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# An Energy-Optimized Medical Oxygen Concentrator for Low-Resource Settings

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**Abstract:** We present a novel approach to produce medical oxygen in low-resource settings at maximal energy efficiency. The oxygen concentration and the required flow can be configured independently by the user and are adjusted automatically by a multivariable feedback controller which exploits the available degrees of freedom, namely the rotational speed of the compressor motor, the opening of a valve restraining outflow, and the switching time of the pressure swing adsorption process. Extensive experiments prove that substantial energy savings can be achieved over a wide range of operating points. The system is suitable both for supplemental oxygen treatment and continuous positive airway pressure applications.

**Keywords:** Medical oxygen, pressure swing adsorption, low-resource settings, energy efficiency.

# 1 Introduction

## 1.1 Medical Oxygen in Low-Resource Settings

Despite declines in child mortality, 6.3 million children and young people under the age of 19 died in 2023, most of them in low-income countries [1]. Public health interventions are vital for child and maternal health in low-resource settings. Equitable access to essential emergency and critical care (EECC) across referral pathways should constitute another integral component of universal health coverage [1, 2]. Medical oxygen is vital for safe surgery and anaesthesia and essential for the care of critically ill patients with respiratory dysfunction – whether through supplemental oxygen, non-invasive support, or mechanical ventilation; therefore, oxygen supply must be ensured at all health facilities providing inpatient care and during transfers of critically ill patients [2–4].

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However, centralized oxygen production and cylinder distribution is often impractical in low-resource settings. A comprehensive strategy is therefore needed to establish reliable oxygen supply, incorporating decentralized solutions such as bedside oxygen concentrators [4].

To provide supplemental oxygen, concentrators should be able to deliver concentrations above 90% at a variable flow range of up to 10 liters per minute (LPM) [5].

Oxygen concentrators can, however, also be modified to function as bubble Continuous Positive Airway Pressure devices (bCPAP), providing an oxygen enriched airflow that matches the patient's peak inspiratory flow demand, similar to high-flow nasal cannula (HFNC) systems [6, 7]. In this application, oxygen concentration should be adjustable between 21% and >90%.

Operation of oxygen concentrators in low-resource settings is frequently complicated by unstable electricity supply [4]. Renewable energy systems can provide a cost-effective and reliable technical solution to ensure stable electricity supply. Notably, their battery backup system represents the most expensive component. Therefore, it is critical to optimize energy efficiency across all electrical loads within healthcare facilities. Since decentralized oxygen provision accounts for over 80% of the energy required by biomedical devices to deliver EECC in small health facilities, exploring technical options to enhance energy efficiency of oxygen concentrators is important [8]. UNICEF's target product profile for resilient oxygen concentrators therefore emphasizes energy efficiency and compatibility with solar power systems; a key requirement is that power consumption should scale with flow rate and should not exceed 40–60 W/LPM [5].

## 1.2 Pressure Swing Adsorption (PSA)

Pressure swing adsorption (PSA) is a common method in medical oxygen concentrators and briefly presented in the following; for details, please refer to [9].

Compressed ambient air is fed alternately into two cylinders filled with a suitable adsorbent (e. g., zeolite). In the active column, nitrogen is adsorbed while the remaining gas – in large part oxygen – is directed into a pressure tank. Because the adsorbent can store only a limited amount of nitrogen and gradually saturates, a valve redirects the airflow to the other column after a certain time (referred to as switching time in the following). While the second cylinder takes over oxygen production, the pressure in the first column drops, nitrogen is released from the adsorbent and flushed out, regenerating the cylinder for the next production cycle.

### 1.3 State of the Art

Several medical oxygen concentrators are available for use in low-resource settings.

The bubble CPAP device by Diamedica delivers a mixture of up to 10 LPM concentrated oxygen and up to 10 LPM ambient air flows, each tunable manually [10]. The final oxygen concentration is thus adjustable by altering the ratio of oxygen to air. The internal PSA element is an oxygen concentrator by DeVilbiss, whose AC powered air compressor motor always operates at nominal speed, regardless of the actual flow produced. This accounts for the high average power consumption of 670 W [10].

The PulmO2 oxygen concentrator addresses this problem by using a DC motor whose power output can the throttled. Thus, it consumes less energy at flow rates below the maximum of 10 LPM [11]. However, oxygen concentration cannot be adjusted and is always above 90%.

### 1.4 Problem Formulation

As explained above, oxygen therapy does not always require both high concentration and high flow. To the authors' knowledge, a solution that offers the possibility to adjust flow and concentration independently and at the same time features high energy efficiency over a wide range of operating points does not yet exist.

Our goal was to find a way to produce oxygen at the concentration and flow required by the user, consuming as little energy as possible. The device should be suitable for essential pediatric emergency and critical care in low-resource settings, in compliance with the UNICEF target product profile [5].

## 2 Method

The new approach presented in this paper is based on the following basic idea and hypothesis: Reducing the rotational speed of the compressor motor in a PSA element will lower its energy consumption but decrease the input pressure, affecting both the flow and the oxygen concentration of the produced gas. Introducing a proportional valve at the patient outlet to reduce flow as needed should simultaneously increase the concentration. This additional actuator can balance between flow and concentration, while the overall oxygen mass flow is controlled by the compressor motor speed.

The remainder of this section presents the hardware setup and the control approach we used in order to evaluate the potential of this idea to improve energy efficiency.

### 2.1 Experimental Setup

We modified a Diamedica Baby CPAP-20 in the following way: Firstly, we replaced its AC motor by an air compressor with an integrated low-voltage brushless DC-motor (BLDC); an electronic speed controller regulates its speed.

Also, additional instrumentation was integrated into the system as illustrated in Fig. 1: Flow sensors (FT) were installed at the compressed air inlet and patient outlet. A pressure sensor (PT) records the pressure at the compressed air inlet, while an oxygen concentration sensor (OT) measures the oxygen concentration at the patient outlet. A proportional valve was installed at the patient outlet for flow control.

A printed circuit board with an ESP32 microcontroller was developed to control all hardware components. This makes it possible to define the PSA switching time at which the valve toggles between the two cylinders. Communication between the microcontroller and PC allows to record measurement data and manually override process parameters.

### 2.2 Multivariable Feedback Control

We implemented a feedback controller to automatically adjust the motor speed and the position of the proportional valve. PSA switching time was varied manually in a first step.

Our goal was to characterize the energy efficiency of the PSA process in different steady operating points. For that reason, we focused on finding a controller which can stabilize the process in a desired equilibrium, while its transient be-

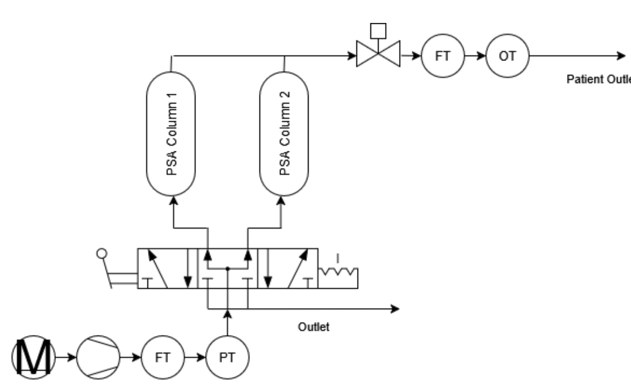


**Fig. 1:** Experimental setup: Process and Instrumentation Diagram

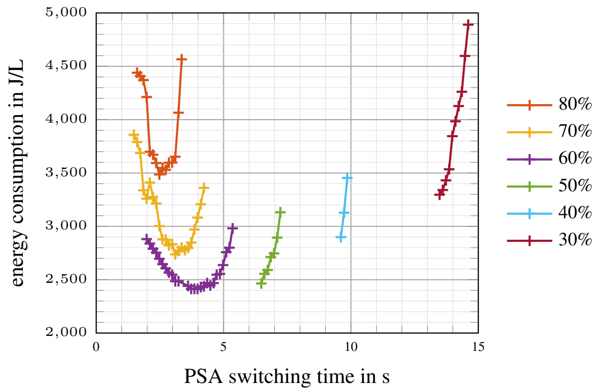


**Fig. 2:** Influence of PSA switching time on energy consumption at a flow rate of 10 LPM, in Joule per liter of pure oxygen

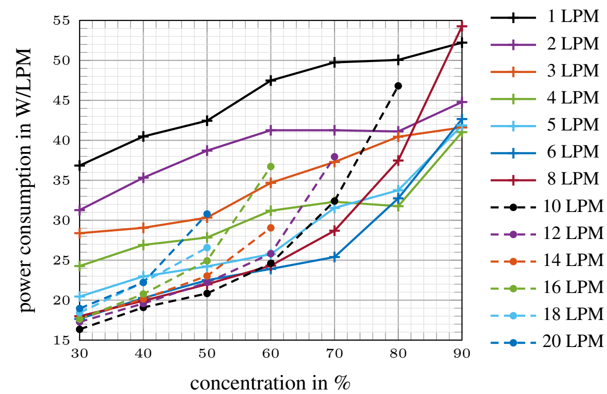


**Fig. 4:** Power consumption at optimal switching time, in Watt per liter of produced gas per minute

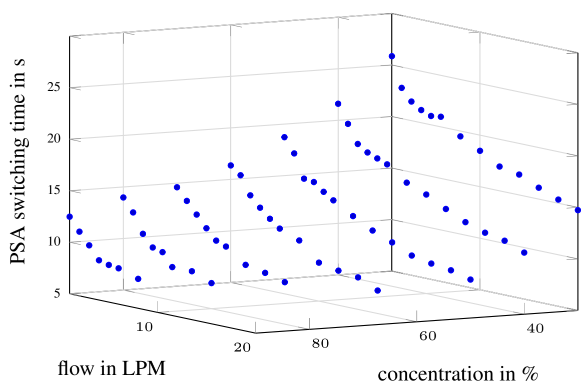


**Fig. 3:** Influence of PSA switching time on energy consumption at a flow rate of 10 LPM, in Joule per liter of pure oxygen

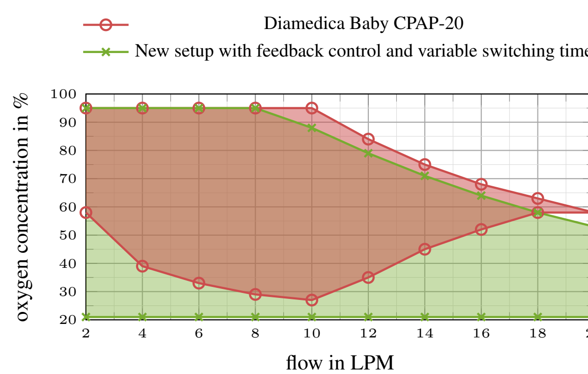


**Fig. 5:** Operating ranges of Diamedica Baby CPAP-20 [10, p. 15] and of the modified setup

havior was of minor importance. Two independent PI controllers turned out to accomplish this goal satisfactorily. In a fast-acting control loop, one PI controller regulates the flow by adjusting the proportional valve position. On a slower timescale, the other controller adapts the motor speed to match the required oxygen concentration.

### 2.3 Measurement procedure

When conducting measurements, it was waited until the process had settled in an equilibrium for a sufficient amount of time, before the next operating point was issued.

Since the parameter space is three-dimensional and each operating point takes several minutes to gauge, running a full 3D grid was not feasible. Also, it turned out that the desired flow and concentration can only be reached if the switching time lies within a certain interval, and that this interval varies with flow and concentration. Therefore, we proceeded along a 2D grid (flow ranging from 2 to 20 LPM, oxygen concentration from 30% to 90%) and varied the switching time manually in a meaningful range where equilibria could be found.

## 3 Results

Exemplary results for flow fixed at 10 LPM are shown in Fig. 2. For instance, oxygen at 60% concentration can be produced at 2.400 J/L if the switching time is around 4 s. For smaller or higher switching times, consumption rises before no equilibrium can be found any more.

For further analysis, we collected those operating points among the set of all equilibria that were optimal for their specific flow and concentration. For example, the optimal operating point in the above mentioned case (60%, 10 LPM) results for 3.8 s switching time, cf. Fig. 2. In Fig. 3, the optimal switching time values are depicted over flow and concentration. The respective power requirement in the optimal operating points is shown in Fig. 4.

Finally, Fig. 5 compares the operating ranges of the original Diamedica Baby CPAP-20 according to its manual [10] (red) with those of the modified test setup (green).

# 4 Discussion

Fig. 2 reveals that for given flow and concentration, prudent choice of the switching time is imperative to achieve optimal energy efficiency – and to find an admissible operating point in the first place. For some cases, the curve is U-shaped with a minimum in a distinct valley. Here, small deviations from optimal switching time have little impact on efficiency. In other cases, the optimal operating point lies at the left boundary of the curve, meaning that the switching time should be chosen as small as possible.

The optimal switching time depends on the desired flow and concentration, as is evident from Fig. 3. Since the points form a rather smooth shape, a parabolic regression surface can be calculated and used for the quasi-optimal feedforward choice of the PSA switching time, depending on the desired oxygen concentration and flow. Observe that one corner of the surface is missing (cf. also Fig. 5) because the concentrator cannot deliver high concentration at excessively high flow.

Please note in Fig. 5 that for flows starting from 10 LPM, our setup delivered less oxygen concentration than expected. Although the motor was running at maximum power, concentration was below the reference values from the datasheet even at nominal operation at 10 LPM. Possible explanations are that the BLDC compressor is slightly weaker than the original, that the zeolith cylinders had degraded, or measurement error.

As Fig. 2 shows at the example of 10 LPM flow, energy consumption drops considerably for lower oxygen concentrations. This is remarkable for two reasons: Firstly, it indicates that the nominal operating point is not the most efficient one. Secondly, one must note that the vertical axis in Fig. 2 denotes energy consumption per liter of *pure* oxygen. Accordingly, it must be multiplied by the concentration in order to obtain energy consumption per liter of *produced gas*. For example, delivering 10 LPM at 60% concentration costs only about $2.400\,\mathrm{J/L} \times 0.6 = 1.440\,\mathrm{J/L}$, corresponding to 240 W, which is only about one third of nominal power use.

# 5 Conclusions and Outlook

We demonstrated a technical solutions to reduce the energy consumption of an oxygen concentrator. The experimental findings confirm that flow and concentration can be controlled independently by adjusting motor speed and outlet valve position. The PSA switching time constitutes an additional degree of freedom with significant influence on the efficiency of the process and the feasibility of an operating point. Power consumption is always below 60 W/LPM, typically even far below 40 W/LPM, as demanded by UNICEF's target product profile.

Improving the energy efficiency of decentralized oxygen provision has several critical implications: It enables enhanced oxygen access in low-resource settings, in particular for neonatal and paediatric respiratory support. It also reduces the costs for renewable energy systems in solar-powered health facilities, as batteries that supply power at night can be downsized. Finally, it facilitates battery-powered oxygen supply solutions for ambulance transfers.

Future work will focus on the optimized integration of the PSA approach into a ventilator and examine its potential for more sophisticated control techniques like automatic adjustment of oxygen concentration depending on SpO2 measurements, cf. [12].

### Author Statement

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