Engineering Aspects on the Design and Realization of Medical Oxygen Concentrator for Oxygen Therapy

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1 Introduction

Medical Oxygen Concentrator (MOC) is a portable standalone medical device used for continuous generation of medical grade oxygen to support patients with respiratory illness or for oxygen therapy. In the present scenario of COVID-19 pandemic, treatment of seriously ill patients depends on Oxygen supply and ventilator support. There is a wide scarcity for oxygen cylinders especially in rural areas. In this situation, an effective functional relief could be medical oxygen concentrators that are mobile, handy and available in short time. Oxygen concentrators are highly reliable but units are costly in the open market. The technology is currently limited to very few countries. Under this scenario, a portable and affordable Medical Oxygen Concentrator is the need of the hour. Considering the above, VSSC, ISRO has realized an Engineering Model (EM) of portable medical oxygen concentrator which is capable of generating oxygen (conc. > 82%) continuously @10 LPM as per World Health Organization standards [1]. It works on the principle of Pressure Swing Adsorption (PSA) which is commonly used for the production of enriched oxygen from air [2–4]. Nitrogen from compressed air is removed by adsorption-desorption cycles in two zeolite columns operating in tandem, resulting in enriched oxygen in the product stream. The MOC was tested extensively as per WHO/ISO norms by ISRO.

Major components of MOC include a series of filters, oil free air compressor, PSA columns, medical grade zeolite, solenoid valves, oxygen accumulator, sensors for oxygen, pressure & flow, flowmeter and humidifier. PSA columns, oxygen accumulator and heat exchanger are designed and fabricated in-house for realizing the engineering model of MOC. Zeolites are microporous, aluminosilicate minerals

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commonly used as adsorbent materials. Medical grade Zeolite of particle size 0.4–0.9 mm is used in this unit. These selectively adsorb nitrogen from air under pressure and provide high purity oxygen. The effect of air flow rate, cycle time and column pressure on oxygen purity was studied thoroughly and operating conditions are optimized. This paper provides an overview of engineering aspects of sub-systems, selection of instruments involved in realizing the MOC.

The major objective of this study was to indigenously design, develop and demonstrate the technology for enrichment of oxygen from air stream by means of a portable Medical Oxygen Concentrator at an affordable cost to meet the oxygen demands of our country.

The developed oxygen concentrator is unique in itself as it is capable of catering the needs of enriched oxygen continuously for two patients at a time. The unit is additionally equipped with adequate safety precautions including safety relief valves between compressor and the PSA column, between oxygen accumulator and delivery to a patient. It also monitors and displays various parameters such as concentration of oxygen, flowrate and delivery pressure. The unit also has various alarm warnings for low/high flow, low/high pressure, low concentration of oxygen and start-up alarm. This will help facilitate the user to be cautious in case, any malfunctioning occurs in the unit. It also has an hour meter to display the total run time of the unit.

2 Material and Methods

2.1 Major Components

Following are the major sub-systems used in MOC and its functions (Table 1).

2.2 Major Sub-Systems

2.2.1 Oil Free Air Compressor

As per WHO norms, the inlet air to PSA columns should be free from oil contaminants. Hence, oil free air compressor is selected for MOC. The capacity of Oil free air compressor is calculated from Eqs. (1) and (2) [5, 6] based on the amount of inlet air flowrate required to generate 10 LPM of oxygen at the outlet.

$$\dot{W} = Z_1 \times T_1 \times \frac{n}{(n-1)} \times \left[\left(\frac{P_2}{P_1} \right)^{\left(\frac{n}{n-1} \right)} - 1 \right] \tag{1}$$

$$T_2 = T_1 \times \left(\frac{P_2}{p_1} \right)^m; \, m = \left(\frac{\gamma - 1}{\gamma \eta_p} \right); \, n = \frac{1}{(1-m)} \tag{2}$$

Table 1 Major components of MOC with their basic functions

Component	Function
Gross particle filter	To remove the impurities present in air (dust and other particles > 10 μ)
High efficiency particulate arrestance (HEPA) filter	To remove 99.99% of bacteria present in the air
Oil free air compressor with noise filter	To push air into the machine and forward it to the zeolite beds and noise filter is provided to meet the sound levels specified as per WHO norms (<40 dB)
Exhaust fan	To remove the heat generated inside the cabinet
Zeolite	Micro porous mineral; Have the ability to trap Nitrogen
PSA column	Filled with zeolite where oxygen separation takes place based on the principle of pressure swing adsorption
Valves (solenoid/SRV and check valve)	To divert air flow on swing mode between the two zeolite beds/To maintain supply pressure of air input and oxygen output
Oxygen accumulator	To maintain sufficient oxygen volume
Sensors (oxygen purity, pressure, flow)	To measure and monitor the parameters for display
Flow meter	To maintain the set oxygen flow (in LPM)
Humidifier	Bubble type, to humidify the oxygen to the patients
Pressure regulator	To regulate the pressure of oxygen at the outlet of the oxygen accumulator
LCD display	To display oxygen purity (%), flow rate (L/min), operating pressure (kPa) and alarms

where,

$\dot{W}$ Work done by compressor per mole
T1 Inlet temperature of air
Z1 Compressibility factor
γ Ratio of specific heat (Cp/Cv)
m Polytrophic temperature exponent
T_2 Outlet temperature of the air
P_1 Inlet pressure of the air
P_2 Outlet Pressure of the air
η_p Efficiency of Air Compressor.

2.2.2 Heat Exchanger

Warm air from the air compressor is passed through coil type heat exchanger, which is then cooled using air drawn from the ambient under forced convection using a fan. The quantity of heat to be removed and heat transfer area is calculated using the following equations [5, 6]

$$\dot{Q} = m_{Air} \times C_{Air} \times \Delta T_{Air} = U A \Delta T \tag{3}$$

$$\frac{1}{U_i} = \frac{1}{h_i} + r_i \frac{ln\frac{r_o}{r_i}}{k} + \frac{r_i}{r_o h_o} \tag{4}$$

where,

$\dot{Q}$ Heat duty of air cooler
Ui   Overall heat transfer coefficient based on inner tube
U   Overall heat transfer coefficient
ΔT Temperature difference across heat exchanger
A   Heat transfer area
ri   Tube inner radius
ro   Tube outer radius
h_i Tube inside heat transfer coefficient
h_o Tube outside heat transfer coefficient.

2.2.3 PSA Column

PSA column for oxygen separation from air was designed assuming a constant flow pattern, one dimensional model [5–8] as given below:

$$(1 - \epsilon_b)\rho_P \frac{\partial q}{\partial t} = k_m \bar{a}(C - C^*) \tag{5}$$

$$k_m \bar{a} = [\frac{1}{k_c \bar{a}} + \frac{d_p^2}{60 D_e m (1 - \epsilon_p)\rho_P}]^{-1} \tag{6}$$

$$Sh = 2.0 + 1.1 Re^{0.6} Sc^{1/3} \tag{7}$$

$$D_e = \frac{\epsilon_p}{\tau}(\frac{1}{\frac{1}{D} + \frac{1}{D_k}}) \tag{8}$$

$$D_k = 9.7x10^3 r_P \sqrt{\frac{T}{M}} \tag{9}$$

where,

$\in_b$ Bed porosity
ρ_P Particle density of adsorbent
q quantity of gas adsorbed/kg of adsorbent
$k_m\bar{a}$ Effective mass Transfer Coefficient
C Concentration of gas at the bulk
C* Concentration that can remain in equilibrium with adsorbent having adsorbate
$\in_p$ Pellet porosity
k_c Mass transfer coefficient
τ Tortuosity factor
D_e Effective diffusivity
D_k Knudsen diffusivity
r_p Pore radius

Sequence of steps followed in the realization of PSA column is summarized in Fig. 1.

Adsorption of nitrogen over zeolite molecules is considered to follow Langmuir's isotherm as per Eq. (10).
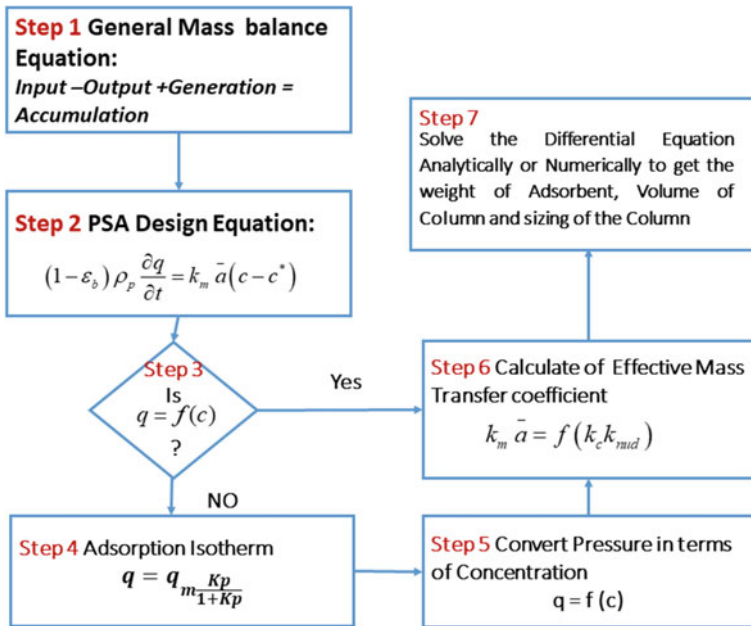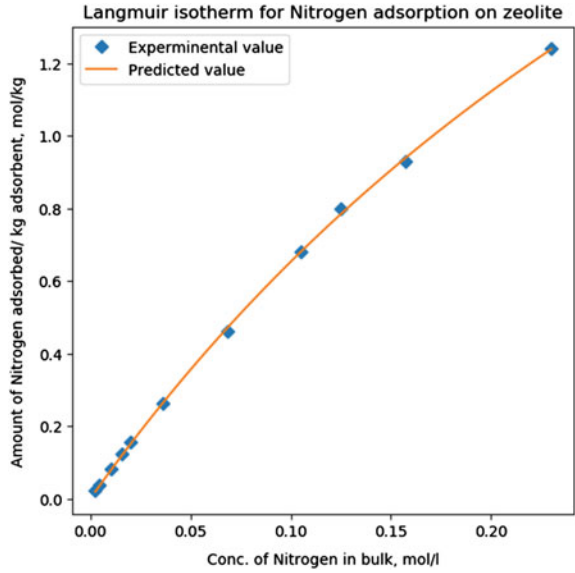
$$q = q_m \frac{Kp}{1+Kp} \tag{10}$$

Fig. 1 PSA column realization sequence

Fig. 2 Experimental and predicted Langmuir isotherm for adsorption of nitrogen molecules on zeolite

where,

qm   maximum quantity of gas adsorbed per kg of adsorbent
K   adsorption equilibrium constant
p   partial pressure of adsorbate.

The experimental values of q versus C as reported in the literature is compared with the predicted values to generate a suitable isotherm equation and the result is shown in Fig. 2.

The pressure drop across PSA column was calculated using Ergun equation.

$$\frac{\Delta P}{L} = \left[\left(\frac{150 \times u \times \mu_g \times (1 - \varepsilon_b)}{(\phi_s \times d_p)^2 \times \varepsilon_b^3} \right) + \left(\frac{1.75 \times \rho_g \times u^2}{\phi_s \times d_p \times \varepsilon_b^3} \right) \right] \qquad (11)$$

where,

L length of the Bed
ϕ_s Sphericity of the adsorbent
ε_b Bed porosity
μ_g Air viscosity
ρ_g Air density
u Velocity
ΔP Pressure drop
d_p Particle diameter

2.3 Realization of MOC

Oil free air compressor capacity, PSA column design including height of packing, diameter of bed, quantity of Zeolite, packing configuration etc. are designed from first principles. Photo of the MOC realized is shown in Fig. 3. A heat exchanger is also designed for effective removal of heat from compressed air. PSA column operates by swinging pressure between two columns through sequential operation of solenoid valves. The outlet from PSA column is connected to oxygen accumulator followed by bacterial filter, flow meter and humidifier. An LED display is mounted in the unit to display the values of discharge pressure, oxygen flowrate and oxygen concentration to the user. Considering the safety aspects, various alarms and interlocks are introduced into the unit which will alert the user for variation in flow, pressure and oxygen purity.

Table 2 gives the details on materials used for realization of sub-systems of MOC.

Fig. 3 Medical oxygen concentrator

**Table 2** Material of
construction for realized
sub-systems of MOC

Sub-system	Material of construction
External cabinet	Polypropylene sheet
Structural framework	GI coated MS square tube
Base plate	Powder coated MS
Internal support	Polypropylene sheet
Heat exchanger	Aluminium coil
PSA column and oxygen tank	Aluminium alloy (Al 6063)

3   Results and Discussion

## 3.1   *Effect of Air Flow Rate on Oxygen Concentration*

Air has a composition of Nitrogen (79%) and Oxygen (20.8%). The inlet air flow rate
to the PSA columns and its adsorption efficiency decides the required outlet flow rate
of oxygen with maximum % purity. The selection of compression with discharge air
flowrate is an important factor for rating the capacity of oxygen concentrator. From
the theoretical studies, a suitable air compressor with a discharge flow rate of 135
lpm was selected and by varying the inlet flow rate from 110 to 130 lpm, the outlet
concentration of oxygen @10 lpm constant output was studied. From the studies, it
was observed that oxygen concentration >82% @ 10 lpm was obtained for an inlet
air flowrate ranging from 115 to 125 LPM (Fig. 4).

Fig. 4 Air flow rate versus
oxygen concentration
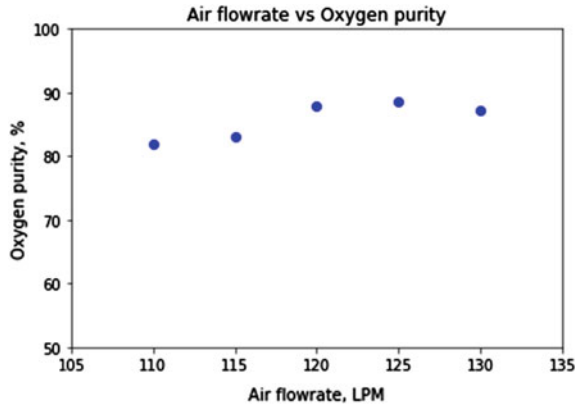
Fig. 5 Cycle time versus oxygen concentration
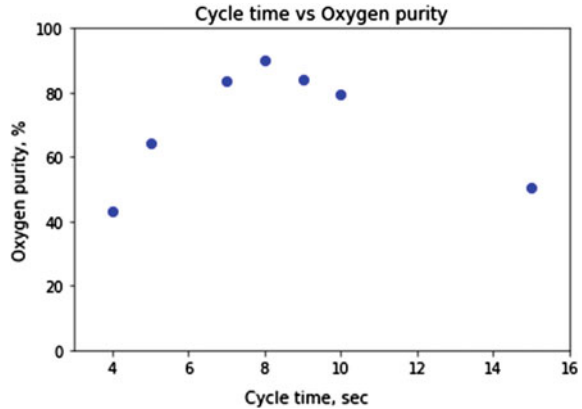


3.2 Effect of Cycle Time on Oxygen Concentration

In the PSA columns adsorption (pressurisation) and desorption (depressurisation) phenomena occurs. During adsorption time, the oxygen molecules pass through and Nitrogen molecules adsorbs on the zeolites due to the quadrupole effect phenomena. Cycle time refers to the total time involved in the generation of oxygen from adsorption. The cycle time is an important factor for the generation of high purity oxygen at rated capacity, here refers to 10 lpm outlet flowrate. The cycle time studies with the manipulation of timings in the programmed software from 4 to 15 s was studied.

From Fig. 5, it is observed that oxygen concentration >82% was obtained for a cycle time in the range of 7–9 s.

3.3 Effect of Pressure on Oxygen Concentration

In general, the adsorption of gas molecules occurs at high pressure. The pressure inside the PSA columns plays a significant role in the adsorption of nitrogen molecules onto the zeolite bed. A compressor with a maximum discharge pressure of 3 bar was selected to operate the PSA column max 2.5 bar. The pressure inside the PSA columns increases with the increase in the cycle time. The optimum pressure to be operated inside the PSA column is to be studied for maximum concentration of oxygen at rated flow. It was noted that PSA column pressure of 1.8–2.2 bar is essential for effective adsorption of nitrogen over zeolites to achieve maximum oxygen purity at a flowrate of 10 LPM (Fig. 6).

Fig. 6 Column pressure versus oxygen concentration
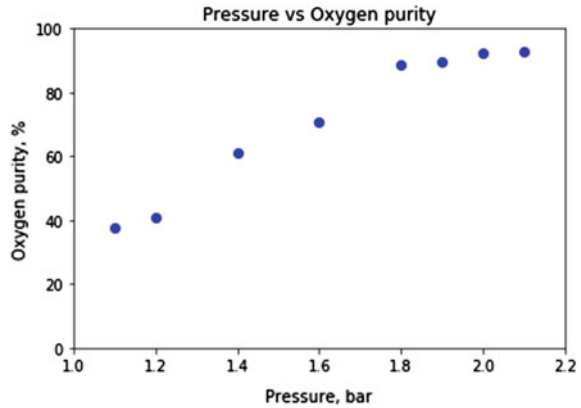
4 Conclusion

Oxygen concentrators are highly reliable but units are costly in the open market. Under this pandemic COVID-19 scenario, VSSC (ISRO) has undertaken quick efforts to design and develop a portable Medical Oxygen Concentrator at an affordable cost. SHWAAS is capable of supplying enriched oxygen continuously @10 LPM adequate for two patients at a time. The working principle involves Pressure Swing Adsorption (PSA) which is commonly used for the production of oxygen from air. The major features of the developed unit are summarized in Table 3.

The unit has successfully undergone various functional and safety tests identified including alarm checks for start-up period; low oxygen concentration; low/high flow; power supply failure; high air temperature; flow measurement accuracy test, and temperature sensitivity test (15 °C and 40 °C), endurance test (40 °C and 95% RH

Table 3 Major features of MOC

Parameter	Value
Rated power	550–600 W
Operating voltage	220 V/50 Hz
Oxygen flow	0.5–10 LPM
Oxygen concentration	85% minimum
Outlet oxygen pressure	50–70 kPa
Alarm	Power failure, low and high pressure, low purity
Noise	≤60 dB
Net weight	43 kg
Dimensions	600 mm H × 500 mm L × 400 mm W
LCD display	Oxygen concentration, flow rate, pressure

for 48 h), fire propagation tests, power efficiency test, protective earth testing (all conductive parts are connected to earth), software testing, EMI & ESD Tests.

An indigenous technology for producing medical grade oxygen (82% min) was successfully demonstrated through an Engineering Model of Medical Oxygen Concentrator complying with ISO/WHO norms to support the nation during this prevailing COVID-19 pandemic situation. This technology can be used for the commercial production of medical oxygen concentrators as part of Aatmanirbhar Bharat.

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