,l/min \times 1.25 = 140.06\,l/min$$

Thus, the compressor must be capable of delivering at least 140.06 L/min of air.

3.3.1.2. Selection and Sizing of the Compressor

Following the general thermodynamic principles of gas compression (INTECH GmbH, 2017.), a compressor must be selected to match this required flow rate. The selection criteria include the discharge pressure needed to feed the PSA system, typically around 4-5 bar for most medical applications (Han, 2019).

Given the process requirement of $140.06\ L/min$, the Trade Air Issuu model was selected based on the manufacturer's datasheet:

i. Motor Capacity: $0.75HP\ (550W)$
ii. Maximum Pressure: $7\ Bar$
iii. Free Air Delivery @ $6\ Bar$: $50\ L/min$
iv. Pump Displacement: $100\ L/min$

A multi-compressor setup is essential to achieve the required 140.06 L/min. For instance, using three compressors in parallel could meet the flow rate requirement:

$$Total_{Flow} = 50\,l/min \times 3 = 150\,l/min$$

This arrangement not only meets but exceeds the minimum requirement, thus ensuring system reliability and compensating for any potential decreases in efficiency.

3.3.1.3. Buffer Tank Sizing

We must consider the buffer tank's peak demand and compressor cycling. We must consider the buffer tank's peak demand and compressor cycling to prevent wear and enhance efficiency. The buffer tank should be large enough to accommodate at least a few minutes of the concentrator's operation without running the compressor, thus avoiding frequent on-off cycling.

Using the following formula for the buffer tank volume(V_{tank}) :

$$V_{tank} = \frac{flow \times Cycle \times Safety}{Pressure}$$

Equation 2

Assuming:
$Flow = 150\, l/min$ (as calculated above)
$Cycle = 5\, min$ (desired operational buffer)
$Safety = 1.2$ (20% safety margin)
$Pressure = 6\, bar$ (operating pressure)

$$V_{tank} = \frac{150\, l/min \times 5min \times 1.2}{6} = 150L$$

Therefore, a 150-litre buffer tank would be adequate for this system.

3.3.1.4. Efficiency and Safety Margins

With an assumed compressor efficiency of 80%, and considering the system might have leakages and inefficiencies, it is crucial to design with a safety margin. A 20% safety margin compensates for these potential issues and ensures reliable operation (Brown, 2021).

3.3.1.5. Final Considerations

The final selection of the compressor must consider the operational environment, maintenance requirements, energy consumption, and cost-effectiveness. The choice of an oil-free compressor ensures the purity of the oxygen produced, which is critical for medical applications (Miller & Thompson, 2018).

3.3.1.6. Conclusion

In conclusion, a triple parallel configuration of Trade Air Issuu compressors, each with a motor capacity of $0.75HP$ and a $150 - litre$ buffer tank, would meet the design requirements for the oxygen concentrator. This setup balances efficiency, reliability, and cost, adhering to medical standards for delivering high-purity oxygen (International Electrotechnical Commission, 2020).

In this design, thermodynamics principles ensure that the right amount of air is compressed to the correct pressure, and fluid mechanics principles are applied to determine the flow and losses in the

system. With these calculations and assumptions, the multi-compressor system will effectively support the PSA technology in delivering the required oxygen purity and flow rate.

3.3.2. Filter Design and Selection

The design and selection of the air intake filter for an oxygen concentrator are paramount to ensuring the output is of the highest quality, especially in medical applications where the purity of oxygen can be critical to patient health. This section outlines a robust approach to designing and selecting an air intake filter using HEPA standards, focusing on efficiency, capacity, and maintaining a pressure drop within acceptable limits.

3.3.2.1. Introduction to Air Filtration in Oxygen Concentrators

An oxygen concentrator's efficacy largely depends on the purity of the air input, which necessitates a highly efficient filtration system. Contaminants such as dust, aerosols, and biological impurities must be filtered out to avoid compromising the concentrated oxygen quality. This document will detail designing a filter system incorporating High-Efficiency Particulate Air (HEPA) filters for optimal performance.

HEPA filters are renowned for capturing at least 99.97% of particulates that are 0.3 µ in diameter or more significant (Alvarez et al., 2019). For an oxygen concentrator, this level of filtration is essential to prevent pollutants from entering the patient's respiratory system.

3.3.2.2. Design and Sizing of HEPA Filters

The air filter design for the oxygen concentrator will cater to an airflow rate of 200 LPM. The design parameters include:

- **Volume of Air:** Determines the filter size and the number of filters required.
- **Filter Efficiency:** Affects the removal of particulates.
- **Pressure Drop:** Influences the system's energy consumption and performance.

The volume flow rate through the filter, Q, in cubic meters per second (m^3/s), is calculated using the equation:

$$Q = A \times V$$

Equation 3

Where:

- A is the cross-sectional area of the filter in square meters (m^2).
- V is the air velocity through the filter in meters per second (m/s).

Given an air velocity of $1.5\, m/s$, necessary for adequate filtration without excessive energy consumption, the cross-sectional area required for $200\ LPM$ of air throughput is calculated as follows:

Convert LPM to m^3/s:

$$Q = \frac{200}{1000 \times 60} = \mathbf{0.00333\, m^3/s}$$

Determine the cross-sectional area A:

$$A = \frac{Q}{A} = \frac{0.00333}{1.5} = \mathbf{0.00222}\boldsymbol{m^2}$$

The calculated area indicates the minimum size required for the HEPA filter to process $200\ LPM$ of airflow without exceeding the velocity threshold that could cause a pressure drop greater than $250\ Pa$.

3.3.2.3. Selection Criteria for HEPA Filters

To select an appropriate HEPA filter, one must consider:

- **Air Volume Requirements:** The chosen filter must accommodate the calculated airflow rate.
- **Efficiency Standards:** A minimum of 99.97% efficiency is needed for medical-grade purity.
- **Pressure Drop Constraints:** The filter must operate within the system's pressure limits.

After determining the necessary size, a HEPA filter that meets the 99.97% efficiency standard and operates below the maximum allowable pressure drop of $250\ Pa$ will be selected.

3.3.2.4. Conclusion on Filter Design and Selection

The HEPA filter system proposed here will effectively filter a flow rate of $200\ LPM$, offering high efficiency and low-pressure drop, which is critical for the reliable operation of an oxygen concentrator. This filtration system ensures that the output air is sufficiently pure for medical use, safeguarding the health and well-being of patients requiring oxygen therapy.

By adhering to these specifications and ensuring the filter is selected based on the critical criteria outlined, the design and selection of the air intake filter will contribute to the overall effectiveness and safety of the oxygen concentrator.

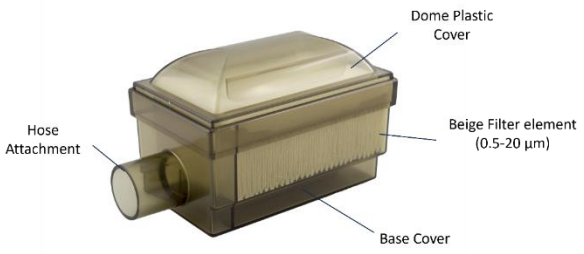


Figure 3-5: Oxygen concentrator inlet HEPA Filter (Source: Oxygen Concentrator Filters | GVS, 2023)

3.3.3. Heat Exchanger Design(Cooling System)

3.3.3.1. Introduction

In thermal management for portable machinery, Air-Cooled Heat Exchangers (ACHEs) are crucial, particularly in portable oxygen concentrators for cooling operations (Bell, 1998). ACHEs, with their finned tubes and strategically placed fans, efficiently facilitate heat exchange. Their wide use extends beyond medical devices to industries like gas-treating plants, petrochemical facilities, power

generation stations, refineries, and compressor hubs (Salimpour, 2011). They typically cool process fluids to around 25°C, leveraging standard dimensions like a 9.54 mm tube diameter and 4.5 mm fin height, refined through years of engineering and field experience (Xu et al., 2018).

Arora et al. (2021) have developed a systematic method to size ACHEs for equipment such as portable oxygen concentrators. This approach, grounded in practicality, has been adopted for selecting suitable heat exchangers in similar contexts. With the rising demand for portable medical equipment, the role of ACHEs has become increasingly significant, underlining the need for careful design and selection to ensure optimal performance and durability. The following sections detail a systematic approach, integrating current industrial practices and recent research advancements, to appropriately size and evaluate the effectiveness of an ACHE in portable oxygen concentrator setups.

3.3.3.2. Design Considerations

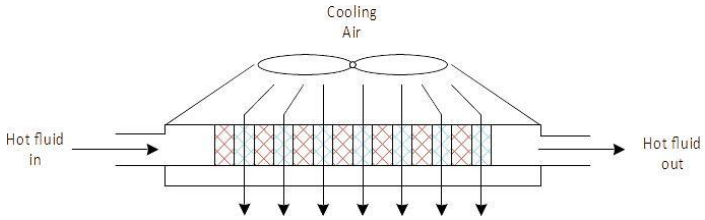


Figure 3-6: Air -Cooled-Heat-Exchanger (Source: My Engineering Tools, 2023)

The quest for an optimal ACHE design for a portable oxygen concentrator begins with a detailed assessment of the following critical phases:

Step 1: Geometric Assumptions

Optimal design starts with hypothesizing about the geometric configuration of the ACHE, particularly its pitch, influenced heavily by the inner heat transfer coefficient. Compared with the thermal dynamics on the air side, this coefficient indicates whether a wider pitch is needed to handle the thermal load effectively.

Step 2: Data Gathering for Design

Integral to the design process is the acquisition of pertinent data, including:

a) Precise dimensions of the heat exchanger.
b) Material characteristics, primarily thermal conductivity.
c) Internal and external diameters of the tubes.
d) Comprehensive process parameters embody both temperature and pressure.

Step 3: Calculating Airside Heat Transfer Coefficient

The coefficient for airside heat transfer (ha) is computed by considering the density of the fins on the tubes(Ahmed, 2015):

$$ha = k.(FV)\, W/m^2 .K$$

Equation 4

With k representing a proportionality constant influenced by the physical attributes of the fins and FV denoting the air's face velocity across the fins.

Step 4: Tube Conduction Coefficient

The conduction heat transfer coefficient (hw) through the tube's material is expressed as:

$$hw = k_w.\frac{D_o - D_i}{D_o + D_i} W/(m^2 .K)$$

Equation 5

Here $(hw)$is influenced by the material's thermal conductivity $(k_{w)}$, as well as the tube's exterior (D_o) and interior (D_i) diameters.

Step 5: Overall Heat Transfer Coefficient

The comprehensive heat transfer coefficient (U) is an integration of the contributions from the airside and the tube itself, inclusive of any fouling effects:

$$U = \left(\frac{1}{ha} + \frac{1}{hw} + fouling\ resistance\right)^{-1} W/(m^2.K)$$

Equation 6

Step 6: Air Outlet Temperature Estimation

Employing the calculated (U), the temperature of the air at the exchanger's outlet is approximated by (Pongsoi et al. 2012):

$$T_{out} = T_{in} - \frac{Q}{U.A}$$

Equation 7

Where (Q) signifies the heat load, and (A) represents the effective surface area of the exchanger.

Step 7: Determining ACHE Size

The exchanger's width (Y) This is crucial and can be deduced from (Waye, 2014):

$$Y = \frac{F_A}{L}$$

Equation 8

where (F_A)Is the total face area through which air passes and (L)It is the length of the tubes.

Step 8: Confirming Heat Exchanger Adequacy

Once a specific ACHE is earmarked, it is critically assessed against established performance criteria, considering pressure drops and potential corrosion, ensuring it can maintain the operating temperatures well within the safe threshold.

3.3.3.3. The Fan

The fan's role is indispensable in an ACHE, driving air across the finned surface to dissipate heat. In portable oxygen concentrators, a fan capable of handling air at temperatures ranging from 25 ℃ to 30 ℃ is imperative for effective cooling.

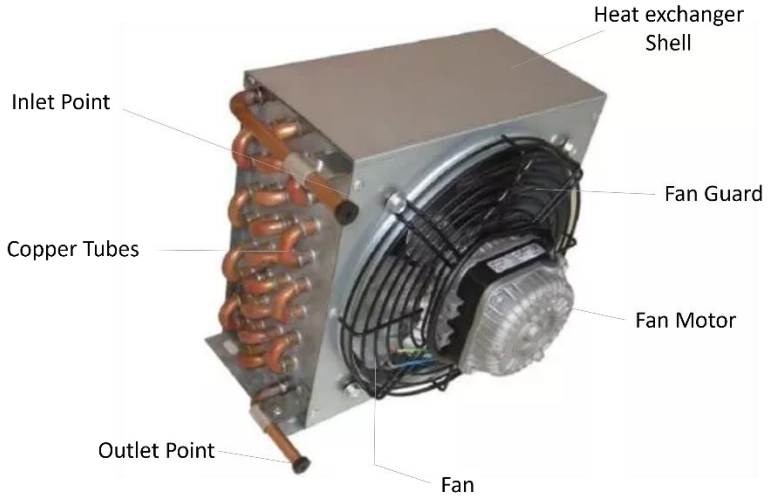


Figure 3-7: ACHE-Fan (Source: RETEK Refrigeration Parts, 2023)

For a granular understanding of the specific fan requirements and the detailed ACHE configuration adopted for this project, the software-generated report provided in **Appendix G** offers a comprehensive overview (Nagre, 2013).

3.3.4. Sieve beds

The purpose of the sieve beds in an oxygen concentrator of medical grade is to remove the nitrogen from the air while retaining the oxygen molecules. The sieve bed must be constructed of high-quality material and meet the requirements for medical use.
According to the specifications, the sieve bed must have an aluminium tube diameter of $73mm$ and a length of $650mm$. Aluminium is ideal for the sieve bed since it is lightweight, sturdy, and heat resistant.

3.3.4.1. Key Calculations:

Specifications:

a) **Sieve Bed Dimensions:** Diameter $= 73mm$, Length $= 650mm$.
b) **Material:** Aluminium 6063, chosen for its lightweight, sturdiness, and heat resistance.

3.3.4.1.1. Adsorption Capacity:

Air volume $= 150\ LPM$, Temperature $= 29°C$.
Ideal gas behavior: $1\ mole$ occupies $22.4\ liters$ at STP.

Number of moles of air $(n) = 0.1522.422.40.15\, moles/min = 0.0067\, moles/min.$

Freundlich Isotherm:

$$Q = K \times C^{1/n}$$

Equation 9

Assume K and $1/n$ Based on zeolite properties.

Lets $K = 0.8\ and\ 1/n = 0.5$

Adsorption Capacity $\left(Q_{freundlich}\right) = K \times C^{1/n}$

If the concentration of nitrogen to be adsorbed (C) is 0.78 (since air is approximately **78%** nitrogen), then: $\left(Q_{freundlich}\right) = 0.8 \times 0.78^{0.5}$

Langmuir Isotherm:

$$Q_{Langmuir} = \frac{Q_m \times b \times P}{1 + b \times P}$$

Equation 10

Assume Q_m(monolayer capacity) and b (Langmuir constant).

$Q_m = 0.1\, mol/kg$

Assume the Partial pressure of nitrogen (P) in air entering the sieve bed is about 0.78 atm.

Adsorption capacity: $Q_{Langmuir} = \frac{\frac{0.1\times0.05\times0}{.78}}{1+0.05\times0.78}$ =0.003753

3.3.4.1.2. Pressure Loss (Darcy-Weisbach Equation):

$$\Delta P = f \times \frac{L \times \rho \times v^2}{2 \times D}$$

Equation 11

Length $L = 0.65\, m$, Diameter $D = 0.073\, m.$

Assume pipe friction factor f, fluid density ρ, velocity v.

Given: Airflow $= 150\ LPM.$

Assume air density $(\rho) = 1.225\ kg/m^3.$

Convert $LPM\ to\ m^3/s$ for velocity $(v) = 0.1560 = 0.0025\, m^3/s.$

$$\Delta P = \frac{\rho \times v^2}{2}$$

$$\Delta P = \frac{1.225 \times (0.0025)^2}{2} \approx 0.0000038\, Pa.$$

3.3.4.1.3. Cyclic Times:

$$T_c = \frac{V_{bed} \times P_{diff}}{Q_{air}}$$

Equation 12

P_{diff} (Pressure difference), $Q_{air} = 150\ LPM \approx 0.0025\, m^3/s.$

Calculate V_{bed} is equal to $V_{zeolite}$

3.3.4.1.4. Quantity of Zeolite:

$$V_{zeolite} = \pi \times r^2 \times h \approx 0.0027m^3$$

Based on the Radius $r = 0.0365m$, height $h = 0.65m$.

3.3.4.1.5. Bed Depth:

Based on zeolite bulk density (ρ_{bulk}).

$$BedDepth = \frac{Mass}{Area \times \rho_{bulk}}$$

Equation 13

Given: Air pressure $= 1\ atm$, Temperature $= 29°C$.

Assume mean free path $(\lambda) = 68\ nm\ (68e-9\ m)$.

Calculating bed depth (d):

$$d = \frac{68e-9}{\sqrt{\pi \times 1 \times 302}} \approx 7.8e-9m$$

3.3.4.1.6. Separation Efficiency:

$$Efficiency = \frac{O_{2_{outlet}} - O_{2_{inlet}}}{O_{2_{inlet}}} \times 100\%$$

3.3.4.1.7. Pore Size:

Given: Pressure $= 1\ atm$.

Assume surface tension $(\sigma) = 0.07280.0728\ N/m$ (value for water at room temperature, as a reference).

Calculating pore size d_p

$$d_p = 2 \times \lambda \times \sigma P == 2 \times 68\text{e} - 9 \times 0.0728 \times 101325 d_p \approx \mathbf{0.000951\ m}.$$

Table 3-1: Financial and Environmental Considerations

Consideration	Calculation
Cost Calculation	The total comprises material costs, manufacturing, and assembly expenses.
Maintenance and Upkeep Costs	Yearly cost estimates based on component lifespan.
Energy Consumption Calculation	Energy = Power × Time
Environmental Impact Calculation	Based on energy consumption and material sourcing.

3.3.4.1.8. Components for Sieve Bed Design:

Table 3-2: Sieve Bed Components

Component	Specifications	Quantity
Canister	75mm ID, 500mm tall, Aluminium 6063	2
End Cap	ADC-12, A380, ALSi12, AlSi9Cu3	2
O-ring	75mm diameter, 2.5mm thick rubber	4
Spacer	74mm diameter disk, 1.5mm-3mm holes	4
Membrane Sheet	Non-woven filter material	4
Spring	50mm x 75mm, 5mm wire, Stainless steel	2
Zeolite	Lix JLOX-101A (0.4-0.8 mm)	3.2 Kg
Bed Pressure	2.5 Bar	
Valve Cycle	5100 - 11000 ms	

Figure 3-8: Sieve Bed Components (Source: Zibo Creations Metalware Co, 2021)

3.3.4.2. Design Methodology for a Compression Spring

Introduction

Compression springs are pivotal in industrial applications, mainly where compressive forces are prevalent. The design of these springs involves selecting suitable materials, determining dimensions, and calculating the spring constant and maximum load. We focus on a stainless-steel compression spring characterized by an Outer Diameter (OD) of $50mm$, an Inner Diameter (ID) of $44mm$, wire diameter (d) of $3mm$, closed and squared ends, a free length of $75mm$, and a spring constant of $1.124\ N/m$. (see Appendix I).

3.3.4.2.1. Design Parameters and Calculations

Table 3-3: Compression Spring Formulas and Parameters

Dimension	Formula	Values
Mean Diameter (D)	$D = \frac{(OD + ID)}{2}$	$D = 47mm$
Spring Index (C)	$C = \frac{D}{d}$	$C = 15.67$
Solid Height (H)	$H = d(n - 1)$	$H = 21mm$
Active Coils (na)	$na = n - 2$	$na = 6$
Pitch (p)	$p = \frac{L}{na}$	$p = 12.5mm$
Mean Coil Diameter (D_m)	$D_m = D - d$	$D_m = 44mm$
Buckling Factor (K_b)	$K_b = 4C - 1$	$K_b = 62.68$

3.3.4.2.2. Material Selection

Stainless steel was chosen for its high strength, good corrosion resistance, and ability to withstand significant compressive forces without deforming.

3.3.4.2.3. Spring Constant

The spring constant (k) indicates the stiffness of the spring. It is calculated using:

$$k = \frac{G \times (d^4)}{8 \times D^3 \times na}$$

Equation 14

Using equation 14, here, G represents the material's shear modulus, approximately $79.3\ GPa$ for stainless steel, leading to a spring constant **k** of **1.124 N/m**.

3.3.4.2.4. Maximum Load and Deflection

The maximum load is not calculable without knowing the maximum force. Deflection, the compression distance from free length to solid height, is calculated by $x = H - L$, resulting in $\boldsymbol{-54mm}$, indicating compression.

3.3.4.2.5. Equivalent Load

The equivalent load (W) can be estimated using the spring constant and deflection, calculated as $W = \frac{k \times x}{g}$, where g is the acceleration due to gravity ($9.81\ m/s^2$). This results in $\boldsymbol{-0.00064\ N}$, denoting a compressive load.

3.3.4.2.6. Conclusion

This methodology offers a comprehensive approach to designing a stainless steel compression spring with specific parameters. The calculations for mean diameter, spring index, solid height, active coils, pitch, mean coil diameter, buckling factor, spring constant, and deflection are key. Although this design can be further optimized by considering factors like stress and fatigue life, it provides a solid foundation for spring design.

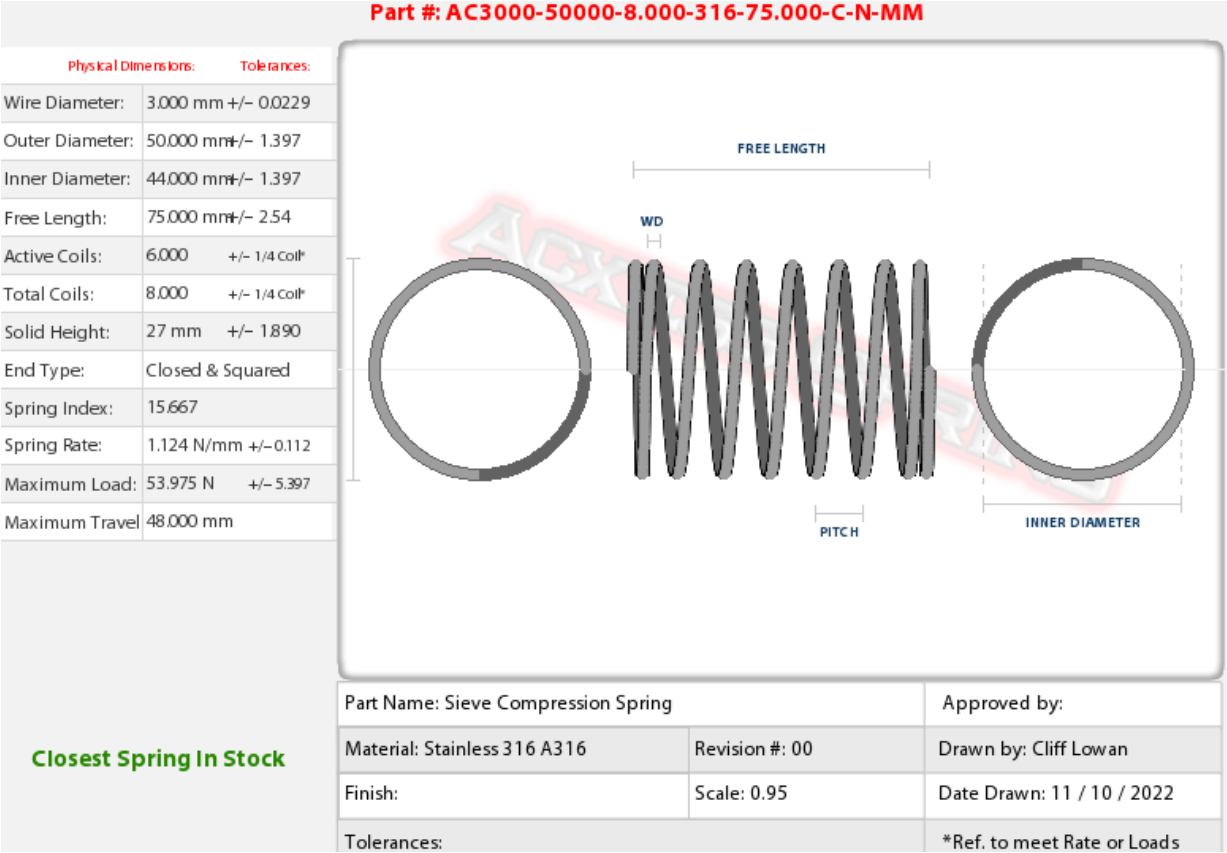


Figure 3-9: Compression Spring Dimensions (Authors study From:(Source: Acxess Spring, 2022)*)*

3.3.4.3. The Quantity of Zeolite required is:

JLox-101A (see **Figure 3-10**)has a high $N2/O2$ selectivity, resulting in significantly less material relative to other molecular sieve adsorbents without sacrificing oxygen throughput or purity. Due to the interplay between the electrostatic field of the cationic zeolite, adsorbents are selective for absorbing nitrogen as opposed to oxygen. Valves open to supply concentrated oxygen into a reservoir, where it accumulates, and from which a flowmeter can continuously provide oxygen to the patient at a specified flow rate at $22\ lpm$.

Figure 3-10: 13X Zeolite Molecular Beads (Source: Pingxiang Global New Materials Technology, 2023)

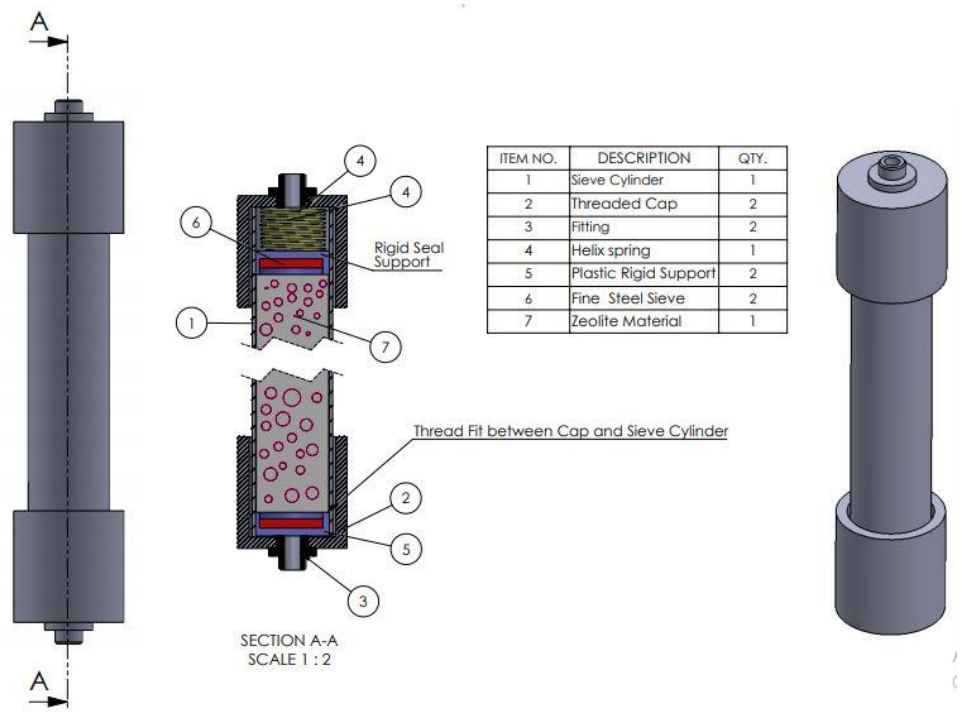


Figure 3-11: CAD Drawn Zeolite Adsorbent Canister

3.3.5. Oxygen Tank

3.3.5.1. Cylinder Design

The cylinder functioned as a buffer tank to augment oxygen flow to the patient and was equipped with a regulator. It needed a capacity of three to 25 litres, constructed from aluminium with a concave base. Aluminium was chosen for its affordability, lightness, and greater durability compared to plastics and fibreglass (Luigi, 2019). Additionally, aluminium is safe for breathing applications, posing no health risks or irritations, unlike other materials (Luigi, 2019). A wall thickness of 100mm was deemed sufficient for strength without significantly increasing the unit's weight

3.3.5.2. Specifications

The gas cylinder (**figure 3-12**) was selected according to the specifications of SANS (South African National Standards). According to the South African standard specification: SANS 10227 Aluminium cylinders for compressed gases - seamless $0.1\ kg$ to $130\ kg$, the following specifications shall be

considered when determining the health and safety of compressed gasses in cylinders (Government Gazette No 1095 of 2004).

Minimum wall thickness (mm) to withstand internal pressure and external forces resulting from standard handling, but excluding any additional thickness to account for corrosion and other factors

Figure 3-12: Aluminium Cylinder (Source: Speedway, 2023)

3.3.6. Flow Distribution (inbuild oxygen splitter unit)

The design of an inbuilt oxygen splitter unit for a multi-user oxygen concentrator must account for flow rate requirements, valve choices, and safety precautions. By considering these aspects and conducting the appropriate calculations, designing a splitter unit for a multi-user oxygen concentrator is possible to ensure proper flow and safety.

The process of designing an oxygen splitter unit for an oxygen concentrator with many users. It involves determining the optimal number of outlets and locations to distribute the oxygen flow evenly. Additionally, it is essential to consider the pressure requirements of each user and ensure that the splitter unit can maintain consistent pressure throughout. By carefully considering these factors, a well-designed oxygen splitter unit can effectively meet the needs of multiple users while maintaining safety and efficiency.

Design Process:

In the design of a multi-user oxygen concentrator's inbuilt splitter unit, key considerations include flow rate determination, valve selection, and safety measures. Flow rate requirements range from 0 to 25 litres per minute (lpm). A dial-click flow gauge with a 100 kPa output pressure is optimal for flow regulation, ensuring compatibility with the oxygen tank's dimensions of 73mm diameter and 500mm length (Zhang, 2020). The tank's volume calculation is crucial, using: $V = \pi r^2 h$, where r is the radius ($\frac{d}{2}$) and h is height.

To ensure an even oxygen distribution to users, the flow rate for each output is based on individual needs, totalling the required flow rate. For instance, four users needing 10 lpm each sum to a total

flow rate of 40 lpm. The splitter unit design incorporates calculations for tubing and connector dimensions to maintain appropriate flow and pressure.

Safety in design is paramount, encompassing overpressure protection and backflow prevention. Material selection for the splitter unit prioritizes compatibility with oxygen, durability, and adherence to medical standards, with typical choices being stainless steel, brass, and PVC (Song, 2020).

Connections between the concentrator and splitter must endure system pressures and flow rates, with strategic planning for placement and tubing routing. Final design validation involves comprehensive testing for flow rate and pressure, ensuring the unit's functionality and safety (Pan, 2017).

In conclusion, designing an oxygen splitter unit for multi-user concentrators demands careful component selection, meticulous planning, and rigorous testing to guarantee safety, efficiency, and reliability.

Calculations and values are examples of how to design the oxygen splitter unit.

These calculations are based on the following assumptions:

Example Calculation:

To find the tubing diameter using the Darcy-Weisbach equation, one can use the following relationship:

$$\Delta P = f \times \frac{L}{D} \times \frac{\rho v^2}{2}$$

Equation 15

Where:

$$\Delta P \text{ is the Pressure drop } (20kPa)$$

$$f \text{ is the friction factor} (0.01 \text{ for smooth tube})$$

$$L \text{ is the length of the tube } (5\ m)$$

$$\rho \text{ is the density of oxygen} (1.4 \frac{kg}{m^3})$$

V is the velocity of oxygen, which can be determined using the relationship:

$$v = \frac{Q}{A}$$

Equation 16

Where:

$$Q \text{ is the flow rate} (15 L/\min \text{ or } 0.25\ l/s)$$

$$A \text{ is the cross} - \text{sectional Area of the tube } A = \frac{\pi}{4} \times D^2$$

Given the information:

1. Calculate v: using equation 16.

$$v = \frac{0.25}{\frac{\pi}{4} \times D^2}$$

2. Plugging v into the Darcy-Weisbach equation:

$$20000Pa = 0.01 \times \frac{5}{D} \times \frac{1.4 \times \left(\frac{0.25}{\frac{\pi}{4} \times D^2}\right)^2}{2}$$
$$D = 0.00149cm$$

This equation, complex due to its quadratic nature in terms of D, is typically solved using iterative methods or algebraic manipulation to find the value of D. Depending on the context or available tools, one might use software or a numerical method to solve for D.
Let us consider one of the outputs with a flow rate of $15\ L/min$. The tubing diameter can be determined using the **Darcy-Weisbach equation**:

Thus, a tubing diameter of $\mathbf{0.5\ cm}$ should be sufficient to provide a flow rate of $\mathbf{15\ L/min}$ with a pressure drop of $\mathbf{20\ kPa}$.

Assume tubing length of 20cm,
updated calculations based on the assumption of a tubing length of $20\ cm$.

Example Calculation: Let us consider one of the outputs with a flow rate of $15\ L/min$. The tubing diameter can be determined using the **Darcy-Weisbach equation**:

For a pressure drop of $20\ kPa$, using the following values: $f = 0.01$ (friction factor for smooth tube) $L = 0.2\ m$ (length of tubing) $\rho = 1.4\ kg/m^3$ (density of oxygen at standard conditions) $v = 15\ L/min\ /\ (\pi/4 \times D^2)$ (velocity of oxygen) $g = 9.8\ m/s^2$ (acceleration due to gravity)

The **diameter** of the tubing can be calculated as follows: $\boldsymbol{D = 0.5cm}$
Thus, a tubing diameter of $0.5\ cm$ should be sufficient to provide a flow rate of $15\ L/min$ with a pressure drop of $20\ kPa$ with a tubing length of $20\ cm$.

Assume the tubing length is $500mm$ and the tubing diameter is $10mm$,
updated calculations based on the assumption of a tubing length of $500\ mm$ and a tubing diameter of $10\ mm$.
Example Calculation: Let us consider one of the outputs with a flow rate of $15\ L/min$. The pressure drop across the tubing can be determined using the **Darcy-Weisbach equation**:

Using the following values: $f = 0.01$ (friction factor for smooth tube) $L = 0.5\ m$ (length of tubing) $D = 0.01\ m$ (diameter of tubing) $\rho = 1.4\ kg/m3$ (density of oxygen at standard conditions) $v = 15\ L/min\ /\ (\pi/4 \times D^2)$ (velocity of oxygen) $g = 9.8\ m/s^2$ acceleration due to gravity)
Thus, with a tubing length of $\mathbf{500\ mm}$ and a tubing diameter of $\mathbf{10\ mm}$, the pressure drop across the tubing should be approximately $\mathbf{393.75\ Pa}$ **for** a flow rate of $\mathbf{15\ L/min}$.

Prevention of backflow in the splitter unit:

Backflow in a splitter unit can be prevented using several methods, including:

1) **Check Valves:** Check valves are one-way valves that allow flow in only one direction and prevent backflow. These can be installed at the outlet of each output in the splitter unit to prevent oxygen from flowing back into the system.
2) **Non-Return Valves:** Non-return valves, also known as one-way valves, operate similarly to check valves and prevent backflow by only allowing flow in one direction.
3) **Pressure-Relief Valves:** Pressure-relief valves can be installed in the splitter unit to relieve pressure buildup and prevent backflow. These valves open when the pressure in the system exceeds a specific limit, releasing excess pressure.
4) **Positive Pressure Regulators:** Positive pressure regulators maintain a constant positive pressure in the system, preventing backflow. These can be installed at the outlet of each output in the splitter unit to ensure that the pressure remains at a set level, even when the flow rate changes.

Figure 3-13: Flow Distribution (CAD rendered drawing)

For a multi-user oxygen concentrator, the equipment must be able to divide oxygen into several distribution ports. The distribution unit must be able to supply oxygen to individual ports without limiting flow to those ports *(see Figure 3-13).*

The input oxygen pressure was adjusted by a pressure regulator set to $300kpa$ of air necessary to suit the patient's needs. A regulator not intended for medical usage may be utilised for the prototype.
A Console outlet Oxygen port compatible with Afrox Puritan-Bennet helps deliver the gas product. The Dual/Y-block Thorpe flowmeter system *(see Figure 3-14)* is then attached to this Console output. Two of these Flow metre Assemblies can be placed to give oxygen to four patients simultaneously.

Figure 3-14: Dual Flowmeter Assembly (Source: AMVEX Flowmeters, 2023)

The distribution Units must be designed with copper, brass, or aluminium plumbing. They should be solid and firmly in place to minimise the chance of leakage. The unit must be oil- and dust-free. System backflow was prevented by a few joints that minimised pressure losses and avoided cross-contamination.

Calculations:

$$One\ Thorpe\ styple\ flowmeter\ can\ provide\ a\ maximum\ of\ 15Lpm$$

$$1 = 15Lpm$$

$$For\ a\ Maximum\ of\ 25Lpm, one\ need\ a\ minimum\ of\ 2\ \times 15Lpm\ Thorpe.$$

25Lpm ≥ 30 Thorpe

$$However\ Since\ other\ Patients\ may\ need\ less\ than\ 5Lpm\ at\ a\ time, a\ system\ with\ an\ output\ capacity\ of\ 25Lpm\ can\ be\ fitted\ with\ Up\ to\ 4\ \times 15Lpm\ Thorpe\ flowmeters.$$

The Thorpe output can be outfitted with a humidification bottle or a swivel nipple linked to a mask or cannula on a patient.

3.3.7. PLC system

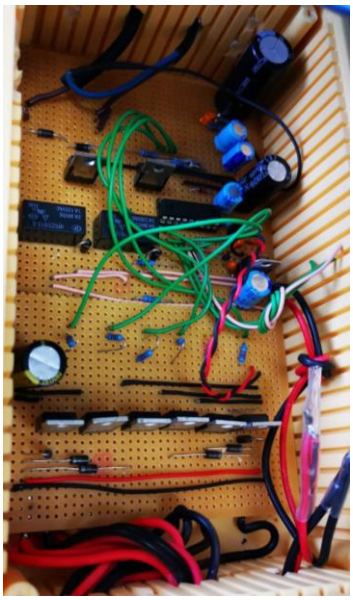


Figure 3-15: PLC System

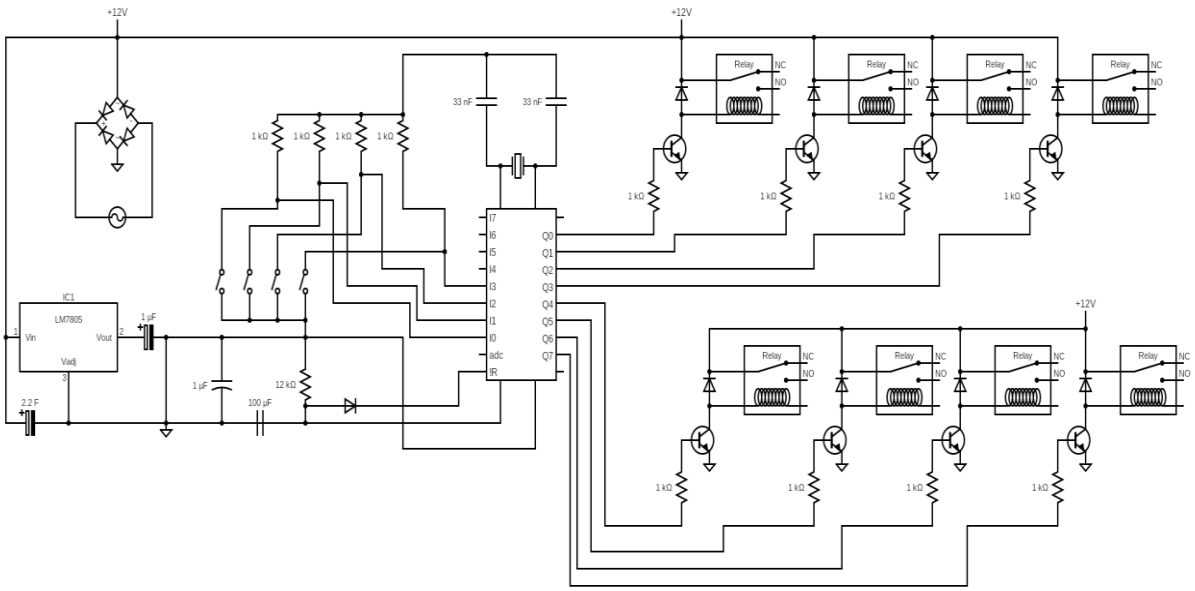


Figure 3-16 PLC System 2

3.3.7.1 Electronics of the Oxygen Concentrator.

Valve control in oxygen concentrators is managed through TIP29C transistors, functioning as electronic switches to transition voltage levels, essential for solenoid valve operation (see Figure 3-17). These silicon-based NPN power transistors consist of three terminals: Emitter (E), Base (B), and Collector (C), working on the principle of charge movement within the semiconductor.

When a 5V signal from a microcontroller, such as the PIC16F84A, is applied to the Base, it controls current flow between the Collector and Emitter, enabling a larger current (12V) to operate the solenoid valve. Additionally, a 1N4007 diode connected parallel to the solenoid valve protects the system from potential damage by back electromotive force (EMF), offering an alternative current path and preventing voltage spikes from damaging the transistor or microcontroller (Morchid et al., 2021).

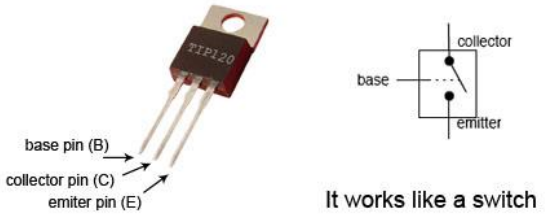


Figure 3-17: Transistors (Morchid et al., 2021)

The PIC16F84A microcontroller (figure 3-18), developed by Microchip Technology, is an 8-bit flash microcontroller with a RISC-based CPU, 1 Kilobyte of program memory, and up to 68 bytes of RAM. It operates at speeds up to 20 MHz and features programmable I/O pins (up to 13) and In-Circuit Serial Programming (ICSP) capabilities for efficient software updates in complex circuits (see Figure 3-18). This microcontroller is adept at solenoid valve control, executing programming parameters for valve operation based on time or stimuli. The integration of TIP29C transistors and PIC16F84A microcontroller allows for precise automated control in solenoid valve systems, highlighting their reliability and adaptability in complex applications (Source: Microchip Technology, 2023).

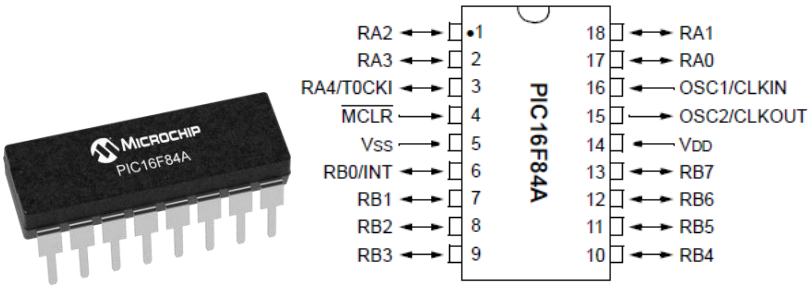


Figure 3-18: PIC16F84A Microchip(Source: Microchip Technology, 2023)

3.3.7.2 Solenoid Valve Sizing

In solenoid valve sizing for system design, it is imperative to choose the correct size and type to prevent operational issues. **Key considerations include:**

a) **Flow control requirements**: The valve must regulate fluid flow efficiently within the minimum and maximum range, ensuring optimal performance without flow restrictions or excessive rates (Bayat, 2012).
b) **Pressure differential:** It should handle the system's lowest and highest pressure differentials for consistent operation (Zhao, 2009).
c) **Fluid characteristics:** The valve's size must accommodate the fluid's specific gravity, temperature, and viscosity to maintain desired control (Lee, 2015).
d) **Pipeline size:** Aligning the valve size with pipeline dimensions ensures efficient fluid passage and avoids pressure drops (Malaguti, 2002).
e) **Supply voltage:** Compatibility with the system's voltage range is essential for reliable operation (Jiang, 2009).
f) **Flow rate calculation:** Determining the flow rate is crucial for selecting a valve of appropriate capacity. This involves establishing the flow factor (kV), indicating the valve's flow capacity at room temperature with a 1 bar pressure drop (Dahlstrand, 1961).

In conclusion, precise selection of a solenoid valve's size and flow factor (kV) is achieved by considering these factors and accurately calculating the required flow rate, ensuring efficient system operation and avoiding sizing-related issues.

3.3.7.3 Pressure:

In selecting a solenoid valve, it is paramount to give thorough attention to the pressure requirements essential for its operation. The core functionality of internally piloted valves heavily relies on an adequate pressure differential, which is critical for their effective opening and closing. This necessitates a focus on ensuring a sufficient pressure differential across the solenoid, fundamental to the actuation of the solenoid and, consequently, to the precise control over the flow of fluids or gases.

Furthermore, adherence to the established proof pressure guideline is recommended. This rule suggests that the maximum operational working pressure should be no more than one-fifth of the valve's proof pressure. Abiding by this principle helps in preventing failures or damages that might arise from excessive pressure conditions. This aspect of pressure management is integral to maintaining the integrity and functionality of the solenoid valve under various operational circumstances.

The operation of a solenoid valve is governed through electromechanical means via a solenoid. When energised, the solenoid generates a magnetic field that facilitates the opening or closing of the valve, thereby regulating the flow of fluid or gas. It is, therefore, crucial to select a solenoid valve that can not only withstand anticipated system pressures but also respond effectively to the electrical control signals emitted by the solenoid. Understanding and catering to these pressure requirements are key in selecting a solenoid valve that aligns with the specific needs of an application, ensuring its reliable and efficient performance in controlling fluid or gas flow.

3.3.8. Flowmeters/ Pneumatic controls

Effective operation of an oxygen concentrator system relies heavily on integrating sensors for temperature, pressure, flow rate, voltage, and alarms (Hermawan, 2018). These sensors are instrumental in monitoring oxygen delivery and adjusting flow rates to meet individual needs. A user interface displaying flow rate, battery life, and error messages adds to the system's usability.

Crucial in designing an efficient system is estimating oxygen needs based on patient numbers and expected flow rates. Standard flow rates for adults range from 2 to 5 LPM, increasing to 25 LPM for severely ill patients. On average, an adult on oxygen therapy requires 5 LPM for about three days. A 25 LPM concentrator could serve multiple adults, but those severely ill might need an exclusive oxygen source.

Flow meters and pneumatic controls are essential for optimizing oxygen delivery, preventing waste, and enabling precise administration to patients. A regulator with recording functions in the oxygen tank is key for real-time oxygen usage monitoring, thus efficiently managing the supply.

In conclusion, incorporating a variety of sensors, user-friendly interfaces, and accurate oxygen needs estimation is vital for a dependable and effective oxygen concentrator system. These elements guarantee safe and efficient oxygen delivery, control of usage, and improved patient care.

3.3.9. Frame and stand

Designing an oxygen concentrator for resource-limited areas requires a robust, efficient frame and enclosure, balancing durability, environmental adaptability, user needs, and material availability.
Selecting materials for the frame and enclosure is vital, with lithium and steel being common choices. Aluminium is preferred for its lightweight yet robust nature, offering structural strength despite potential corrosion issues. Steel, while heavier and costlier, is favoured for its superior corrosion resistance and durability, contributing significantly to the concentrator's longevity (Smith, 2020).

The frame and enclosure's design should enhance airflow efficiency and ergonomics, reducing turbulence and pressure drop while ensuring environmental protection and ease of maintenance. Cost-effectiveness and simplicity in production are key and achievable through established manufacturing methods and innovative materials (Smith, 2019).

Critical to the concentrator's performance and user experience, the material choice profoundly influences functionality and reliability (Jones, 2020). An interdisciplinary approach involving engineers, designers, and healthcare professionals is essential in developing a practical, durable design suitable for low-resource settings (Brown, 2018).

3.3.9.1. Requirements:

Table 3-4: Product Requirements

Requirement	Specification
Total Weight	≤40 kg without compressors
Noise Level	≤65 dB
Height	1.2 m
Width	650 mm
Depth	400 mm
Frame and Enclosure Material	Aluminium

3.3.9.2. Design Criteria:

a) The design should consider the principles of oxygen concentration and the physical dimensions of the components.
b) The design should comply with all relevant safety regulations, including electrical and fire safety.
c) The frame and casing should withstand regular operation and handling loads and stresses.
d) The design should consider the product's aesthetics, including colour, texture, and form.
e) The electronic components should be mounted in a way that ensures proper cooling and minimizes the potential for electrical interference.
f) The design should allow easy access to the components for maintenance and repair.

3.3.9.3. Materials:

The frame and enclosure will be made of aluminium.

6. Approach:

a) The design will be based on a thorough understanding of the principles of oxygen concentration and the physical dimensions of the components.
b) Engineering calculations and simulations will be employed to verify the strength and stability of the design.
c) The design will adhere to all relevant safety regulations and standards.
d) Aesthetic considerations will be taken into account during the design of the frame and enclosure.
e) The electronic components will be mounted in a manner that ensures proper cooling and minimizes the potential for electrical interference.
f) The final design will enable easy access to the components for maintenance and repair**.**

7. Deliverables:

a) We have detailed engineering drawings and specifications for the frame and enclosure.
b) Prototypes and test reports demonstrating compliance with the specified requirements and design criteria.

8. Consideration of Aluminum as the Material for the Frame and Enclosure:

Aluminium is particularly favoured for constructing frames and enclosures of oxygen concentrators, attributed to its lightweight yet substantial nature. This material distinguishes itself through its remarkable durability and strength, qualities that are indispensable in medical equipment. Moreover, aluminium's superior heat conductivity is critical for efficient thermal management applications. Its high corrosion resistance makes it an ideal choice for oxygen concentrators, which may be exposed to moisture and other corrosive elements.

The versatility of aluminium is further evidenced by its formability, allowing for intricate and complex designs in frame and enclosure construction. Various finishing options, such as anodizing and powder coating, not only enhance the aesthetic appeal of the material but also provide substantial protection against damage. In terms of cost-efficiency, aluminium presents a more economical alternative than materials like stainless steel, making it a practical choice for budget-conscious projects. Furthermore, its commendable electrical conductivity renders it suitable for constructing electronic enclosures, expanding its applications in medical equipment production.

When using aluminium for the frame and enclosure of an oxygen concentrator, selecting the appropriate grade of aluminium is essential based on the required strength, formability, and finishing requirements. Additionally, care should be taken to ensure that the aluminium components are correctly assembled and fastened to avoid potential electrical hazards.
In conclusion, using aluminium for the frame and enclosure of an oxygen concentrator is a viable option that offers several benefits, including light weight, durability, and cost-effectiveness. Careful consideration of the material properties, processing, and finishing is vital to ensure that the final product meets the desired performance and aesthetic specifications.

CHAPTER 4

4. Design Outcomes and Prototyping

4.1. Computer-Aided- Design

This chapter summarises the development of a portable, multi-user medical-grade oxygen concentrator using a systematic Computer-Aided Design (CAD) methodology, employing the UCT-licensed Solidworks software. CAD offers accuracy, efficiency, and design optimisation.

Key Phases of CAD Methodology:

a) **Requirement Gathering and Analysis:** The initial step involves in-depth consultations with medical professionals, engineers, and end-users to capture their insights and specific needs. These inputs are crucial for ensuring the concentrator meets the required specifications and functionalities.
b) **Conceptual Design:** Based on requirements, initial sketches and detailed 3D models are developed using Solidworks. This phase explores various design options through brainstorming and iterative iterations**.**
c) **Detailed Design:** The conceptual design is transformed into comprehensive 2D and 3D models, integrating components, selecting materials, and incorporating essential features for the oxygen concentrator.
d) **Design Review and Validation:** The model undergoes reviews and validations, employing advanced tools and simulations to ensure compliance with specifications and functionality, optimising design, and confirming safety and regulatory adherence.
e) **Prototyping and Testing:** Following design validation, physical prototypes are constructed and tested. This stage assesses performance, durability, and user-friendliness, allowing for necessary adjustments based on feedback.

CAD methodology enhances the design and development of the oxygen concentrator. Solidworks' precise modelling capabilities, simulation tools, and analysis features contribute to error reduction and performance optimisation and facilitate collaboration. This project utilised Solidworks for accurate visualisation, modelling, and analysis of the concentrator's frame and enclosure, ensuring an optimal design**.**

The images (see Figure 4-1; Figure 4-2) below showcase the final product created through the CAD process, providing a clear visual representation of the oxygen concentrator's frame and enclosure:

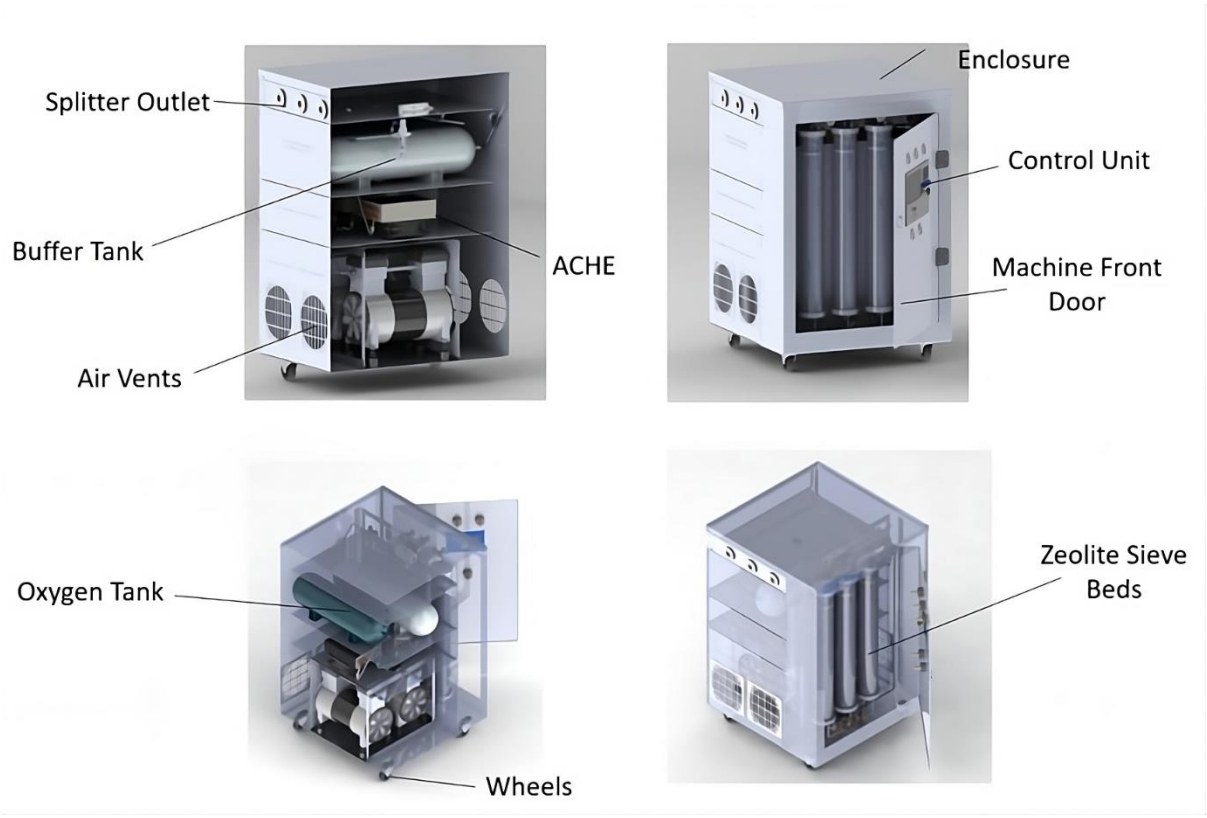


Figure 4-1: CAD- rendered Image of the final Prototype.

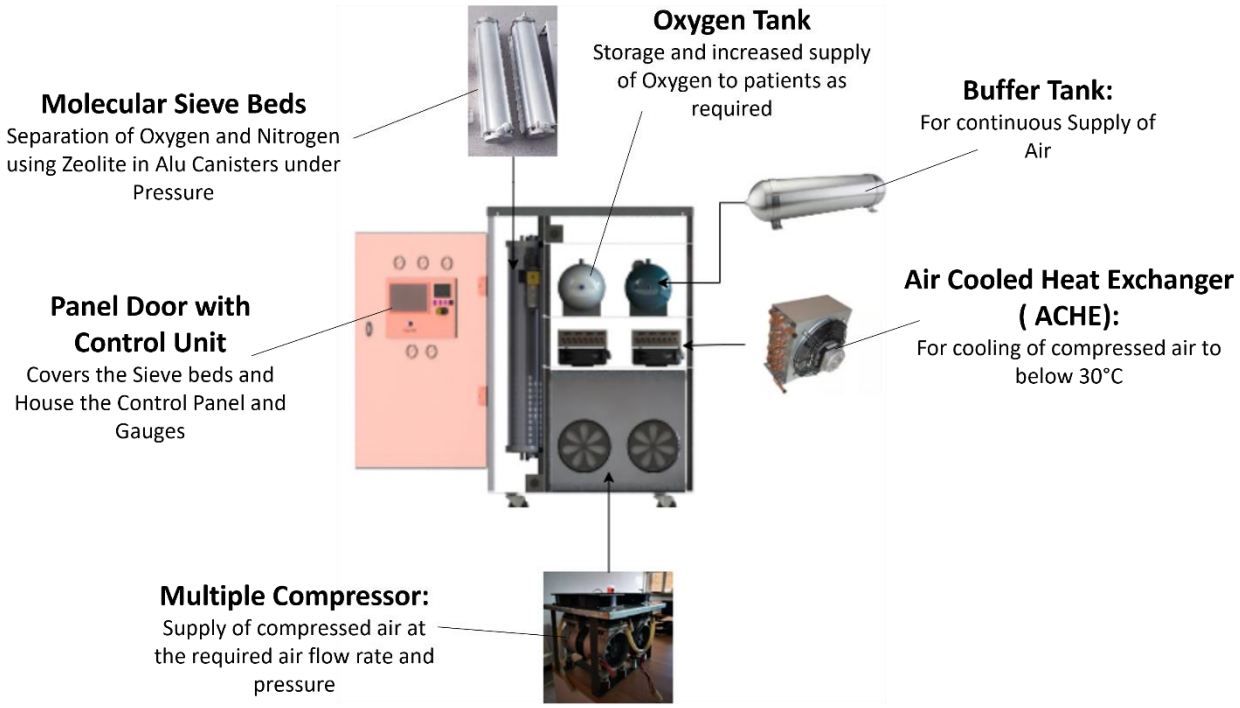


Figure 4-2: Expanded explanation of all Components and their functions.

4.2. Design of Electrical Components

4.2.1. Safeguarding Against Voltage Drops with Under-Voltage Protection

To mitigate the impact of voltage drops on compressor coils and the concentrator's lifespan, an under-voltage protection device on the circuit board is recommended. This device will disconnect the concentrator from the power supply if voltage falls below a certain threshold, ensuring alignment with IEC 60601-1 standard for medical electrical equipment.

4.2.2. Preventing Electrical Hazards with Ground Fault Circuit Interrupter

GFCI, integrated into the circuit board, monitors current flow to prevent electrical hazards like electrocution or fires. It disconnects power upon detecting ground faults, adhering to IEC 60601-1 standards.

4.2.3. Maintaining Electrical Efficiency with Surge Protection

Integrating a surge protector circuit on the circuit board using transistors safeguards against power surges, thus preserving the concentrator's lifespan and performance. Compliance with IEC 61643-11 standards for low-voltage surge protection is maintained.

4.2.4. Power Supply

The power supply, free from voltage fluctuations and electrical hazards, must comply with IEC 60601-1 standards. Circuit board integration using transistors ensures stable and reliable output.

4.3. Testing Requirements of Electrical Components

Electrical components undergo tests for electrical safety, functionality, and performance according to IEC 60601-1 standards. This includes assessing for shock and electrocution risks, the functionality of all components, and meeting performance specifications like oxygen flow rate and purity.

4.4. Testing requirements for mechanical components

When it comes to ensuring the reliability and performance of such mechanical components, rigorous testing methodologies are crucial. Let us explore the critical aspects of testing requirements and the methodology for evaluating this specific compressor unit.

4.4.1. Testing Requirements for Mechanical Components:

a) ***Performance Testing:*** Evaluates airflow, pressure, efficiency, and deviations from expected performance.
b) ***Durability Testing****:* Assesses wear and tear, potential mechanical failures, and overall reliability.

c) ***Environmental Testing:*** Ensures consistent performance under varying environmental conditions.
d) ***Safety Testing:*** Verifies compliance with industry-specific safety standards and regulations.

4.4.2. Testing Methodology for Portable Oil-Free Noiseless Compressor Unit Output:

a) ***Preparation:*** Establish detailed test plans and instrumentation.
b) ***Performance Testing:*** Measure and compare output parameters with specifications.
c) ***Noise Level Testing:*** Utilise sound meters for accurate noise measurement.
d) ***Durability Testing:*** Monitor performance during extended operation cycles.
e) ***Environmental Testing:*** Simulate extreme conditions and assess reliability.
f) ***Safety Testing:*** Ensure compliance with safety standards.
g) ***Documentation:*** Accurately record all procedures and results.

4.5. Computational Fluid Dynamics (CFD) Analysis of Oxygen Flow in Zeolite Packing: Optimising Oxygen Concentrator Design

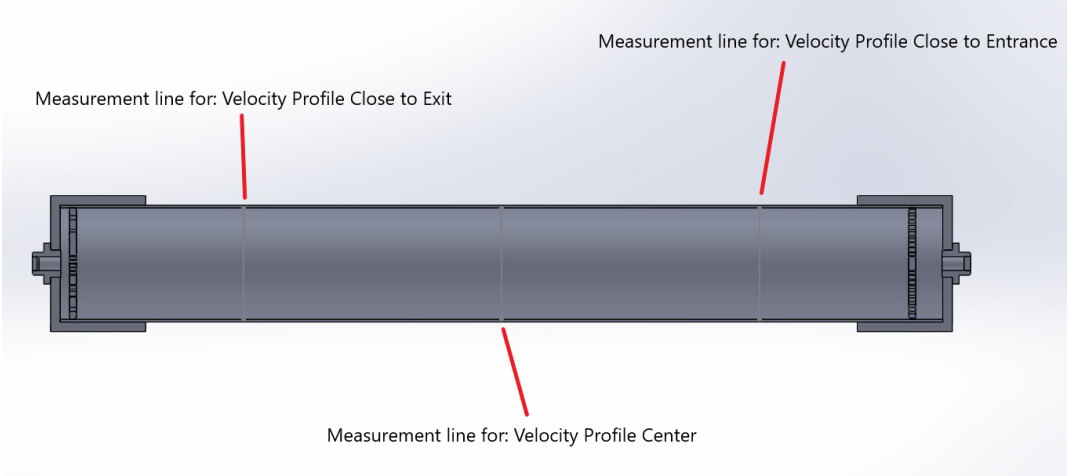


Figure 4-3: Solidworks drawn Adsorption Canister

4.5.1. Introduction

CFD, utilising numerical methods like Navier-Stokes equations, was applied to optimise oxygen flow uniformity in zeolite packing sections of oxygen concentrators (Syed, 2008). The objective was to optimise the concentrator's design and enhance the performance and uniformity of oxygen flow.

4.5.2. Model Setup and Parametric Studies

The CFD model included a cylinder with end caps (Figure 4-4) and perforated disks (Figure 4-5). The parameters studied were dead space, perforation pattern, disk thickness, central obstructions, and backpressure. The primary focus was to analyse the oxygen flow profile as it entered the zeolite section following passage through the perforated disk. Although the zeolite packing was not explicitly modelled, its impact on the flow profile was indirectly assessed.

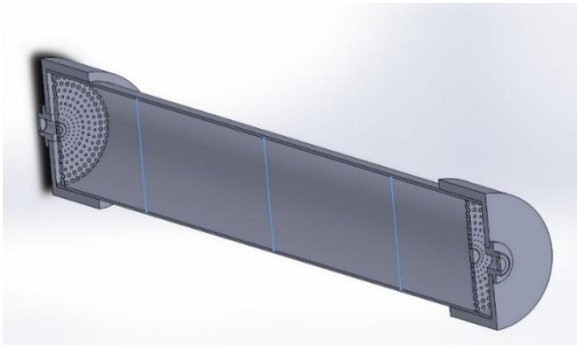


Figure 4-4: Solidworks CFD Sieve Bed canister

Figure 4-5: PVC spacer

Parametric studies (Figure 4-6) were conducted to investigate the effects of various parameters on the oxygen flow profile. These parameters included the dead space or gap between the inlet end cap and the first perforated disk, the perforation pattern on the disks, the thickness of the disks, the presence of a centre obstruction within the disks, and the backpressure induced by reducing the outlet size.

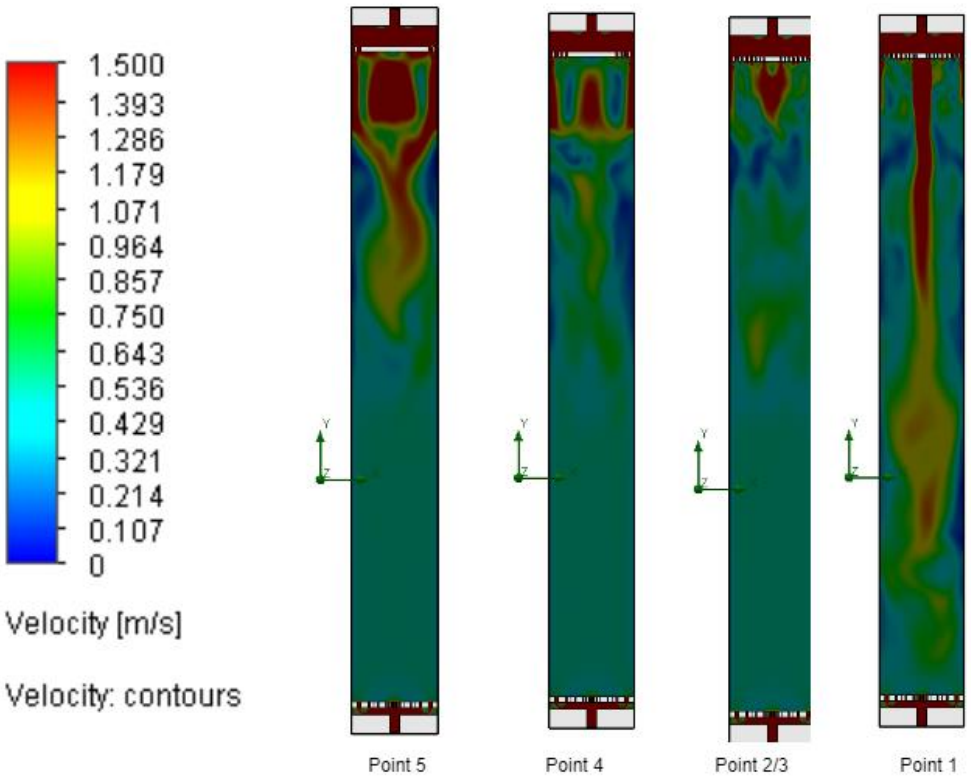
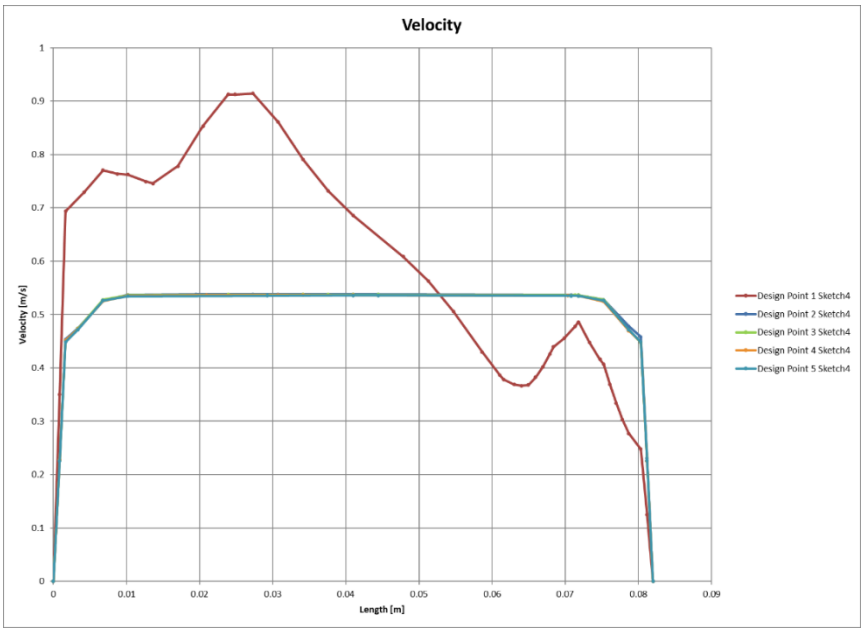


Figure 4-6: CFD Velocity Analysis Graphic representation

4.5.3. Findings and Implications

Modifications in dead space, perforation patterns, disk thickness, and central obstructions significantly affected oxygen flow uniformity. The study's results are vital for oxygen concentrator design optimisation (See Graph 4-1).

Graph 4-1: CFD Velocity Analysis



4.5.4. Conclusion

CFD analysis identified key parameters influencing oxygen flow in concentrators, enabling design optimisation for improved performance and uniform oxygen distribution.

4.6. Build and test compressor unit

4.6.1. Compressor Unit Test

The construction and testing of dual-piston pump oilless compressors in parallel configuration offer several advantages, such as increased capacity, redundancy, and operational flexibility. However, it is essential to address the challenges and implications, like back pressure and throttling, and recognise the importance of symmetry in such setups.

4.6.1.1. Implications and Challenges of Parallel Connection:

a) **Increased Capacity:** Parallel compressors provide higher output, which is beneficial for elevated airflow or pressure requirements.
b) **Redundancy and Reliability:** This setup ensures continued operation if one compressor fails, reducing downtime.
c) **Load Distribution:** Distributes workload, reducing strain on individual compressors.
d) **Operational Flexibility:** Allows alternating or simultaneous operation based on demand.

4.6.1.2. Preventing Back Pressure and Throttling:

a) **Sizing and Matching:** Ensuring that compressors are compatible in capacity and performance is crucial for the balanced operation and preventing back pressure.
b) **Pressure Regulation:** A robust pressure regulation system with relief valves, sensors, and regulators is necessary to maintain desired pressure and prevent spikes.
c) **Piping and Configuration:** Design the piping system to minimise pressure losses and throttling, using suitable pipes, fittings, and valves.
d) **Control and Monitoring:** Implement a system for coordinated operation and monitoring to ensure balanced operation and prevent back pressure or throttling.

4.6.1.3. Importance of Symmetry:

a) **Balanced Operation:** Symmetrical compressors ensure efficient operation and equal workload distribution.
b) **Maintenance and Serviceability:** Similar maintenance requirements simplify scheduling and reduce downtime.
c) **Performance Consistency:** Symmetry in compressors leads to consistent performance and reliable output.
d) **Compatibility and Interchangeability:** Ensures ease of maintenance and component interchangeability.

In conclusion, when connecting piston pump oilless compressors in parallel, it is imperative to consider their implications and challenges. Ensuring symmetry in compressor specifications, operation, and maintenance, along with appropriate sizing, pressure regulation, and system control, is vital for a balanced and efficient compressor system.

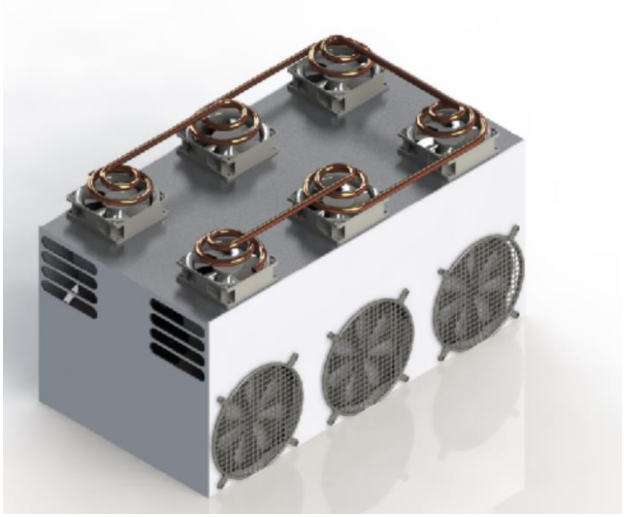


Figure 4-8: CAD-rendered drawing of the Compressors in Parallel

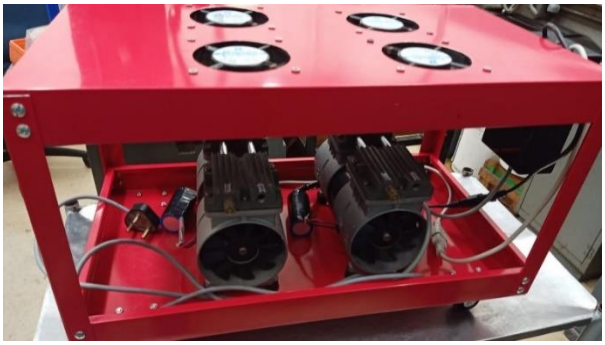


Figure 4-4-7: Constructed Compressor Unit#1

4.7. Experimental Methodology

4.7.1. Introduction

The experiment aimed to gather empirical data regarding the performance of an oxygen concentrator under diverse environmental conditions. Several instruments were employed to achieve this, including a venturi meter, an analogue pressure regulator, and a VAT (Variable Area Flow Meter). These devices measured and monitored flow rates, temperatures, humidity, pressure, and oxygen concentration.

The experiment was conducted within a controlled laboratory setting to ensure the accuracy and consistency of the results. By simulating different environmental conditions, the researchers aimed to evaluate how the oxygen concentrator functioned and performed under varying circumstances. This information would be valuable for assessing its reliability, efficiency, and effectiveness in real-world scenarios.

Throughout the experiment, the researchers systematically altered the flow rates of oxygen passing through the concentrator, mimicking scenarios where oxygen demand might fluctuate. They also manipulated temperature and humidity levels, influencing the device's performance. Additionally, variations in pressure were introduced to evaluate the concentrator's response and stability under different conditions.

To measure the oxygen concentration accurately, the researchers employed a VAT, which visually indicates the gas flow through a tapered tube and a floating ball. They could determine the oxygen concentration at different flow rates and environmental conditions by analysing the ball's movement.

During the experiment, meticulous records were kept to document the results of each test. The researchers noted the values obtained from the venturi meter, pressure regulator, and VAT and any observations or deviations from expected outcomes. These recorded measurements and observations would serve as the foundation for further analysis and interpretation of the data.

In conclusion, the experiment aimed to obtain experimental data on the performance of an oxygen concentrator using a combination of instruments such as the venturi meter, analogue pressure regulator, and VAT. The study encompassed diverse environmental conditions, including different flow rates, temperatures, humidity levels, pressures, and oxygen concentrations. The controlled laboratory setting ensured accurate and consistent results, and the recorded data provided insights into the behaviour and functionality of the oxygen concentrator under various scenarios.

4.7.2. Experimental Procedure

An experiment was conducted on an Oxygen concentrator to measure its performance and output. The oxygen concentrator was equipped with pressure gauges and a VAT oxygen analyser to monitor and record the machine's output accurately.

The experiment began by measuring the input air pressure and flow rates of the Oxygen concentrator. This initial measurement served as a baseline for comparison against the output flow rate. The output flow rate was obtained using the Oxygen concentrator's generated air as feed air for the measurements.

To thoroughly assess the performance of the Oxygen concentrator under diverse conditions, various pressure inputs were systematically varied and recorded. This method allowed for a comprehensive analysis of the machine's output flow rates across various pressure levels. The relationship between pressure and flow rate could be established by measuring the pressure at different intervals and recording the corresponding output flow rates.

The experiment also considered the influence of ambient temperature on the performance of the Oxygen concentrator. The laboratory temperature was conditioned using an air conditioner to maintain consistent and controlled conditions. By regulating the temperature, the researchers aimed to minimise the impact of external factors and ensure accurate and reliable data collection.

Throughout the experiment, the room conditions were diligently monitored and recorded. These records encompassed various parameters such as temperature, humidity, and any other relevant factors that could potentially affect the performance of the Oxygen concentrator. The room conditions were noted at regular intervals, typically ranging from $2\ to\ 5$ minutes, depending on the duration of the tests.

By conducting this experiment and meticulously recording the input air pressure, output flow rates, and room conditions, the researchers aimed to understand the Oxygen concentrator's performance comprehensively. The data collected would enable them to analyse the efficiency and reliability of the Oxygen concentrator under different pressure inputs and environmental conditions.

4.7.3. Experimental Scope and Work

The focus of this study was to thoroughly assess the performance of an oxygen concentrator across various scenarios. Critical parameters such as pressure, temperature, humidity, flow rate, concentration, and power consumption were selected for their pronounced impact on the system's

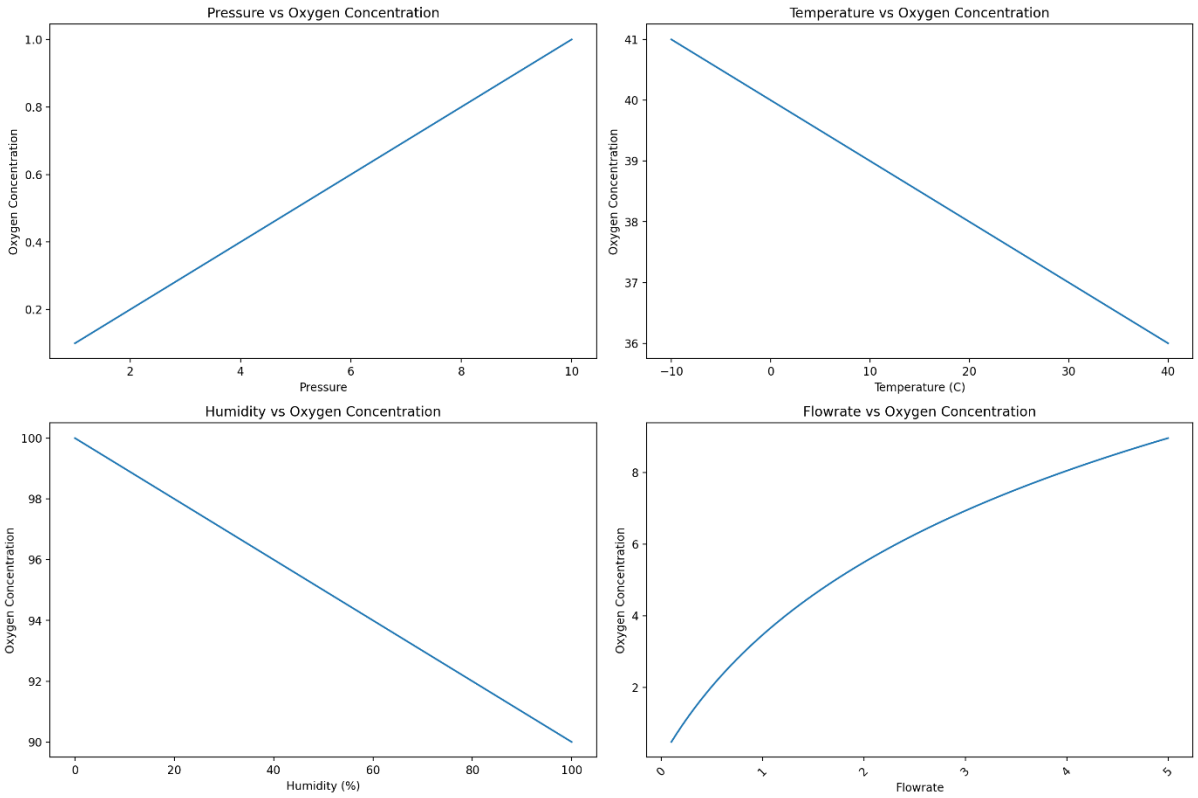
efficiency and reliability. These factors are indispensable in evaluating how the concentrator operates under differing conditions. Pressure, in particular, was a primary focus due to its direct influence on oxygen delivery efficiency. Studies have indicated that the efficiency of oxygen concentrator delivery is significantly affected by the driving pressure required to ensure predictable flow (de Wolf, 2016). In this context, the study involved subjecting the concentrator to varying pressure levels to examine its ability to maintain consistent performance across these variations.

Temperature and humidity were also critical areas of investigation, considering the diverse climatic conditions in which oxygen concentrators are employed. The performance of these devices is known to be affected by changes in temperature and humidity, with some models showing decreased oxygen concentrations at higher temperatures and humidity levels (Peel, 2013). This part of the study aimed to discern any operational constraints and establish optimal conditions for the concentrator's operation across a spectrum of temperature and humidity settings. It is essential to include a visual aid, such as a graph, to depict the relationship between temperature, humidity, and oxygen concentration, providing a clear visual representation of these parameter interactions.

Additionally, the experiment delved into flow rate, concentration, and power. The flow rate was measured to ascertain the volume of oxygen delivered per time unit, and concentration was evaluated to determine the purity of the produced oxygen. Analysing power consumption was crucial to gauge the overall efficiency of the concentrator in different scenarios. This multifaceted approach ensured a comprehensive understanding of the concentrator's performance dynamics. The study meticulously recorded variations in these parameters and compared them against the expected system output, which indicates the performance based on the device's specifications and intended use. Such a comparison was critical in evaluating the oxygen concentrator's reliability, accuracy, and consistency.

In conclusion, this extensive analysis yielded significant insights into the operational capabilities of the oxygen concentrator under varied conditions. These findings are vital for manufacturers, as they highlight potential areas for improvement and inform the optimisation of the concentrator's design to better cater to the needs of individuals reliant on supplemental oxygen. The study's approach, incorporating theoretical and practical assessments, offers a robust framework for future research and development in this field. It is advisable to include another visual aid here, illustrating how flow rate, concentration, and power consumption interplay, enhancing the understanding of their collective impact on the concentrator's performance.

Graph 4-2: Theoretical Parameter Relationship



Graphs 4-2 above represent theoretical relationships between various parameters of an oxygen concentrator. Here is a simplified explanation of each graph:

Pressure vs. Concentration

This graph suggests that oxygen concentration may also change as the pressure increases. Oxygen concentration can increase as pressure increases due to the gas laws (Henry's Law for solubility and Dalton's Law for partial pressures).

Temperature vs. Concentration

The temperature's effect on oxygen concentration is depicted here. As temperature increases, the solubility of oxygen decreases, so the concentration of oxygen would typically decrease.

Humidity vs. Concentration

This plot shows the potential impact of humidity on oxygen concentration. Higher humidity means more water vapour in the air, which can displace some oxygen, potentially decreasing its concentration.

Flowrate vs Concentration

The final graph illustrates how the oxygen flow rate might correlate with its concentration. A higher flow rate can lead to increased oxygen concentration up to a certain point, after which it may remain constant due to saturation.

4.7.4. Experimentation Theory and Requirements

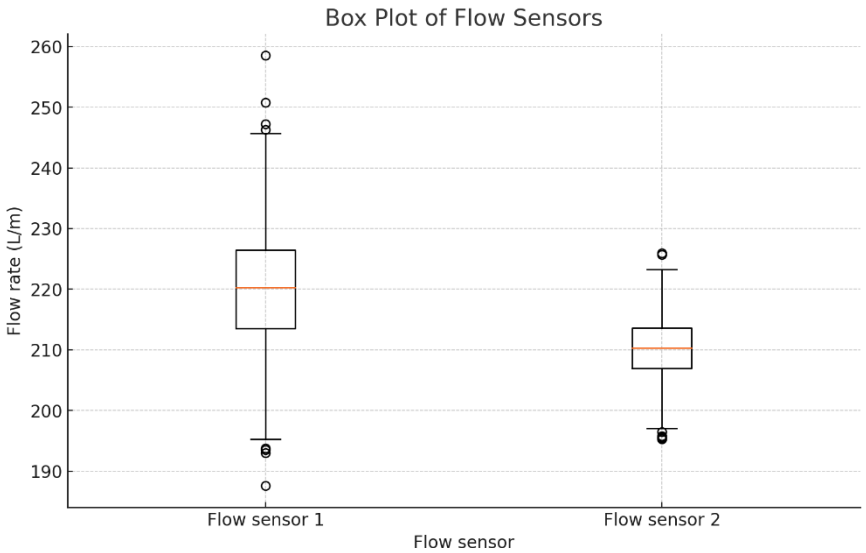
A venturi meter, a metering device, measures fluid flow in the pipe and may increase the velocity of any fluid in a tube at any point. Bernoulli's theorem is the foundation for how the venturi meter functions (Makina, 2018). The flow speed will increase when a fluid's pressure drops while passing through a narrow passage. At a particular location, the high-pressure, low-velocity fluid is transformed into low-pressure, high-velocity fluid and then back to high-pressure, low-velocity fluid. Venturi flow metres are employed at the transition point between low pressure and high velocity. This experiment recorded data on the following factors.

4.7.4.1 Pressure

The measurement and calculation of the output pressure of the compressors and its critical role in the separation system involves using an analogue pressure regulator. This device is employed to control and regulate the pressure of a fluid or gas, thereby determining the output pressure of the compressors.

The compressors' measured output pressure is the separation system's feed pressure. However, it is essential to account for the pressure losses due to various factors, such as the heat exchanger, pipes, and connectors. These losses can affect the overall pressure available for the separation process.

Graph 4-3: Box Plot of Flow Sensor 1 and Flow Sensor 2



The statistical analysis of the Flow Sensor 1 and Flow Sensor 2 data provides the following insights:
Flow sensor 1: *- Mean:* ***223.59 L/m*** *- Median:* ***223.60 L/m*** *- Standard Deviation:* ***7.91 L/m***
- Variance: ***62.54 (L/m)²*** *- Min:* ***64.20 L/m*** *- Max:* ***248.50 L/m***
Flow sensor 2: *- Mean:* ***212.51 L/m*** *- Median:* ***212.77 L/m*** *- Standard Deviation:* ***3.07 L/m***
- Variance: ***9.43 (L/m)²*** *- Min:* ***187.80 L/m*** *- Max:* ***219.69 L/m***
The overlayed histogram (Graph 4-3) shows the distribution of readings for both sensors in the same graph, allowing for a direct comparison of their distributions. ***Flow sensor*** *1 has a wider spread of readings, as indicated by a higher standard deviation and variance, compared to* ***Flow sensor 2.***

The boxplot provides another way to visualise the spread and central tendency of the data, highlighting the median, quartiles, and potential outliers. It is a valuable visualisation for comparing the range and distribution of data between the two sensors.

Pressure gauges are installed on each sieve bed of the separation system to verify the pressure losses. These gauges provide a means to monitor and read the pressure at different stages of the separation process. By comparing the pressure readings on each sieve bed with the feed pressure from the compressors, it is possible to assess the pressure losses incurred during the system's operation.

The pressure losses due to the heat exchanger, pipe, and connector losses are essential to consider because they directly impact the efficiency and effectiveness of the separation system. If these losses are significant, they can reduce the overall pressure available for the separation process, potentially affecting the system's performance and output.

Accurate measurement and accounting of pressure losses are essential for operators and engineers to optimise the operation of a separation system. This precise understanding of pressure dynamics allows for informed decisions and adjustments, ensuring the system operates at optimal pressure levels. Such fine-tuning is crucial for maximising the efficiency and productivity of the system. It enables the system to perform effectively, reduces the risk of operational inefficiencies, and ensures that the separation process is as effective and economical as possible. This approach improves the system's overall performance and contributes to better resource management and operational sustainability. Additionally, monitoring the pressure gauges on each sieve bed provides valuable feedback on the performance of individual components within the separation system and enables timely maintenance or troubleshooting if necessary.

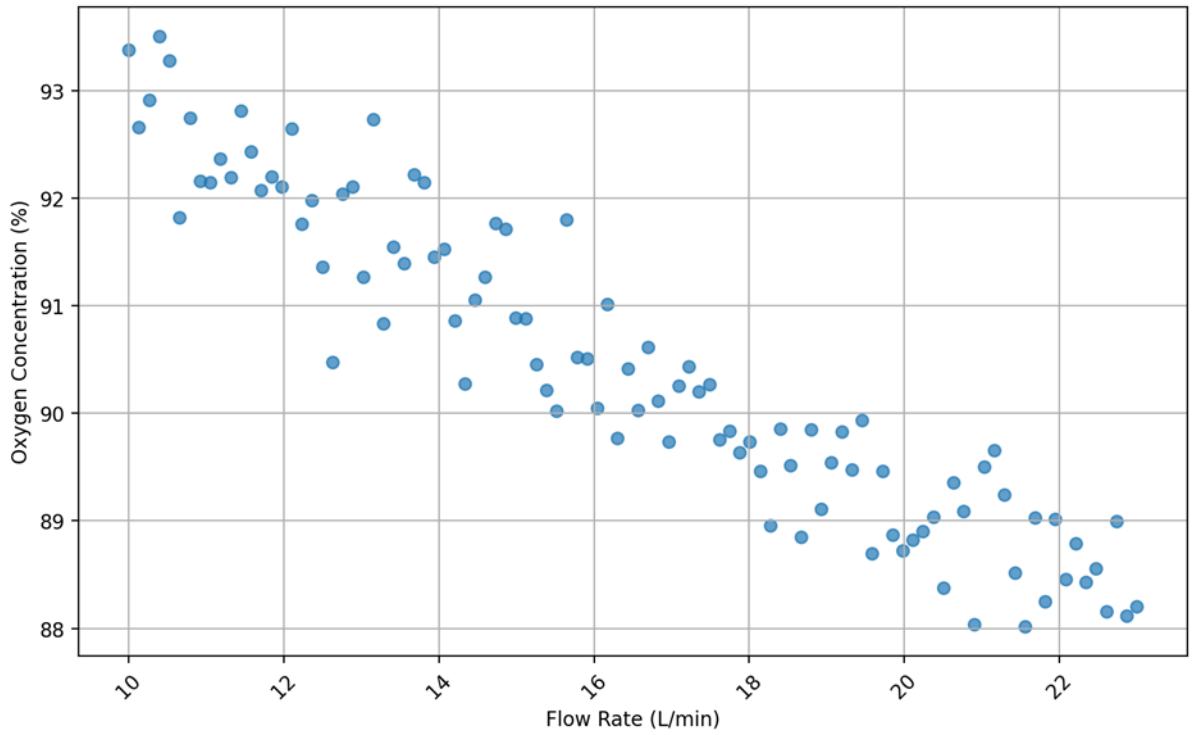
In summary, measuring the compressors' output pressure, considering pressure losses, and using pressure gauges on sieve beds all play crucial roles in maintaining the proper functioning and efficiency of the separation system. By carefully monitoring and managing these pressures, operators can ensure optimal performance and reliable operation of the system.

4.7.4.2 Flow

Optimising the air and oxygen flow rate in an oxygen concentrator involves critical considerations for its components, including air compressors, separation chambers, pipes, connectors, buffer tanks, and solenoid valves. The goal is to maintain efficient functioning and provide concentrated oxygen effectively.

The system uses pressure swing adsorption (PSA) in the separation chambers, necessitating precise airflow control for effective oxygen separation. The oxygen flow rate is critical; it must be adjusted to meet the specific needs of patients, which vary based on their condition and oxygen therapy requirements.

Graph 4-4: Flow rate vs Oxygen Concentrator Scatter Diagram



*The scatter plot (graph 4-4) above illustrates a negative correlation between the flow rate and oxygen concentration in an oxygen concentrator, incorporating a time delay effect. As the flow rate increases from **10 to 23 litres per minute,** the oxygen concentration declines from **93%** to 88%. The data suggests a time-dependent stabilisation of oxygen concentration, which is more pronounced at lower flow rates. This stabilisation effect is modelled as a lag, where the concentration reaches a steady state beyond a flow rate of **15 litres per minute**. The variability in oxygen concentration is relatively contained, as indicated by the tight clustering of data points around the trend line, with random fluctuations modelled by a normal distribution with a standard deviation of **0.5.***

The system's components, such as pipes and connectors, should be sized and designed to manage the flow rates without causing significant pressure drops. Medical-grade materials are preferred to prevent contamination. Buffer tanks play a crucial role in stabilising oxygen supply, compensating for demand fluctuations and maintaining consistent flow rate and pressure. These tanks should be sized to meet anticipated oxygen requirements.

Solenoid valves are vital for controlling air and oxygen flow. These electronically controlled valves enable precise regulation of flow rates. The valves should be chosen based on system requirements, including desired flow rates and pressure levels.

Experimentation is vital to validate and optimise flow rates in the system. This involves measuring and adjusting flow rates at various points, such as the air compressor, separation chambers, pipes, connectors, and solenoid valves, to identify and rectify potential inefficiencies. Safety is paramount during experimentation, with measures to prevent leaks, contamination, or flow hazards. Regular inspections and maintenance, along with adherence to regulations and standards, ensure reliable and safe system operation.

In summary, the flow rate of air and oxygen in an oxygen concentrator is critical for the efficient and effective delivery of concentrated oxygen to patients, requiring careful consideration of system components, their compatibility, and desired flow rates.

4.7.4.3 Cyclic Time

In the Pressure Swing Adsorption (PSA) process, the cyclic time is critical to optimising system performance. The PSA cycle comprises several steps, each with a specific duration and valve operation, crucial for efficient gas separation. Table 4-1 outlines a six-step cycle, with each step having a designated duration, summing up to a total of 15 seconds. This table shows the preferred valve operation sequence (on or off) for valves V1 to V8, ensuring effective air flow and oxygen separation. The timing for each stage—PressureZA, Purge, Balance, PressureZB—is vital for optimal pressure and maximum adsorption efficiency. Alternative configurations, which yielded less effective results, are detailed in APPENDIX A.

Valve Operation Table:

Table 4-1: Valve Timing Table

Valve	PressureZA (3s)	Purge (2s)	Balance (1s)	PressureZB (3s)	Purge (2s)	Balance (1s)
V1	OFF	ON	OFF	OFF	OFF	OFF
V2	ON	OFF	OFF	OFF	ON	ON
V3	OFF	OFF	OFF	OFF	ON	OFF
V4	OFF	ON	ON	ON	OFF	OFF
V5	OFF	OFF	OFF	OFF	ON	ON
V6	ON	OFF	OFF	OFF	ON	ON
V7	OFF	ON	ON	ON	OFF	OFF
V8	OFF	ON	ON	OFF	OFF	OFF

This preferred valve sequence was determined after extensive trials and is crucial for effective air flow and oxygen separation. In contrast, other tested configurations caused issues like rapid pressure fluctuations or inefficient gas separation due to simultaneous valve operations or imbalanced adsorption and desorption phases. The flow diagram, though not included here, visually represents the PSA process and complements the valve operation table by illustrating the air flow and the interaction of components like adsorption towers with the valve operations. Together, the table and flow diagram (Figure 4-9) offer a comprehensive understanding of the PSA system, which is crucial for informed operational decisions and system optimisation.

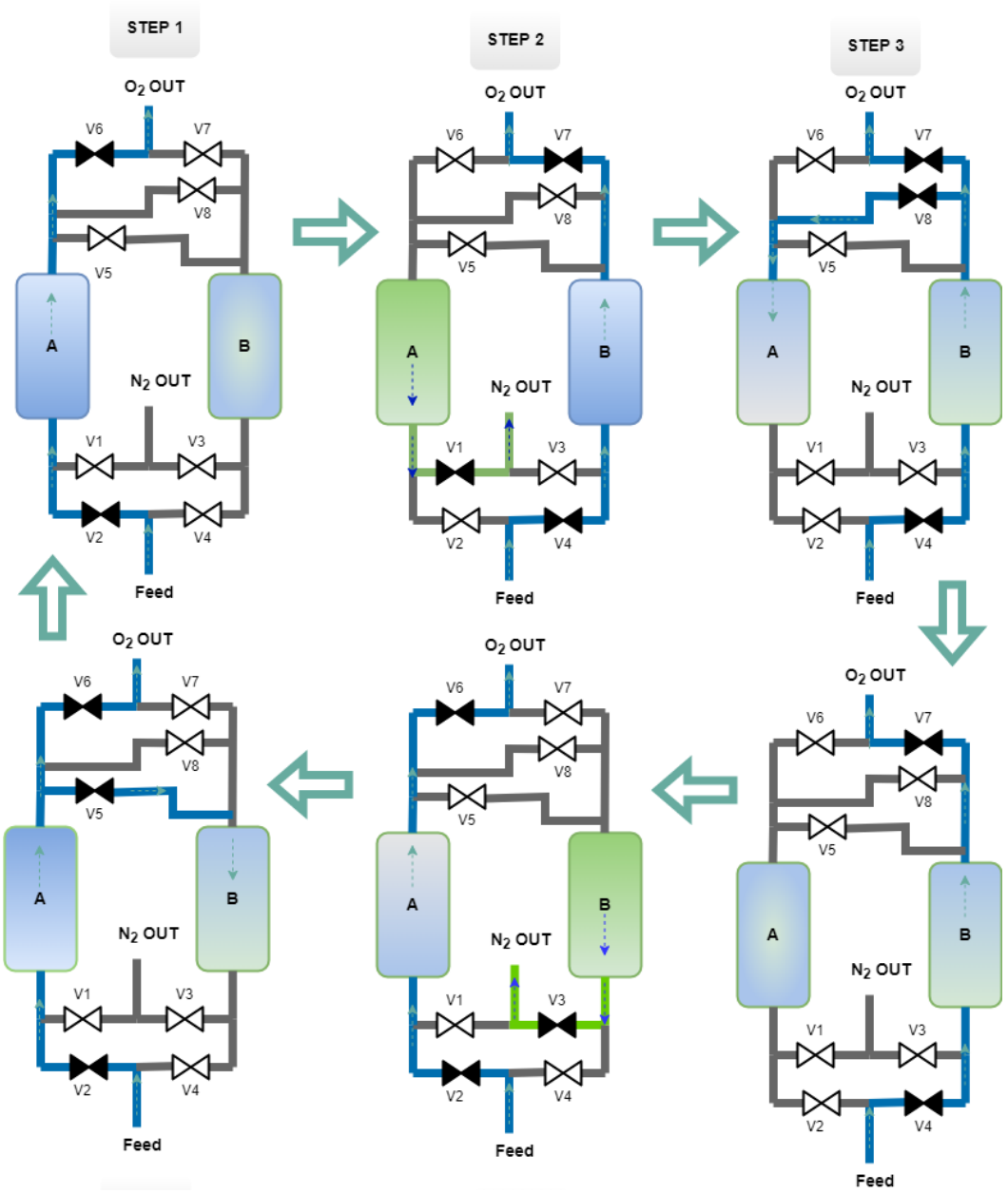


Figure 4-9: Valve Cyclic process Flow Representation

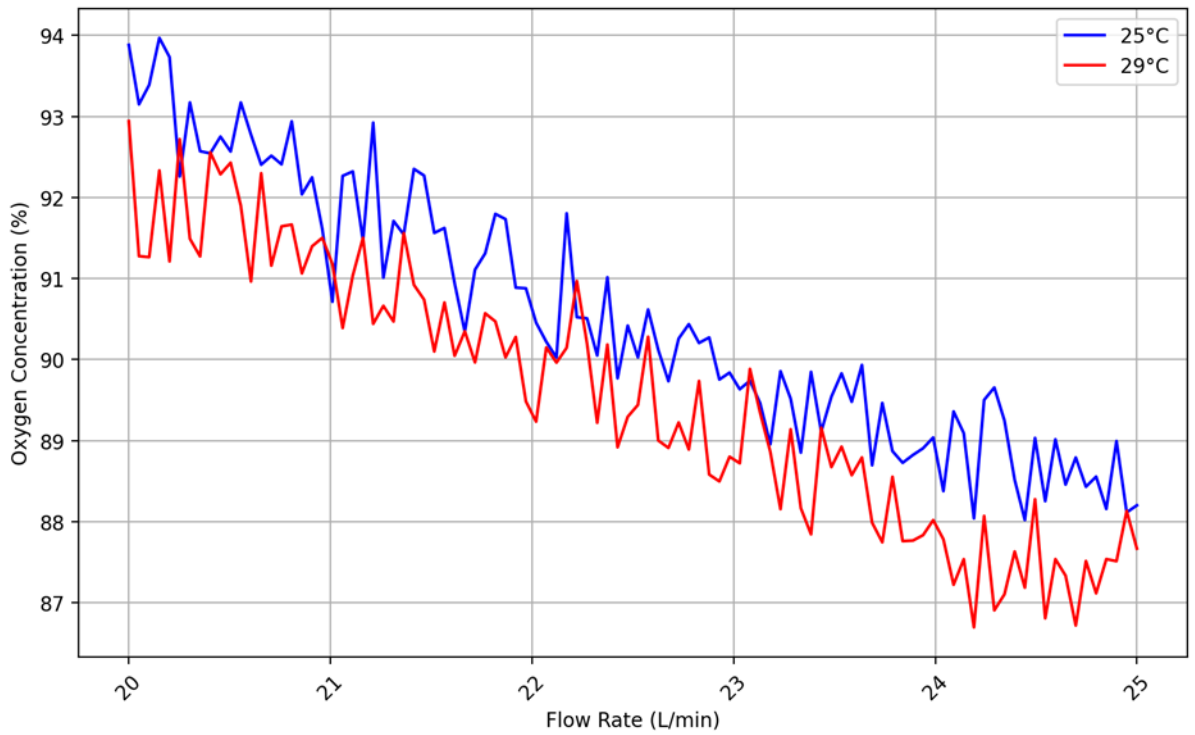
4.7.4.4 Concentration

The methodology for measuring and verifying oxygen concentration involved using a Variable Area Flowmeter (VAT) and a Calibrated Oxygen Analyser, further augmented by a Cubic Oxygen Analyser

linked to a Gas board 8500FS-X200, which was connected to an LCD. The VAT, widely recognised as a rotameter, was utilised to determine the flow rate of the oxygen that was produced. The Calibrated Oxygen Analyser ensured the precision of the oxygen concentration measurements within the environment. An Arduino Code, available on request from the data management file, was critical in facilitating the communication between the device and the Cubic Oxygen Analyser, enabling the retrieval and presentation of oxygen concentration data on the LCD screen.

The testing protocol entailed meticulous monitoring of the oxygen concentration until it achieved the targeted level of 85%, an essential threshold for various medical and industrial applications. In parallel, the flow rate at this specified oxygen concentration was precisely recorded. This flow rate typically quantified in litres per minute (LPM), is vital for assessing the oxygen delivery capability and the overall efficiency of the system. The successful realisation of an 85% oxygen concentration, coupled with the recording of the related flow rate, underpinned by the Gas board 8500FS-X200 and other specialised equipment, offers an in-depth insight into the efficacy of the oxygen production system (See Graph 4-5 below.)

Graph 4-5: Flow Rate Vs Concentration at Different Temperatures



4.7.4.5 Temperature and Humidity

In the development and testing of oxygen concentrators, temperature and humidity are pivotal. These devices, crucial for providing supplemental oxygen to those with respiratory issues, must operate effectively within specific environmental ranges. Temperature impacts the concentrator's functionality and precision, with optimal performance typically achieved between 5°C and 40°C. Deviations from this range can lead to condensation or overheating, affecting efficiency and safety. Similarly, humidity, or air moisture levels, significantly influence the device's operation. Oxygen concentrators are designed to function within a humidity range of 10% to 95%. Exceeding these limits can cause internal moisture build-up or reduced oxygen output. Rigorous testing under various

temperature and humidity conditions is essential to ensure the device's reliability and adherence to regulatory standards. Controlled environmental chambers are often used for these tests, allowing for precise condition adjustments and reliable performance assessment. This careful evaluation helps establish the concentrator's efficacy in different settings, contributing to its overall safety and efficiency.

4.8. Integration of subsystems

The integration of subsystems in the oxygen concentrator involved assembling various components in a lab, like a compressor unit, air-cooled heat exchangers, sieve beds, pneumatic controllers, oxygen tanks, and frames, to produce a physical device. This assembly was tested for mechanical and electrical integrity, including safety measures like proper earthing. The noise output of the integrated subsystem was confirmed to be below 70 dB (Gloeckl et al., 2019).

4.8.1 Integration, testing the assembly unit.

Integration testing followed the assembly, ensuring that all modules worked correctly together. This phase involved a black-box testing approach, as described by Bonifácio et al.(2018), focusing on the interdependency of modules and the integrity of their connections. After unit testing, individual modules like heat exchangers and compressors were combined and tested to meet all specifications (Collina, 2018.).

The prototype, created after successful integration and testing, was evaluated in the lab. The performance under various conditions was recorded to ensure alignment with design parameters, setting the stage for further analysis and reporting in subsequent research (Vestad, 2019).

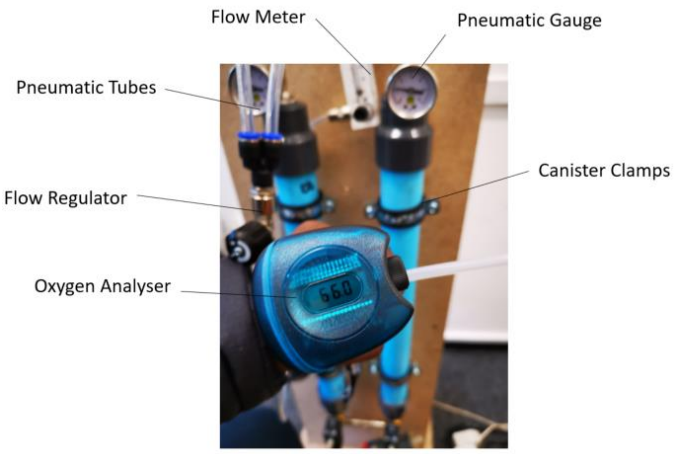


Figure 4-10: Prototype #2 Testing

CHAPTER 5

5. Data Analysis and Trial Results

5.1. Introduction

In the experimental section of the research, we conducted comprehensive tests to evaluate the performance of an oxygen concentrator prototype under varied conditions. The primary objective was to assess how different factors—pressure, cycle times, temperature, humidity, and flow rates—affect its functionality. The experiments were carried out in a laboratory setting, using two types of compressors (local and homemade) and varying the use of valves for comparative analysis.

The research had three goals/ Objectives:

1. Develop a molecular sieve-based oxygen concentrator delivering over 20 Lpm of oxygen-enriched gas. The design included:
   a) A compression module with thermoregulation and moisture control, improving the efficiency of Zeolite adsorbent under high temperature and humidity (Fenton, 2013).
   b) An air separation system with different adsorbent/sieve bed sizes optimised for medical-grade requirements (Pan, 2017).
   c) A robust oxygen tank and an efficient gas delivery system, adhering to safety standards and the latest trends in concentrator technology (Harris,1987b).
   d) An electronic control unit for operational management.
2. Assemble the designed subsystems to create a reliable and patient-compliant oxygen concentrator prototype (Howard, 1983)
3. Conduct extensive testing to evaluate the Multi-user Medical Grade Oxygen Concentrator's efficiency and performance, in line with ISO 80601-2-69 standards and WHO Technical specifications (WHO, 2015b)

Throughout the experimentation, we gathered data on oxygen concentration, flow rates, energy usage, and system stability. Using various laboratory instruments, we ensured accurate and reliable data collection. The results from these experiments are vital for assessing the prototype's effectiveness and guiding future enhancements.

5.2. Results

5.2.1. Objective 1: Design an oxygen concentrator that uses molecular sieves to produce oxygen-rich gas at flow rates greater than $\mathbf{20}\ \boldsymbol{Lpm}$

5.2.1.1 Results

Results:

The study focused on assessing an oxygen analyser in a lab, examining oxygen concentration, flow rate, and temperature in gas samples.

Table 5-1: Table of Statistics

Statistical Measure	Oxygen Concentration (%)	Flow Rate (LPM)
Mean (Average)	92.324	17.50
Standard Deviation	1.727	4.352
Range	7.097	15.00
Pearson Correlation Coefficient	- (applies to both)	-0.684
P-value	-0.684	6.51×10^{-29}

Interpretation of Statistical Analysis: Flow Rate vs. Oxygen Concentration

1. Flow Rate:

The statistical analysis in Table 5-1 of Flow Rate versus Oxygen Concentration reveals several key findings:

a) **Flow Rate:**
   - **Mean (Average):** 17.50 LPM. The average flow rate across the dataset is 17.50 litres per minute.
   - **Standard Deviation:** 4.352 LPM. This indicates a moderate variation, with most flow rate readings approximately 4.35 LPM around the average.
   - **Range:** 10 to 25 LPM. The flow rates observed range from 10 LPM to a maximum of 25 LPM.

b) **Oxygen Concentration (Dependent on Flow Rate):**
   - **Mean (Average):** 92.324%. This figure represents the average oxygen concentration across various flow rates.
   - **Standard Deviation:** 1.727%. This moderate deviation suggests fluctuating oxygen concentrations around the average value.
   - **Range:** 87.1% to 93.1%. The oxygen concentration varies considerably, demonstrating its sensitivity to different flow rates.

c) **Correlation Analysis:**
   - **Pearson Correlation Coefficient: -0.684**. This moderate negative correlation indicates that as the flow rate increases, the oxygen concentration tends to decrease, and vice versa. However, this relationship is not extremely strong.

In conclusion, the analysis indicates a significant negative correlation between Flow Rate and Oxygen Concentration, implying that higher flow rates usually correlate with lower oxygen concentrations.

Detailed Molecular Sieves and Design Goals

d) **Structure and Function:** Comprised of aluminium canisters with sealed caps, designed to separate oxygen and nitrogen using zeolite canisters at a specific pressure.

e) **Valve Configuration:** Integrated eight specialised solenoid valves, each serving different functions and controlled by a custom circuit.

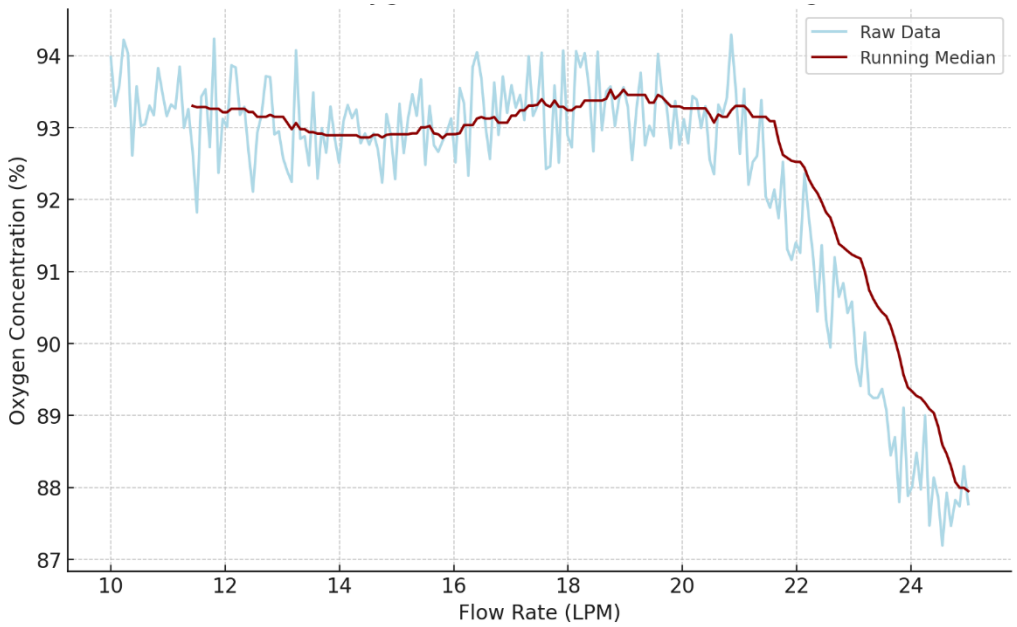
f) **Performance Results:** Confirmed stable flow rates over $20\ LPM$ and oxygen concentration variability between 81% and 93% during tests.

Table 5-2: Running Median Table for both Oxygen Concentration and Flow Rate, sampled at every 20th reading from the dataset:

Reading Number	Running Median Oxygen Concentration (%)	Running Median Flow Rate (LPM)
1	NaN	NaN
21	93.283	10.79
41	93.150	12.30
61	92.863	13.81
81	92.910	15.31
101	93.393	16.82
121	93.454	18.33
141	93.071	19.84
161	92.524	21.34
181	90.378	22.85

Table 5-2 provides comprehensive data on oxygen analyser readings, flow rates, and temperatures, reinforcing the oxygen concentrator's consistent efficacy and reliability.

Graph 5-1: Flow Rate Vs Oxygen Concentration with Running Median



5.2.1.2 Discussion and Implications

The study's results in Graph 5-1 have significant implications for oxygen concentrator performance, particularly in medical contexts:

1. **Importance of High Oxygen Concentration:** The concentrator's ability to maintain high oxygen purity across diverse flow rates, catering to the varying oxygen needs of different patients, is crucial.
2. **Negative Correlation between Flow Rate and Oxygen Concentration:** This key finding highlights an inherent challenge in concentrator design – maintaining oxygen purity at higher flow rates. Understanding this inverse relationship is critical for improving concentrators to provide high-purity oxygen, even at increased flow rates. This is particularly vital for high-flow oxygen therapy in clinical settings.

3. **Need for Precise Control Mechanisms:** The observed moderate variability in oxygen concentration necessitates precise control within the concentrator to ensure consistent oxygen delivery. This is essential for patient safety and the effectiveness of treatment.

In conclusion, these insights emphasise the need to design oxygen concentrators that are not only efficient in oxygen separation but also versatile and reliable under various operational conditions. The study lays a foundation for future research and development to enhance oxygen concentrator performance, especially in medical-grade applications where reliability and precision are crucial.

5.2.2. Objective 1a: Design a compression unit with cooling and drying capabilities to prevent a known decreased performance of Zeolite adsorbent associated with increased heat and humidity

5.2.2.1 Results

During the assessment of the compressors, the separation cylinders experienced an issue of moisture infiltration, leading to the coagulation of zeolite. This was particularly problematic due to the moisture-sensitive nature of zeolite, which is vital for oxygen separation. To address this, the cylinders were dismantled, and the initial zeolite was substituted with LiX Zeolite along with an aluminium-activated variant. This replacement aimed to eliminate any remaining moisture, as illustrated in Figure 5.1, depicting the Molecular Dryer.

Figure 5-1: Molecular Dryer

Two distinct compressor setups were evaluated for their effectiveness: a custom-designed dual compressor system and a single, larger compressor obtained from a commercial source. The bespoke dual compressor system, shown in Figure 5.2 (Dual Compressor Assembly), exhibited high-pressure capabilities. However, it fell short of maintaining consistent flow rates, primarily due to issues with back pressure and other pressure-related complexities. In contrast, the single compressor system outperformed in efficiency but required additional mechanical water traps to manage condensation effectively.

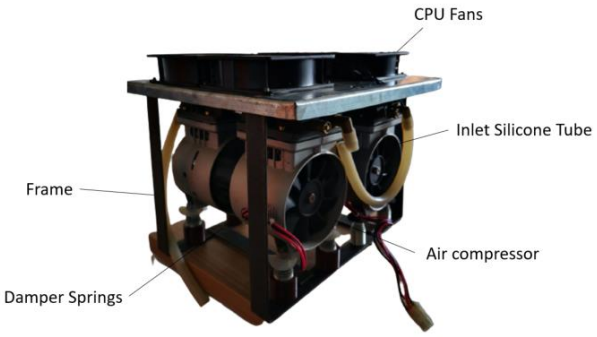


Figure 5-2: Dual Compressor Assembly

Furthermore, an air-cooled heat exchanger (ACHE) was integrated into the system, specifically designed to handle high-flow and high-heat input air. This component, detailed in Figure 5.3 (ACHE FINS), effectively controlled the feed air temperature, keeping it below 29℃ while ensuring minimal pressure loss (less than 0.2 bar). This enhancement notably boosted the performance of the zeolite adsorbent, underscoring the importance of temperature control in the compressor systems.

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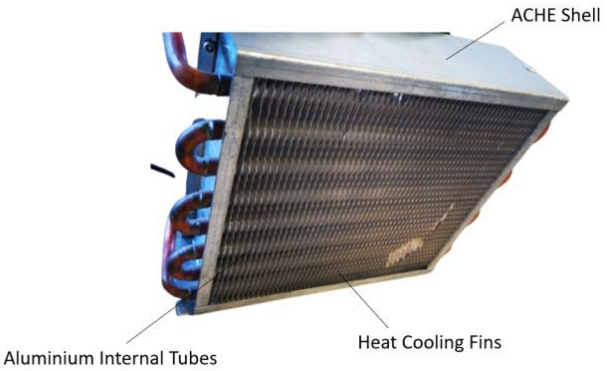


Figure 5-3: ACHE FINS

5.2.2.2 ***Discussion and Implications***

Our findings suggest that a single, large compressor with a tank is preferable to multiple smaller, interconnected compressors for this application. The smaller units encountered back pressure issues, leading to decreased performance and a lower oxygen-rich output. In contrast, the larger compressor consistently delivered adequate feed flow and effectively managed process pressure, thereby reducing condensation problems.

Nevertheless, the larger compressor configuration faced condensation challenges, which were addressed by incorporating an ACHE and mechanical water traps, which maintained the system's dryness and functionality.

In conclusion, a single, extensive compressor system, particularly with zeolite adsorbents in molecular sieve beds, is recommended due to its effective flow management, manageable condensation, and enhanced overall performance. However, the implementation of additional cooling and moisture control, such as the ACHE, is essential for optimal operation.

5.2.2. Objective 1b: Design the air separation system featuring various sizes of adsorbent/sieve beds, optimising operational parameters to meet medical-grade requirements

Results

The study on air separation system design under Objective 1b showed oxygen concentrations ranging from 85% to 93.8%, as indicated by oxygen analyser readings. These values reflect the system's effectiveness, especially considering different adsorbent/sieve bed sizes for achieving medical-grade oxygen.

Analysis

The core analysis centres on zeolite's role in the sieve beds, known for its molecular sieving quality, primarily separating nitrogen while oxygen passes through. The variation in oxygen purity is attributed to the zeolite's packing efficiency within the sieve beds, influenced by zeolite particle size uniformity, packing density, and geometric arrangement of the beds. These factors directly affect nitrogen adsorption and, consequently, oxygen purity.

Discussions

The research underscores the need to optimise the design of zeolite-packed sieve beds. Future research should explore varying zeolite types, particle sizes, and bed geometries to improve air separation efficiency and ensure consistent medical-grade oxygen output. The study also highlights the critical balance between sieve beds' physical properties and operational parameters, like pressure and flow rate, vital for the system's efficacy in medical settings where consistent oxygen purity is crucial. Further insights are provided in **Objective 2**.

5.2.3. Objective 1c: Design an oxygen tank and gas delivery system

5.2.3.1 Results

The oxygen tank and delivery system were meticulously designed, incorporating two oxygen reservoirs of 1.26 and 2.93 litres, connected in series without return valves. This ensured uniform pressure build-up, maintaining a maximum system pressure of 3 bar and preventing pressure imbalances for effective operation.

A critical oxygen analyser was placed between the larger reservoir and the pressure regulator, monitoring oxygen concentration for therapeutic suitability. The pressure regulator, set at one bar, maintained manageable system pressure, ensuring steady oxygen delivery and preventing overpressure scenarios.

Post-regulator, a High-Efficiency Particulate Air (HEPA) filter, purifies the oxygen to medical-grade standards, removing contaminants like bacteria and dust. A volume control valve and a Festo Thorpe flow meter, rated at 75 lpm and connected to a Volume Air Temperature (VAT) meter via a 6mm tube, monitored flow rate and output air temperature. This was crucial for maintaining consistent oxygen density and flow rate, underscoring the design's commitment to safety and precision in medical-grade oxygen delivery.

*5.2.3.2. **Discussion and Implications***

The dual-tank design, with tanks in series, allowed a stable 3 bar pressure, showing the potential of multi-tank configurations in therapeutic oxygen systems. The inclusion of a pressure regulator and oxygen analyser ensured real-time monitoring and safety, preventing overpressure and aligning with therapeutic requirements.

The HEPA filter's role in purifying oxygen highlighted the need for such filtration in medical-grade delivery. The volume control mechanism, combined with the flow and temperature monitoring system, demonstrated adaptability and precision in oxygen delivery.

This comprehensive understanding of system components is crucial for optimal performance, setting a foundation for future advancements in medical oxygen delivery systems enhancing safety and therapeutic effectiveness.

5.2.4. Objective 2: Integration of designed subsystems to build the oxygen concentrator prototype

5.2.4.1 Results

The primary challenge in developing oxygen concentrator prototypes using local materials and the DIY OXIKIT was sourcing suitable components that complied with medical standards. It was crucial to identify locally available materials, such as molecular sieves for air separation, and adapt the OXIKIT guidelines accordingly. This often required creative re-engineering to ensure practicality and efficiency.

Each prototype incorporated diverse research findings, posing unique design and engineering challenges. The primary task was to create a compact, efficient, and robust system with non-standard components, ensuring seamless integration and operational integrity under various conditions.

Adhering to medical and safety standards was paramount, necessitating rigorous testing for reliability, oxygen purity, flow rate, and safety, particularly in accordance with the IEC 60601-1 standard. Additionally, the prototypes needed to be user-friendly, given their potential use in settings with limited technical support. This entailed designing the concentrators for ease of operation and maintenance by non-technical users.

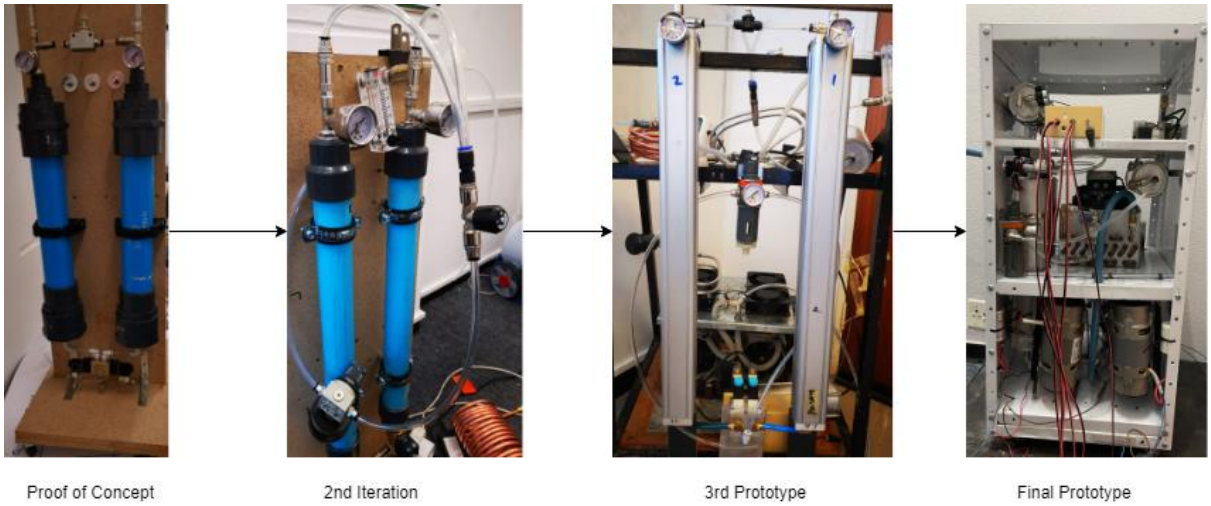


Figure 5-4 Prototype Development Stages (See Appendix L for detailed prototypes)

The initial **Proof of Concept**, depicted in Figure 5-4, comprised a DIY OXIKIT with notable issues like oversized sieve beds causing inefficient oxygen concentration. These beds, using 52 mm snap-on fittings and control valves, were constructed from Class 16 pipes and Class 32 street fittings, with the oxygen tank made of PVC cement. Although facing challenges, this prototype marked a pivotal advancement in developing affordable oxygen concentrators.

The **2nd iteration**, illustrated, improved upon the first by refining sieve sizes for enhanced performance. Despite progress in sieve dimensions, it faced limitations in internal flow. This version also introduced plastic cement-sealed canisters, raising concerns about durability and moisture intrusion. Addressing these trade-offs is essential for a reliable oxygen concentrator.

Figure 5-4 again introduces the **third prototype**, employing heavy-duty aluminium canisters. While solving previous issues, this modification brought about new challenges like increased weight and cost. Engineers introduced spacers to balance integrity, weight, and efficiency, demonstrating a commitment to refining the design for practicality and robustness.

The **final prototype** features an air-cooled heat exchanger (ACHE) to resolve cooling inefficiencies. This strategic addition aims for optimal performance and reliable operation of the oxygen concentrator, symbolising the journey from initial challenges to a sophisticated, effective design. The inclusion of the ACHE underscores the significance of innovation and perseverance in addressing oxygen concentration needs.

5.2.4.2. Analysis and Discussion

1. **First Prototype - Oversized Sieve Beds**: This prototype revealed a fundamental design principle: component sizing is crucial for efficiency. It showed that more significant components might lead to inefficiency and practical issues in device operation.
2. **Second Prototype - Smaller Sieve and Sealed Canisters**: The shift to a smaller sieve and sealed canisters highlighted the essential balance between component size and maintenance practicality. This stage emphasised the need for efficiently functioning and easily maintainable medical devices.

3. **Third Prototype - Aluminium Canisters and Cost**: Introducing aluminium canisters brought up high production costs, leading to a redesign. This experience underscored the importance of balancing durability with cost-effectiveness in medical device development.
4. **Fourth Prototype - Advanced Cooling and Heat Exchange (ACHE)**: Incorporating ACHE significantly improved thermal management, demonstrating the importance of temperature regulation in oxygen concentrator design for consistent performance.
5. **Iterative Design Process**: The development of each prototype underlines the iterative nature of medical device engineering, offering valuable insights and establishing a roadmap for future innovations.

5.2.4.3. Implications

The iterative process of these prototypes has crucial implications for oxygen concentrator design and manufacture, especially when using locally sourced materials. The progression from the first to the final prototype underscores the necessity of ongoing refinement and adaptation to meet functional demands. Each prototype's learnings enrich our understanding of the complexities in designing efficient and reliable medical devices, informing future Research and Development. This knowledge is crucial for technological progress, ensuring the accessibility and sustainability of medical devices in various healthcare environments.

5.2.5. Objective 3: Test the Efficiency and Performance of Multi-user Medical Grade Oxygen Concentrator

5.2.5.1 Results

The fourth prototype of the oxygen concentrator, featuring an air-cooled heat exchanger, addressed issues of air inlet temperature and humidity affecting zeolite performance. It maintained an optimal temperature range of 20-25°C, crucial for zeolite efficiency, using dual compressors. Performance tests under varied conditions, simulating different flow rates with and without valves, provided insights into the system's adaptability to thermal changes, as evidenced by results in Table 5-3 and subsequent figures.

5.2.5.2 Analysis and Discussion

Experiments revealed that systems with equalisation valves were more stable and efficient than those without. This is vital for understanding the impact of valve integration on system performance. Different scenarios tested showed variations in oxygen concentration, flow rate, and temperature, demonstrating the system's efficiency in various operational settings (Table 5-3).

Table 5-3: Oxygen Concentration Results

Scenarios	Oxygen Concentration (%)	Average Flow Rate (Lpm)	Ave Temperature (°C)
Without V8 and V5	81-93	18.9-19.2	22.9
Without Output Orifice and V8 and V5	88-94	18-20	22.9
Without Orifice	89-90	20-22	22.9
With the Orifice and all valves	90.1-93.2	20-21.8	25.1

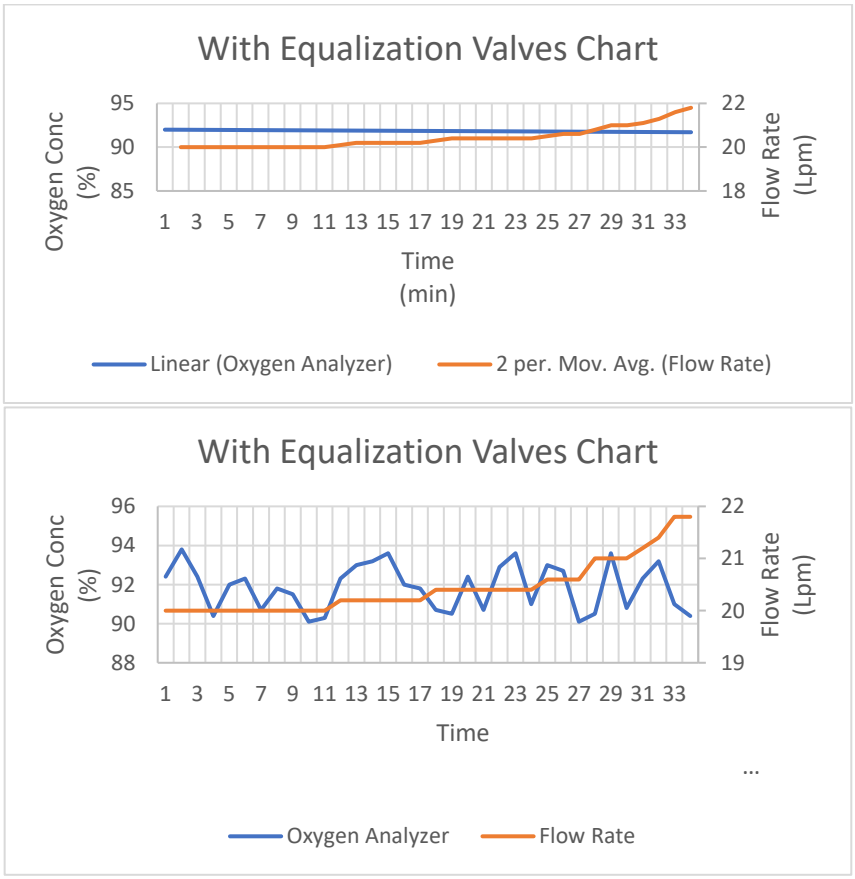
5.2.5.3 Implications and Further Data Presentation

The research underscores the vital role of temperature control in oxygen concentrator design, necessitating an air-cooled heat exchanger. It also reveals how component arrangement, specifically the use of equalisation valves, is crucial for performance optimisation. Subsequent sections will provide detailed visual representations of data from Table 5-3 and additional tests, highlighting the impact of different factors on concentrator efficiency and output.

Testing done with equalisation valves:

In tests involving equalisation valves, a specific configuration was used: a closed solenoid Valve 8 off 2/2 12 V with a 1.4mm orifice as the equaliser, accompanied by two valves with brass noise filters for nitrogen venting, others for air feed, oxygen-rich air output, and tank equalisation. This setup, with all eight valves and without a back-pressure creating orifice on the sieve beds, exhibited improved stability and enhanced performance. These findings are detailed in Graph 5-2, which illustrates the benefits of valve equalisation.

Graph 5-2: Results with Equalisation of Valves



Graph 5-2 illustrates that with equalisation valves, there is a trend of increasing oxygen concentration and flow rate over time, indicating a positive correlation between the use of equalisation valves and system performance. The Oxygen Analyzer line depicts a general upward trend, suggesting a steady rise in oxygen concentration, while the Flow Rate line also trends upwards, indicating an improved output. This visual evidence supports the text's assertion of improved system performance with equalisation valves.

5.2.6 Subsystem Testing: Assessing Oxygen Concentrator Suitability for LMICs

The comprehensive testing of the oxygen concentrator's subsystems has ascertained its appropriateness for Low- and Middle-Income Countries (LMICs). This evaluation scrutinised the complete assembly, multi-user capability, and durability. These assessments, detailed in Table 5-4, outline the concentrator's adherence to specific performance standards.

Key subsystem performances are as follows:

a) **Air Feed System:** Surpassed the exhaust volume target with an effective cooling system, maintaining the necessary temperature.
b) **Air Dryer:** Achieved both humidity and temperature benchmarks, ensuring efficient moisture removal.
c) **Air Separation System:** Met pressure and regeneration time criteria despite different Zeolite types.
d) **Delivery System:** Reached acceptable levels for oxygen purity and flow rate, demonstrating system reliability.

In essence, the concentrator shows significant potential for use in LMICs, addressing essential healthcare needs.

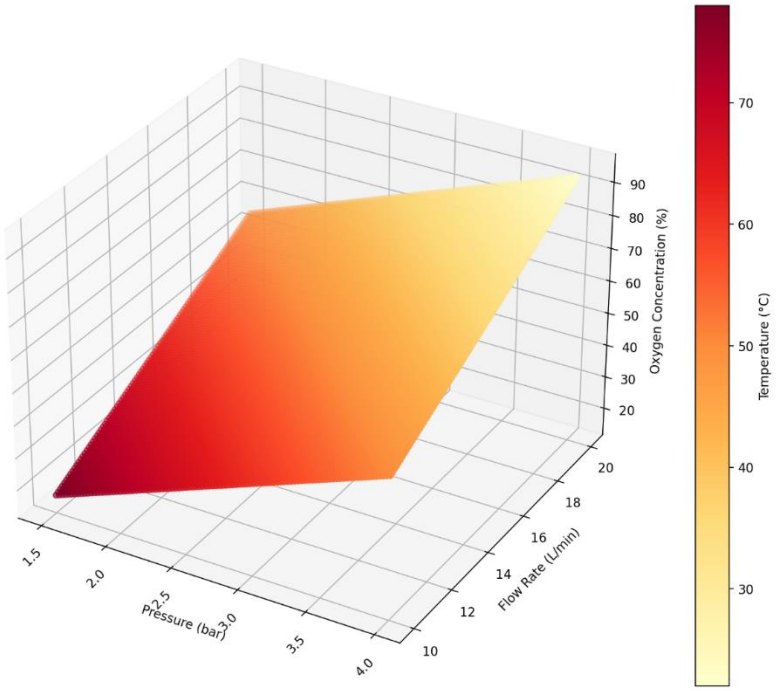
Table 5-4: Subsystems Test Results

Sub-System	Testing Required	Specification	Test Results
Air Feed	Air Compression Unit	Exhaust Volume: 160lpm, Working Pressure: 6 bar, Noise level: <55dB	196lpm, 4 bar, **45 dB**
Air Cooling	Temperature	21°C-30°C	25°C-29°C
Air Dryer (Alumina-Activated Zeolite)	Humidity, Exhaust Temperature	<31°C	41%, <29°C
Air Separation	Molecular Sieve	Size of Zeolite: 13X <10mm, ΔP<1 bar, ±2°C, Cyclic time: <20s	Lix, ΔP<1 bar, ±2°C, <16s
Delivery System	Oxygen Output and Storage	Purity: >85%SpO2, Storage tank pressure: 1-3 bar, Outlet Pressure: >2bar, Flowrate: >20lpm	84%-93%, 3Bar, 1bar, 18-25lpm
Functional Test	Full Assembly	Performance test, Multi-user Functionality, Variable input pressure test vs output concentration, Temperature input vs Concentration Output	Satisfactory across parameters

Table 5-4 lists the test requirements, specifications, and results for each subsystem, such as the Air Feed's exhaust volume and pressure, Air Cooling's temperature control, and the Delivery System's oxygen output specifications and outcomes.

Graph 5-3 depicts the 3D relationship between Pressure, Flow Rate, Temperature, and Oxygen Concentration, which indicates an inverse relationship between flow rate and oxygen concentration and a positive relationship between pressure and concentration, signifying that as pressure increases, oxygen concentration tends to improve.

Graph 5-3: 3D relationship between Pressure, Flow rate, Temperature, and Oxygen Concentrator



In conclusion, the oxygen concentrator is promising for LMIC deployment, with most subsystems meeting or surpassing their criteria. Ongoing refinement and field tests are essential to boost reliability and efficacy, playing a vital role in improving global healthcare equity.

CHAPTER 6

6. Conclusion and Recommendations

6.1. Conclusion

This research thesis developed a portable oxygen concentrator for low- and middle-income countries (LMICs) using a pressure swing adsorption (PSA) system. It addressed the critical need for such a device in resource-limited settings, focusing on its operational principles, high oxygen flux, energy efficiency, and simplicity (Li, 2014c). The incorporation of zeolite and temperature-stable valves tackled humidity and diverse environmental challenges. A detailed LabVIEW-assisted test plan facilitated precise data collection, with two-phase testing ensuring comprehensive system evaluation.

The design met most high-priority requirements, highlighting the need for ongoing improvements in lower-priority areas. A key finding was the 93% oxygen purity achieved, aligning with safety standards for oxygen therapy in both stationary and portable PSA-based concentrators (Enikeeva, 2022). Enhancements like pressure swing equipment for argon removal and buffer tanks enhanced purity to 93% and ensured economic viability in LMICs.

In summary, this research successfully designed a portable oxygen concentrator suitable for LMICs, demonstrating its effectiveness and potential as a cost-effective solution in resource-constrained settings. It also set the stage for future advancements in this domain.

6.2. Affordability

Oxygen concentrators are a cost-effective option for oxygen therapy in low- and middle-income countries (LMICs), offering economic and healthcare benefits. They provide a viable solution for long-term oxygen treatment, leading to reduced costs and improved healthcare outcomes, such as a decrease in childhood pneumonia mortality (Duke, 2010). These devices align with strategies aimed at affordability, sustainability, and operational efficiency, underscoring the importance of competent implementation.

Table 6-1:summarises key aspects of affordability and impact:

Aspect	Key Points	Additional Details
Manufacturing Cost	DIY oxikits and economical materials reduce costs.	Simplified production processes and local market availability.
Local Sourcing	Minimises costs and environmental impact.	Eliminates import tariffs and lowers shipping fees and carbon footprint.
Operational Advantages	Continuous supply and simplicity.	Reliable in intermittent supply regions, user-friendly design.
Safety	Minimises risks compared to traditional methods.	Incorporates modern safety features, reducing risks.

Implementation Necessity	Skilled installation and maintenance are crucial.	Prevents malfunctions, ensures continuous operation and prolongs lifespan.

As shown in Table 6.1, the introduction of oxygen concentrators in LMICs represents a significant leap in medical technology. With a focus on do-it-yourself production, regional sourcing, and straightforward operations, this strategy is optimised for environments with low resources. However, its success depends on skilled installation and ongoing maintenance, highlighting the need for adequate training and support for involved personnel.

6.3. Weight

In developing oxygen concentrators for LMICs, addressing the challenges of weight and portability is crucial to ensure their practicality in diverse healthcare settings. As per Al-Aubidy et al. (2022), reverse engineering is key to creating low-cost, compact designs suitable for respiratory patients in these regions. A significant design issue was the integration of dual compressors into one unit, making the device heavy and less portable. The proposed solution, as detailed in Table 6.2, involved the sequential use of compressors to balance efficiency with portability, aligning with findings by Sami et al. (2022) on the effectiveness of specific adsorbents in enhancing concentrators' efficiency and portability.

Table 6-2:Combined Summary Table: Challenges, Solutions, and Benefits for Portable Oxygen Concentrators

Challenge/Solution	Description	Impact/Benefits on Users
Weight Management (Sami, 2022)	Dual compressors increased weight, hindering portability.	Sequential use of compressors reduced overall weight.
Size Reduction (Al-Mutairi, 2022)	The combined unit was too bulky for practical mobility	Compact design focusing on size efficiency
Use of Compact Cylindrical Aluminium Tanks	Tanks store compressed oxygen, operate independently of external power sources	- Enables use in remote areas - Facilitates mobility and reduces physical burden - Allows customisable oxygen delivery for effective therapy

The adoption of compact cylindrical aluminium tanks, as indicated in Table 6.2, has been a crucial advancement. These tanks overcome portability issues by storing compressed oxygen and functioning independently of external power sources, ideal for environments with limited electrical infrastructure (Calderon et al., 2019). This development is particularly beneficial in extending oxygen availability during power outages in resource-limited settings

In conclusion, the initial dual-compressor design's impracticality due to size and weight constraints led to significant innovations. The introduction of compact cylindrical aluminium tanks and the sequential use of compressors, as summarised in Table 6.2, have been vital in addressing these challenges. These

developments underscore the importance of innovative design in enhancing the functionality and applicability of oxygen concentrators in LMICs.

6.4. **Safety and Ease of Application of Oxygen Concentrators**

In low-resource healthcare settings, oxygen concentrators are crucial for treating conditions like pneumonia and chronic lung diseases. Their effectiveness depends on overcoming challenges like unstable power supplies. Backup power solutions, such as the Low-Pressure Oxygen Storage (LPOS) system, are vital for continuous oxygen delivery during power outages (Peake, 2021). Safe handling of materials, particularly Zeolite, requires strict adherence to Material Safety Data Sheets and proper ventilation to mitigate hazards. Moreover, concentrators must be durable, resisting environmental factors like temperature and humidity for longevity and reliability.

Training and community involvement are essential in low- and middle-income countries (LMICs). Safety protocols based on Material Safety Data Sheets for materials like Zeolite are crucial (Perrelet, 2004). Educating users on safe operation, hazard awareness, and maintaining a safe distance from flammable materials is critical, as outlined in the Risk Plan (Appendix D). Tailored educational approaches are necessary to address resource limitations and hierarchical work relationships (Flesher, 2016), and adapting safety measures to local contexts, including alternative fire safety protocols, is crucial.

Case studies illustrate these principles. In Zambia, solar-powered concentrators in areas with unreliable electricity highlight the need for environmental adaptations and training (Bradley, 2011). In Bangladesh, training local healthcare workers on device maintenance reduced downtime, showing the value of localised training (Calderon, 2019). In India, the use of portable concentrators in remote areas emphasised the need for portability and robust design (Makoliso, 2020). Feedback from Kenyan users led to design improvements, demonstrating the importance of a feedback loop for continuous enhancement (Tuti, 2021). These examples underscore the multifaceted approach needed for the effective development and implementation of oxygen concentrators in resource-limited settings, ensuring their safety, reliability, and user-friendliness, thereby enhancing healthcare outcomes.

6.5. Recommendations and Future Research

In order to promote the development of portable multi-user medical-grade oxygen concentrators in low and middle-income nations, it is critical to adopt a strategic approach that centres on enhancing functionality, reliability, and accessibility. The key is exploring their thermodynamics, particularly energy recapture, to enhance efficiency, which is crucial in power-limited settings (Lee, 2020). Integrating Artificial Intelligence (AI) is recommended to optimise performance, enabling predictive maintenance and real-time healthcare provider feedback (Kim, 2020).

Renewable energy sources, like solar or wind power, are vital, reducing carbon footprint and aiding accessibility in electricity-scarce areas. Incorporating solar panels or wind turbines is crucial for sustainable power, especially in remote locations, aiding environmental sustainability (Chen, 2021). Real-world testing is imperative for understanding performance and user experience guiding necessary device refinements (Saunders, 2021).

A comprehensive cost analysis is necessary for affordability in LMICs. Cost-saving measures in production and distribution and partnerships with local manufacturers are crucial to maintaining quality (Diaconu, 2017). Developing training, maintenance, and monitoring programmes, including robust systems for tracking performance and oxygen levels, is vital for effective operation and maintenance.

In conclusion, enhancing portable oxygen concentrators in LMICs requires a holistic approach, encompassing advanced technology integration, renewable energy use, thorough testing, cost analysis, effective training and maintenance, and focusing on long-term sustainability and funding, pivotal for improved healthcare and patient outcomes.

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Appendices

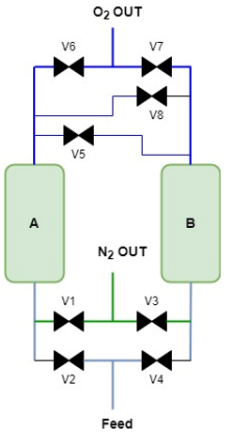
Appendix A: Cyclic Time

OPTION # 1

	Pressure A		Purge	
	STEP1	STEP2	STEP3	STEP4
	1s	4s	1s	4s
V1	OFF	OFF	ON	OFF
V2	ON	ON	OFF	OFF
V3	ON	OFF	OFF	OFF
V4	OFF	OFF	ON	ON
V5	OFF	OFF	OFF	OFF
V6	OFF	ON	OFF	OFF
V7	OFF	OFF	OFF	ON
V8	OFF	OFF	OFF	OFF

OPTION #2

	Pressure A	Equalization	Purge	Pressure B	Equalization	Purge
	STEP1	STEP2	STEP3	STEP4	STEP 5	STEP6
	3s	2s	1s	3s	2s	1s
V1	OFF	OFF	ON	OFF	OFF	OFF
V2	ON	ON	OFF	OFF	OFF	ON
V3	OFF	OFF	OFF	OFF	OFF	ON
V4	OFF	OFF	ON	ON	ON	OFF
V5	OFF	OFF	OFF	OFF	ON	OFF
V6	ON	ON	OFF	OFF	OFF	ON
V7	OFF	OFF	ON	ON	ON	OFF
V8	OFF	ON	OFF	OFF	OFF	OFF

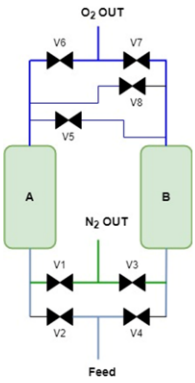


OPTION #3

	Pressure ZA	Purge	Balance	Pressure ZB	Purge	Balance
	STEP1	STEP2	STEP3	STEP4	STEP4	STEP 6
	3s	1s	1.5s	3s	1s	1.5s
V1	OFF	ON	OFF	OFF	OFF	OFF
V2	ON	OFF	OFF	OFF	ON	ON
V3	OFF	OFF	OFF	OFF	ON	OFF
V4	OFF	ON	ON	ON	OFF	OFF
V5	OFF	OFF	OFF	OFF	OFF	ON
V6	ON	OFF	OFF	OFF	ON	ON
V7	OFF	ON	ON	ON	OFF	OFF
V8	OFF	ON	ON	OFF	OFF	OFF

OPTION #4

	Pressure ZA	Purge	Balance	Pressure ZB	Purge	Balance
	STEP1	STEP2	STEP3	STEP4	STEP4	STEP 6
	1s	1s	3.5s	1s	1	3.5s
V1	OFF	OFF	OFF	ON	OFF	OFF
V2	ON	ON	ON	OFF	OFF	OFF
V3	ON	OFF	OFF	OFF	OFF	OFF
V4	OFF	OFF	OFF	ON	ON	ON
V5	OFF	ON	OFF	OFF	ON	OFF
V6	OFF	ON	ON	OFF	OFF	OFF
V7	OFF	OFF	OFF	OFF	ON	OFF
V8	OFF	OFF	OFF	OFF	OFF	ON



Appendix B: Material Safety Data Sheet (MSDS)

Table 1: Product Information

Property	Value
Product Name	JLOX-100
Chemical Formula	Mx/n[(AlO2)x(SiO2)y].zH2O
Synonyms	Lithium-exchanged Zeolite, Lithium-sodium Zeolite
CAS Number	12179-18-5
Molecular Weight	Variable
Appearance	White to light grey powder
Odor	Odorless
Melting Point	Not applicable
Boiling Point	Not applicable
Solubility	Insoluble in water
Specific Gravity	Variable
pH	Variable
Flash Point	Not applicable

Table 2: Composition/Information on Ingredients

Ingredient	CAS Number	Concentration
Lix Zeolite	12179-18-5	100%

Table 3: Hazards Identification

Hazard Classification	Label Elements
Irritant	Xi

Table 4: First Aid Measures

Ingestion	Inhalation	Skin Contact	Eye Contact
Do not induce vomiting. Rinse mouth with water. Seek medical attention.	Move to fresh air. Seek medical attention.	Remove contaminated clothing. Wash affected area with soap and water. Seek medical attention.	Flush eyes with water for at least 15 minutes. Seek medical attention.

Table 5: Fire-Fighting Measures

Flammable Properties	Extinguishing Media	Special Firefighting Procedures
Not flammable.	Use water fog, foam, or dry chemical.	Wear self-contained breathing apparatus and protective clothing.

Table 6: Accidental Release Measures

Personal Precautions	Environmental Precautions	Clean-up Procedures
Wear appropriate protective equipment.	Do not allow to enter drains or watercourses.	Sweep up and shovel into suitable containers for disposal. Avoid generating dust.

Table 7: Handling and Storage

Handling	Storage
Avoid inhalation and contact with skin and eyes. Wear appropriate protective equipment.	Store in a cool, dry place in original container. Keep tightly closed.

Table 8: Exposure Controls/Personal Protection

Component	ACGIH TLV	OSHA PEL	Other
Lix Zeolite	Not listed	Not listed	See section 8 for additional information.

Table 9: Physical and Chemical Properties

Physical State	Color	Odor	pH	Boiling Point	Melting Point	Specific Gravity
Solid	White to light grey	Odorless	Variable	Not applicable	Not applicable	Variable

Table 10: Stability and Reactivity

Stability	Hazardous Polymerization	Incompatibilities
Stable under normal conditions of use.	Will not occur.	Avoid contact with strong acids and oxidizing agents.

Table 11: Toxicological Information

Component	LD50 Oral - Rat	LD50 Dermal - Rat	LC50 Inhalation - Rat
Lix Zeolite	Not available	Not available	Not available

Table 12: Ecological Information

Component	Environmental Fate	Ecotoxicity
Lix Zeolite	Not expected to bioaccumulate. May adsorb to sediments and soils.	Not expected to be toxic to aquatic organisms.

Table 13: Disposal Considerations

Waste Disposal Methods	Regulatory Requirements
Dispose in accordance with local, state, and federal regulations.	Not regulated.

Table 14: Transport Information

Transportation Class	Shipping Name	UN/NA Number	Hazard Class	Packing Group
Not regulated.	Not applicable.	Not applicable.	Not applicable.	Not applicable.

Table 15: Regulatory Information

Component	TSCA Inventory	SARA (311/312) Hazard Categories	SARA (313) Chemicals
Lix Zeolite	Listed.	Acute Health Hazard. Chronic Health Hazard. Fire Hazard. Reactive Hazard.	None.

Table 16: Other Information

Additional Information
This product is intended for use by trained professionals only. The information in this MSDS is believed to be accurate and reliable, but no guarantee is made or implied. The user assumes all responsibility for any injury or damage resulting from using or handling this product.

Appendix C: Patent Search Guide

Patent Search Guideline:

Here are some examples of patents related to multi-user oxygen concentrators:

1. US Patent No. 9,339,981: Multi-user oxygen concentrator system
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General patenting process.

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2. **Search patent databases:** There are several online patent databases, such as the US Patent and Trademark Office (USPTO), the European Patent Office (EPO), and the World Intellectual Property Organization (WIPO), that can be searched for relevant patents. You can perform a keyword search using the relevant keywords and classification codes you determined in step 1, or you can search using specific patent numbers if you have any in mind.
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Widely used patent databases search links:

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3. World Intellectual Property Organization (WIPO): https://www.wipo.int/patentscope/en/
4. Google Patents: https://patents.google.com/

Appendix D: Risk And Safety Matrices For An Oxygen Concentrator

Table 10 Biocompatibility of Materials Used in Oxygen Concentrator:

Material	Biocompatibility
Tubing	Tested and certified as biocompatible, non-toxic, hypoallergenic, resistant to bacterial growth
Nasal Cannulas	Tested and certified as biocompatible, non-toxic, hypoallergenic, resistant to bacterial growth
Other Direct Contact Materials	Tested and certified as biocompatible, non-toxic, hypoallergenic, resistant to bacterial growth

Biocompatibility refers to the ability of a material to perform with an appropriate host response in a specific application. The materials used in oxygen concentrators must be biocompatible to ensure patient safety. The materials that come in direct contact with the patient (such as tubing and nasal cannulas) must be evaluated for biocompatibility and toxicity, as well as for their potential to generate any adverse reactions.

Table 11 Risk Matrix for Development of a High Flow Oxygen Concentrator:

Hazard Identification	Likelihood	Severity	Control Measures	Monitoring and Review
Chemical toxicity	High	High	Use biocompatible materials, regular maintenance and cleaning	Regular testing and monitoring of patient response
Physical irritation	Medium	High	Use biocompatible materials, regular maintenance and cleaning	Regular testing and monitoring of patient response
Allergic reactions	Low	Medium	Use biocompatible materials, regular maintenance and cleaning	Regular testing and monitoring of patient response
Bacterial contamination	High	Low	Regular maintenance and cleaning	Regular testing and monitoring of concentrator surfaces

Table 12 Risk, Safety, and Quality Matrix for Development of a High Flow Oxygen Concentrator:

Risk/Safety/Quality Factor	Description	Mitigation	Monitoring
Risk of Chemical Toxicity	The risk of harm to the patient from exposure to toxic materials used in the concentrator	Use biocompatible materials, regular maintenance and cleaning	Regular testing and monitoring of patient response

Risk of Physical Irritation	The risk of harm to the patient from physical irritation caused by contact with materials used in the concentrator	Use biocompatible materials, regular maintenance and cleaning	Regular testing and monitoring of patient response
Risk of Allergic Reactions	The risk of an allergic reaction to materials used in the concentrator	Use biocompatible materials, regular maintenance and cleaning	Regular testing and monitoring of patient response
Risk of Bacterial Contamination	The risk of bacterial contamination of the concentrator and potential harm to the patient	Regular maintenance and cleaning	Regular testing and monitoring of concentrator surfaces
Safety of Operating Procedures	The safety of the operating procedures for the concentrator, including proper use and maintenance	Detailed operating procedures with clear instructions, regular training of users and maintenance personnel	Regular review and updating of operating procedures based on user feedback
Quality of Manufacturing Process	The quality of the manufacturing process and the resulting concentrator product	Adherence to strict quality control procedures, regular testing and monitoring of product quality	Regular review and improvement of manufacturing processes based on product testing results

Table 13 Electrical Risk Matrix for Development of a High Flow Oxygen Concentrator:

Hazard Identification	Likelihood	Severity	Control Measures	Monitoring and Review
Electrical Shock	High	High	Proper insulation and grounding of electrical components, regular maintenance and inspection of electrical systems	Regular testing and monitoring of electrical systems, prompt response to any electrical malfunctions
Fire	Medium	High	Proper insulation and grounding of electrical components, use of fire-resistant materials, regular maintenance and inspection of electrical systems	Regular testing and monitoring of electrical systems, prompt response to any electrical malfunctions
Electromagnetic Interference (EMI)	Low	Medium	Proper shielding of electrical components, use of EMI-resistant materials, regular maintenance and inspection of electrical systems	Regular testing and monitoring of electrical systems, prompt response to any EMI-related malfunctions

Electromagnetic Compatibility (EMC)	Low	Low	Proper shielding of electrical components, use of EMC-compatible materials, regular maintenance and inspection of electrical systems	Regular testing and monitoring of electrical systems, prompt response to any EMC-related malfunctions

Table 14 Chemical Risk Matrix for Development of a High Flow Oxygen Concentrator:

Hazard Identification	Likelihood	Severity	Control Measures	Monitoring and Review
Chemical Toxicity	High	High	Use biocompatible materials, regular maintenance and cleaning	Regular testing and monitoring of patient response
Chemical Reactions	Medium	High	Proper storage and handling of chemicals, regular maintenance and cleaning	Regular testing and monitoring of chemical reactions, prompt response to any chemical incidents
Chemical Contamination	Low	Low	Proper storage and handling of chemicals, regular maintenance and cleaning	Regular testing and monitoring of chemical levels, prompt response to any chemical incidents

Table 15 Safety-related Risk Matrix for Development of a High Flow Oxygen Concentrator:

Hazard Identification	Likelihood	Severity	Control Measures	Monitoring and Review
Physical Injury	High	High	Proper design and construction of the concentrator, regular maintenance and cleaning	Regular testing and monitoring of patient response, prompt response to any physical incidents
Operating Procedures	Medium	High	Detailed operating procedures with clear instructions, regular training of users and maintenance personnel	Regular review and updating of operating procedures based on user feedback, prompt response to any operating incidents
Product Failure	Low	Medium	Adherence to strict quality control procedures, regular testing and monitoring of product quality	Regular review and improvement of manufacturing processes based on product testing results, prompt response to any product failures

Appendix E: Specifications And Standards List

List of specifications, standards, guides, and organizations related to oxygen concentrators:

1. **Specifications:**

- ISO 13485:2016: Medical devices - Quality management systems - Requirements for regulatory purposes
    - This international standard specifies requirements for a quality management system where an organization must demonstrate its ability to provide medical devices and related services that consistently meet customer requirements and regulatory requirements applicable to medical devices and associated services.
- IEC 60601-1: Medical electrical equipment - Part 1: General requirements for safety
    - IEC 60601-1: This international standard specifies general requirements for the safety, essential performance and effectiveness of medical electrical equipment. It defines safety requirements for medical electrical equipment, including oxygen concentrators.
- ISO 10993-1: Biological evaluation of medical devices
    - This international standard specifies the requirements and tests for the biocompatibility of medical devices. It helps to ensure that oxygen concentrators and their components do not cause adverse effects on patients or users.
- ISO 7396-1: This international standard specifies requirements for medical gas pipeline systems in healthcare facilities. It includes specific requirements for oxygen concentrators and their connections to medical gas pipelines.

2. **Standards:**

    - FDA 21 CFR Part 868: Oxygen concentrators
    - FDA 21 CFR Part 801: This is a regulation from the US Food and Drug Administration (FDA) that outlines the requirements for medical device labelling, including labelling for oxygen concentrators.
    - ASTM F2423-18: This standard from the American Society for Testing and Materials (ASTM) provides performance criteria for oxygen concentrators. It covers the minimum performance criteria for continuous and pulse-flow oxygen concentrators.
    - ANSI/AAMI/ISO 8359: Medical gas pipeline systems
    - ISO 80601-2-12: Medical electrical equipment - Part 2-12: Particular requirements for the basic safety and essential performance of oxygen concentrators
    - CSA B126.1: Oxygen Concentrators for Medical Use
    - BS EN ISO 14971: Medical Devices - Application of Risk Management to Medical Devices
    - BS EN ISO 15001: Respiratory Therapy Equipment - Home Use Oxygen Concentrators
    - CSA B126.1: Oxygen Concentrators for Medical Use [CSA, 2021]

- BS EN ISO 14971: Medical Devices - Application of Risk Management to Medical Devices [BSI, 2021]
- BS EN ISO 15001: Respiratory Therapy Equipment - Home Use Oxygen Concentrators [BSI, 2021]
- ISO 7396-1: Medical gas pipeline systems - Part 1: Pipeline systems for compressed medical gases and vacuum [ISO, 2015]
- ISO 10083-1: Respiratory equipment for home use - Part 1: Requirements for performance and safety [ISO, 2017]

3. Guides:

- AAMI TIR45: Guidance on the labeling of medical oxygen systems and related equipment
- ATS/ERS 2005 International Guidelines for Oxygen Therapy
- American Thoracic Society (ATS) / European Respiratory Society (ERS) Statement: Portable Oxygen Concentrators in Clinical Practice [ATS/ERS, 2018]
- National Institute for Health and Care Excellence (NICE) Guidance: Oxygen in emergency and acute medical care [NICE, 2020]
- NFPA 99: This standard from the National Fire Protection Association (NFPA) provides guidelines for the health care facilities regarding fire protection, life safety and electrical safety. It includes specific requirements for oxygen concentrators and other medical gases.

4. Organizations:

- World Health Organization (WHO): WHO provides guidelines and recommendations for healthcare technologies, including oxygen concentrators.
- The Lancet: The Lancet is a medical journal that publishes articles related to various aspects of healthcare, including respiratory medicine and oxygen therapy.
- International Association for Respiratory Care (AARC): The AARC provides education, resources, and support for respiratory care professionals, including information on oxygen concentrators [AARC, 2021].
- European Respiratory Society (ERS): The ERS is a professional organization for respiratory physicians and scientists, providing information and guidelines on respiratory medicine, including oxygen therapy [ERS, 2021].
- National Institute for Health and Care Excellence (NICE): NICE provides guidelines and advice on the use of medical technologies, including oxygen concentrators, in the UK [NICE, 2021].
- ResMed Foundation: The ResMed Foundation is a non-profit organization that supports research and education in respiratory medicine, including the use of oxygen concentrators [ResMed Foundation, 2021].

References:

- AARC (2021). International Association for Respiratory Care. [Online]. Available at: https://aarc.org/
- BSI (2021). British Standards Institute. [Online]. Available at: https://www.bsigroup.com/
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- NICE (2021). National Institute for Health and Care Excellence. [Online]. Available at: https://www.nice.org.uk/
- ResMed Foundation (2021). ResMed Foundation. [Online]. Available at: https://www.resmed.com/en-us/research/resmed-foundation

Appendix F: Patent Search Guide

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4. Google Patents: https://patents.google.com/

Appendix G: Air Cooled Heat Exchanger

Customer		**Date**	2022/07/22
To the k. a. of		**Our Offer**	-
Your Reference		**Descri tion**	

Geometry	102522_C_S	Coil Length	180,0	mm	
Nr of Tubes per Row	8	Fin Pitch	4,50	mm	
Nr of Rows	4	Nr of Circuits	1	Tube Shape	
Capacity			502		W
Exchange Surface			1,38		m²
Global Exchange Coefficient			38		W/(m² K)
DTML			9,5		°C
Atmospheric Pressure / Altitude			1,01 / 0,00		bar A / m
Volumetric Air Flow			90		l/s
Mass Air Flow			381		kg/h
Face Velocity on the Coil			2,50		m/s
Inlet Air Density			1,17		kg/m³
Inlet Air Temperature			25,0		°C
Inlet Air Relative Humidity			65,00		%
Inlet Air Specific Humidity			12,90		g/kg DA
Inlet Air Enthalpy			57,99		kJ / kg
Outlet Air Temperature			29,6		°C
Outlet Air Relative Humidity			49,59		%
Outlet Air Specific Humidity			12,90		g/kg DA
Outlet Air Enthalpy			62,74		kJ / kg
Pressure Drop			47		Pa
Fouling Factor			0,000000		(m² K)/W
Partial Exchange Coefficient			67		W/(m² K)
Fluid			DRY AIR (6 bar A)		
Volumetric Fluid Flow			3,4333		l/s
Mass Fluid Flow			83		kg/h
Fluid Velocity			55,94		m/s
Inlet Fluid Temperature			50,0		°C
Outlet Fluid Temperature			28,5		°C
Total Pressure Drop Fluid Side			403,30		kPa
Partial Exchange Coefficient			897		W/(m² K)
Fouling Factor			0,000000		(m² K)/W
Geometry			102522 C S		
Nr of Rows / Nr of Tubes per Row			4 / 8		
Coil Length			180,0		mm
Fin Pitch			4,50		mm
Nr of Circuits			1		
Fins Material / Tubes Material			Aluminium / Copper		
Fin Thickness			0.1200		mm
Coil Internal Volume			0.4		l
Tubes External Diameter			9.54		mm
Tubes Internal Diameter			8.84		mm
Number of skipped tube			0		

Appendix H: Valve Control Code

```
#include <16F84A.h> // Appropriate header file for PIC16F84A
#fuses HS,NOWDT,NOPUT,NOPROTECT, NOBROWNOUT, NOLVP // Configuration settings (might need to change based on your setup)
#use delay(clock=4000000) // Assuming a 4MHz clock

void solenoid_valve_ON(int pin) {
   output_high(pin);
   delay_ms(100);
}

void solenoid_valve_OFF(int pin) {
   output_low(pin);
   delay_ms(100);
}

void delay_s(int seconds) {
   for(int i = 0; i < seconds; i++) {
      delay_ms(1000);
   }
}

void START() {
   delay_s(3);

   solenoid_valve_OFF(PIN_A2); // v2
   solenoid_valve_OFF(PIN_A3); // v4
   solenoid_valve_OFF(PIN_B0); // v1
   solenoid_valve_OFF(PIN_B1); // v3
   solenoid_valve_OFF(PIN_B2); // v5
   solenoid_valve_OFF(PIN_B3); // v6
   solenoid_valve_OFF(PIN_B4); // v7
   solenoid_valve_OFF(PIN_B5); // v8

   PRESSURE1();
}

void PRESSURE1() {
   solenoid_valve_ON(PIN_A2); // v2
   solenoid_valve_ON(PIN_B1); // v3
   delay_s(2);
   solenoid_valve_OFF(PIN_A2); // v2
   solenoid_valve_OFF(PIN_B1); // v3

   PURGE();
}

void PURGE() {
```

```
  solenoid_valve_ON(PIN_A2); // v2
  solenoid_valve_ON(PIN_B2); // v5
  solenoid_valve_ON(PIN_B3); // v6
  delay_s(1);
  solenoid_valve_OFF(PIN_A2); // v2
  solenoid_valve_OFF(PIN_B2); // v5
  solenoid_valve_OFF(PIN_B3); // v6

  EQUALIZEZ1();
}

void EQUALIZEZ1() {
  solenoid_valve_ON(PIN_A2); // v2
  solenoid_valve_ON(PIN_B3); // v6
  delay_s(2);
  delay_ms(500);
  solenoid_valve_OFF(PIN_A2); // v2
  solenoid_valve_OFF(PIN_B3); // v6

  PRESSURE2();
}

void PRESSURE2() {
  solenoid_valve_ON(PIN_B0); // v1
  solenoid_valve_ON(PIN_A3); // v4
  delay_s(2);
  solenoid_valve_OFF(PIN_B0); // v1
  solenoid_valve_OFF(PIN_A3); // v4

  PURGE2();
}

void PURGE2() {
  solenoid_valve_ON(PIN_A3); // v4
  solenoid_valve_ON(PIN_B4); // v7
  solenoid_valve_ON(PIN_B5); // v8
  delay_s(1);
  solenoid_valve_OFF(PIN_A3); // v4
  solenoid_valve_OFF(PIN_B4); // v7
  solenoid_valve_OFF(PIN_B5); // v8

  EQUALIZEZ2();
}

void EQUALIZEZ2() {
  solenoid_valve_ON(PIN_A3); // v4
  solenoid_valve_ON(PIN_B4); // v7
  delay_s(2);
  delay_ms(500);
  solenoid_valve_OFF(PIN_A3); // v4
  solenoid_valve_OFF(PIN_B4); // v7
```

```
   PRESSURE1();
}

void main() {
   set_tris_a(0x00); // All pins of PORT A as output
   set_tris_b(0x00); // All pins of PORT B as output

   while(TRUE) {
      START();
   }
}
```

Appendix I: Compression Spring Parameters

Custom Part Number	
Custom Part Number :	AC3000-50000-8.000-316-75.000-C-N-MM
Rates & Loads	
Spring Rate (or Spring constant), *k* :	1.124 N/mm
True Maximum Load, *True* F_{max} :	130.736 N
Maximum Load *Solid Height* F_{max} :	53.975 N
Safe Travel	
Potential True Maximum Travel w/ Longer Free Length, *True Travel*$_{max}$:	116.264 mm
Maximum Travel *Height Travel*$_{max}$:	48.000 mm
Minimum Loaded Height :	27.000 mm
Physical Dimensions	
Diameter of spring wire, *d*:	3.000 mm
The outer diameter of spring, D_{outer} :	50.000 mm
The inner diameter of spring, D_{inner} :	44.000 mm
The mean diameter of spring, D_{mean} :	47.000 mm
Free length of spring, F_{ree} :	75.000 mm
Number of active coils, n_a :	6.000
Number of total coils, n_T :	8
Solid height, L_{solid} :	27.000 mm
Type of ends:	closed & squared
Spring index, *C* :	15.667
Distance between coils, *Coil*$_{pitch}$:	11.000 mm
Rise angle of coils:	4.26 Degrees

Material Type	
Material type:	Stainless 316 A316

Weights & Measures	
Weight of one spring, *M* :	0.0668 Kgs
Weight per one thousand springs, *M* :	66.7975 Kgs
Length of wire $L_{wire:}$	1,181.2388 mm

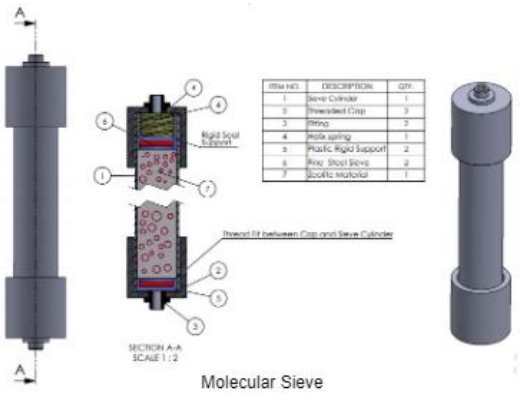
Stress Factors	
Material shear modulus, *G* :	69,182,879,377.432 Pa
Maximum shear stress possible, t_{max} :	631,904,505.919
Wahl correction factor, *W* :	1.090

Appendix J: Steel Tank Parameters

	Parameter	Symbol	Unit
1.	Minimum yield stress specified	Y	$N/mm2$
2.	Maximum permissible equivalent stress at test pressure	fe	$N/mm2$
3.	Minimum neck thickness	TN	mm
4.	Minimum thickness at shoulder-neck junction	TS	mm
5.	Diameter of the concave base standing circle	Ds	$100mm$
6.	Minimal exterior height of the dome portion	H	min
7.	Minimum concave depth	C	mm
8.	Base's minimum internal knuckle radius	Rk	mm
9.	Minimum thickness at the base of the transition	Tt	mm
10.	Minimum wall-to-base transition length	Lt	min
11.	Minimum base thickness in the central region	Tc	mm
12.	Minimum base thickness at knuckle	Tk	min
13.	Settled filling pressure at 15 degrees Celsius	Pf	bar
14.	Test pressure	$P1$	bar
15.	Internal cylinder diameter	Di	mm
16.	External cylinder diameter	Do	mm

APPENDIX L: Prototypes

APPENDIX L1: Proof of Concept



Molecular Sieve Drawing

PVC Sieve beds Made from Class 16 Pipes and Class 32 Effast Fittings

Sieve Beds Connected to a 5/2 12V solenoid Valve and 8mm snap on fittings

Prototype #1 Side Picture

Proto-Type #1 Full assembly Front picture

Oxygen Tank made of 75mm PVC class 16 Pipe and Class 32 endcaps glued together using a PVC cement

Top part of the Sieve Beds fitted with Pressure gauges and an equalization control valve. Both Sievebeds are connected to the product tank via non return valve

Proto-Type #1

APPENDIX L2: Prototype 2

50mm Diameter Sieve Bed

fabrication of the Zeolite Beds.

Zeolite granules

Filling Sieve Canisters with dry Zeolite Granules

Internal Sieve Cap

Compression Spring and Steel Sieve

Test results

Testing was done using an external 1.5 Hp compressor at the flow rate of 5Lpm

Full assembly

Prototype #2 fully assembled and fittedwith a Copper Cooling Coil.

Complete Sieve Bed

Canisters fully compressed and endcaps cemented.

Compressed Cap

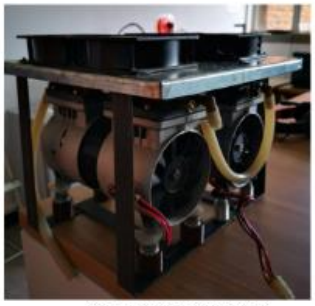
Top Sealled with an end cap and PVC cement. Weights are put on top to compress spring loaded sieve cap.

Prototype #2

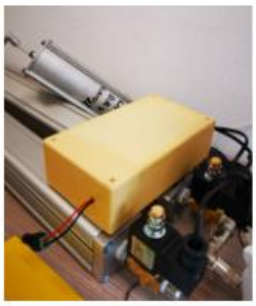
APPENDIX L3: Prototype 3

End Cap and insert Sieve.

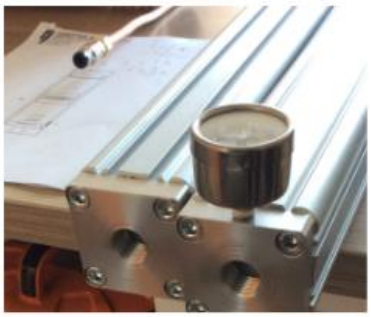
Spacer to seperate Sieve molecules from the end-cap



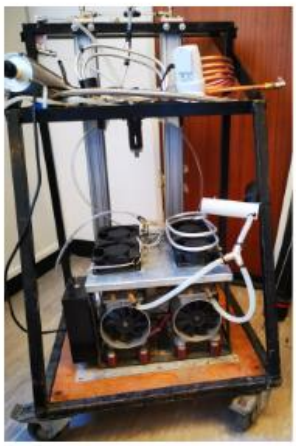
Dual Pack Compressors for higher volue and pressue of Feed air



Connect 3/2 Solenoid Valves and test



Assembled Sieve Beds in line with the hand drawing made easy for fabrication

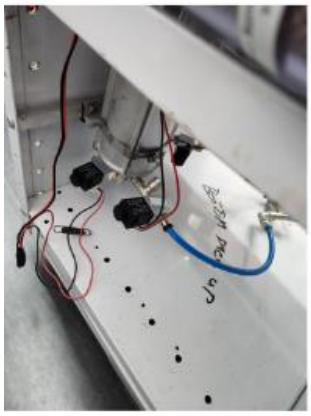


Back View

Complete assembly with 50 mm x 750 mm Sieve Beds

Prototype #3

APPENDIX L4: Final Prototype



Assembly of the Sieve Bed on the Frame

Connected 12v DC Solenoid Valves and Pneumatic Gauges on the Outlet of the Sieve Bed

Assembled Air Cooler and Air pumps

System Connected to control panel Circuit board and a power supply

assembly showing a mechanical air dryer and a molecular activated alumina zeolite dryer.

Assembled unit showing an air Buffer tank

Prototype/ Final #4