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On-Board Oxygen Generation Using High Performance Molecular Sieve

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ABSTRACT

The majority of high performance combat aircrafts presently being operated by Indian Air Force are fitted with conventional oxygen systems in which a replenishable store of oxygen is carried, most often as liquid oxygen and the flow of gas to each crew member is controlled by an individual pressure demand regulator in which the oxygen is diluted with cabin air to provide breathing gas. Moreover, in-flight refueling capability of present generation fighter aircraft has made it possible to fly for long durations (6 h to 8 h). In such case, the oxygen source becomes one of the limiting factors. In order to meet this requirement, a large supply of gaseous oxygen or liquid oxygen have proven to be a costly affair and the onboard oxygen generating system (OBOGS) has become a very convenient and attractive proposal. The OBOGS employs molecular sieves to adsorb nitrogen from engine bleed air using pressure swing adsorption technique, wherein two molecular sieve beds are continuously cycled between steps of pressurisation (adsorption) and depressurisation (desorption) to generate oxygen enriched breathing gas for aircrew. This paper describes the design of OBOGS using high performance Lithium-based low Silica X-type (Li-LSX) molecular sieves and its performance characteristics. It consists of two Zeolite beds filled with Li-LSX material which adsorbs nitrogen from engine bleed air tapped from environmental control system pipe line. The two beds are cycled by a 5/2 way solenoid valve. The input air is supplied to the solenoid valve through a coalescent filter to reduce moisture from it and a pressure regulator is fitted at the upstream of solenoid valve to regulate the system pressure. The experimental setup for evaluation of OBOGS is also discussed. The OBOGS, presented in this paper, meets all the performance requirements as specified in MIL-C-85521 (AS).

Keywords: Molecular sieves; Pressure swing adsorption; On-Board oxygen generation

1. INTRODUCTION

The present generation fighter aircrafts have capabilities far in excess to the human tolerance. Contrary to the earlier routine sorties of 1 h duration, the modern aircrafts are capable of flying a 6 h - 8 h sortie with air to air refueling. In order to meet the life support requirements of such aircrafts, it is essential to provide a system that could support the pilot for long duration by preventing the harmful effects of the flight stresses and also by augmenting his efficiency through a technologically advanced life support system. The on-board oxygen generating system (OBOGS) is the basis of such systems[1]. Use of OBOGS in military aircraft eliminates the logistic tail associated with liquid or gaseous oxygen system, improves safety, reduces aircraft turnaround time, extends mission duration and significantly lowers operational costs.

The primary source of breathing gas in OBOGS based life support system is engine bleed air. In most turbine-driven aircraft, bleed air is readily available at temperatures and pressures which can be conditioned to a range appropriate for oxygen generation. In most aircraft installations, bleed air from already conditioned environmental control system (ECS) line is tapped directly to OBOGS. The OBOGS system consumes only 0.5 Kg/min to 0.6 Kg/min of bleed air which is miniscule compared to throughput of modern turbine engines.

The critical component of OBOGS is the molecular sieve bed which separates oxygen from the aircraft engine bleed air by pressure swing adsorption (PSA) technology[2,3]. Using this technology, nitrogen is preferentially adsorbed in the molecular sieve at moderate pressures, thereby, concentrating oxygen. Molecular sieve has a greater affinity for nitrogen as the nitrogen is polar molecule, possesses a slight dipole moment which allows the nitrogen molecule to compete more effectively for adsorption sites within the molecular sieve. Oxygen and argon are nonpolar, and therefore, do not take part in adsorption process. Control of the oxygen concentration is accomplished by either diluting the product gas with cabin air or by varying one of the concentrator parameters, such as cycle time[4,5]. For a given design of oxygen concentrator, there is an optimum cycle time which maximises the oxygen concentration for a given product flow. Shortening the cycle time below this optimum value decreases the concentration of oxygen since the oxygen wave front does not have sufficient time to propagate through the molecular sieve bed, and the gas flow is reversed before the oxygen wave front reaches the end of the bed. If the cycle time is

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lengthened beyond the optimum time, the oxygen concentration decreases because nitrogen breaks through into the product gas. If air pressure is applied and the beds are not cycling, the bed receiving the air flow will eventually becomes saturated with nitrogen and no separation will occur. The oxygen concentration increases with increase in inlet pressure and operating altitude but decreases with increase in product flow rate.

2. MATERIALS AND METHODS

2.1 The On-Board Oxygen Generating System

The on-board oxygen generating system (OBOGS) is typically comprised of an air filter, a pressure regulating valve, a solenoid valve, two molecular sieve beds, a purge orifice, two Non-return valves (NRV) and a buffer tank as shown in Figure 1. The adsorbent beds (BED1 and BED2) are alternately cycled through steps of pressurisation and blow-down or venting. During each step of operation one bed is pressurised while the other bed is vented. During the first step of the cycle, pressurised air enters the bed and the molecular sieve adsorbs the nitrogen from the air. This pressurised bed produces a flow of concentrated oxygen which exits as product gas. During this same period the other bed is vented to atmosphere and then purged with a portion of the product oxygen which enters through the purge orifice. This venting and purging removes the adsorbed nitrogen from the molecular sieve and prepares the molecular sieve for the next pressurisation step. In the second step of the cycle the role of the beds is reversed ensuring continuous flow of oxygen enriched gas at the concentrator outlet. The two bed system provides output with unsteady gas pressure and fluctuating oxygen concentration and meets the breathing requirements of single and twin crew. The product gas pressure and concentration swings are damped out by using a small buffer tank (plenum) at the output of concentrator.

The air extracted from ECS is routed through a coalescing filter, pressure regulator and inlet solenoid valve to the molecular sieve beds. The inlet pressure regulator controls the pressure to the beds. The inlet air filter removes particulates including water and oil aerosols. While the conditioned bleed air is normally of good quality, the inlet filter is essential to protect the beds in the event of loss of an engine oil seal or failure of the water separator in the ECS. Since the bleed air may contain oil and water aerosols, the inlet filter is capable of coalescing these vapors into droplets and drains the residue from the filter element and housing. The liquid water must not contact the molecular sieve. An effective inlet air filter is vital for reliable OBOGS performance. The function of the inlet 5/2 way solenoid valve is to direct the flow of inlet air into the molecular sieve beds during pressurisation and depressurisation. The time required for the valve to pass through a step of bed pressurisation and depressurisation is termed cycle time. The control of oxygen concentration by OBOGS is achieved by two speed cycle operations involving switching of the cycle time between two discrete speeds, one fast and one slow. The slow cycle operation (high cycle time) produces low concentrations and faster operation (low cycle time) higher concentration. An electronic controller is employed to control the operation of solenoid valve.

In our prototype of OBOGS (shown in Fig. 2), the two beds containing zeolite material (molecular sieve) along with plenum are fabricated in monolithic block without any joints and fittings. The passages for input air supply and processed product flow are provided within the bed structure without any tubes. The number of joints and fittings is reduced to avoid leakage problems during use. By this design, the number of components in OBOGS concentrator assembly is reduced significantly resulting in higher reliability. A specially designed diffuser plate has been incorporated at the inlet of each bed to diffuse the air through the molecular sieves evenly and without any flow channeling. Plumbing and air passages are designed to handle higher flows at low inlet pressures. The purge orifice size has been optimised with cycle time to achieve higher concentration of oxygen in the product gas and the optimum cycle time established is 14s. Improved molecular sieve and filling technique has also been employed to obtain better performance. Molecular sieve beads are retained in position by applying spring load to prevent their movement during pressure swing, otherwise fracture of the molecular sieves and dusting can result due to sieve beads rubbing with each other.

The OBOGS developed by DEBEL is a retrofit to replace the existing LOX system. The system is designed within available envelop of LOX bay of fighter aircrafts and is mounted on the standard LOX system mounting plate presently being used in Tejas and Mirage aircrafts. It can be tailored for fitment into many of the fighter aircrafts of Indian Air Force.

2.2 Molecular Sieves

In oxygen concentrators, the molecular sieves typically used are zeolites of type A and X. Presently, most of aircraft

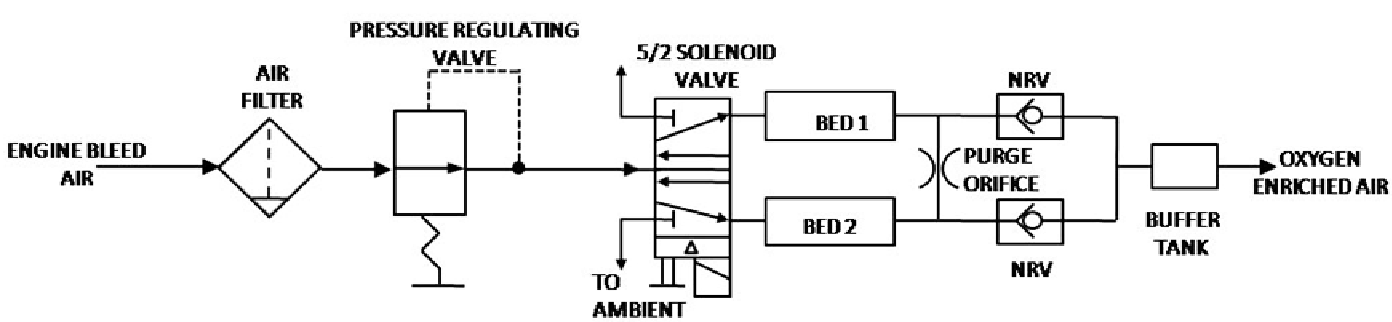

Figure1. Schematic of OBOGS

Figure 2. OBOGS developed by DEBEL.

molecular sieve oxygen concentrator systems use either 5A or 13X zeolite molecular sieve adsorbents. Both sieves are synthetic crystalline zeolites possessing a uniform crystal framework and, hence apertures or pores with precise dimensions. The basic building blocks of the crystal are SiO_4 and AlO_4 tetrahedra with exchangeable cations. The type of frame work and exchangeable cation will determine the dimensions of the crystal pores. The presence of these cations gives rise to the strong electrostatic fields within the crystal lattice. The degree to which a gas molecule adsorbs within a particular molecular sieve is primarily determined by the temperature, pressure, and the adsorbate molecule's kinetic diameter, polarity, and degree of unsaturation[6]. The choice of molecular sieve type for use in aircraft oxygen concentrators not only depends on product oxygen concentrations at various breathing flow rates, but also on the types and concentrations of contaminants foreseen in the aircraft operational environment. Molecular sieves containing the 13X crystal are more effective at removing chemical contaminants from the aircraft engine bleed air and give better OBOGS performance. Lithium based Low SilicaX-type zeolite (Li-LSX) is currently best available molecular sieve for oxygen generation and the same is employed in the OBOGS described in this paper. The molecular sieve used is OXYSIV MDX manufactured by M/s UOP, USA.

2.3 Experimental Setup

The schematic of test setup for performance evaluation of OBOGS is as shown in Fig. 3. The unit mounted is the test setup outside altitude chamber for on ground evaluation and is connected to the input supply through an ON/OFF Valve (OV-1), pressure regulator (PR-1) and ON/OFF Valve (OV-2). A pressure gauge (PG-1) is mounted at the inlet to monitor the inlet pressure to OBOGS. The unit is mounted inside the high altitude simulation chamber for carrying out the high altitude performance evaluation and is connected to the input supply through an ON/OFF Valve (OV-9) placed outside the chamber. A pressure regulator (PR-3) is placed inside the chamber to regulate the pressure and the pressure is monitored by pressure gauge (PG-3). The PR-3 regulates the input pressure to prevailing test altitude and is measured by PG-3 which is referenced to the altitude chamber pressure. The input air supply (AS) to the setup shall be provided at 6 bar (g) to 8 bar (g) pressure and 800 LPM-NTP flow. The pressure gauge PG-2 monitors the output pressure during various tests. The Altitude indicator (AI) is also a pressure gauge/sensor with pressure indicator. The flow control valve (FCV-1) controls the flow through the OBOGS and flow meters FM-1, FM-2 and FM-3 measure the outlet flow during the functional tests. Each flow meter is provided with ON/OFF Valve (OV-6, OV-7 and OV-8) at the inlet to divert the flow to it when in use. The Servomax make paramagnetic oxygen analyser (OA) measures the oxygen concentration in the product gas at various flow rates. The samples for O_2 concentration measurement were continuously drawn through pressure regulator (PR-2) and flow control valve (FCV-2) and a flow of 400 cc/min - 600 cc/min at 0.3 bar (g) pressure is given to the oxygen analyser. The vacuum pumps (VP-1 and VP-2) evacuate the chamber to different altitudes and the altitude in the chamber is controlled manually by controlling the ambient bleed air flow rate to the chamber though flow control valves FCV-3 and FCV-4. The ON/OFF valves OV-11 and OV -12 isolate the vacuum pump when not in use. The valve OV-10 is provided to bleed ambient air into the chamber to lower the altitude at faster rate. The solenoid valve of OBOGS is powered by M/s Retract Systems make power supply having inbuilt electronic timer.The product oxygen concentration was recorded at various flow rates from 0 to 100 LPM at normal temperature and pressure (NTP) i.e.,

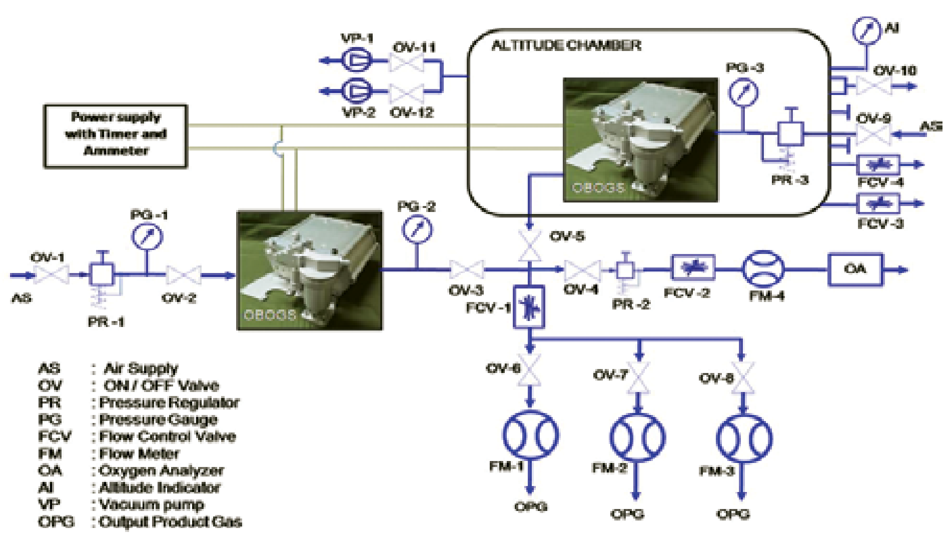

Figure 3. Experimental setup for evaluation of OBOGS.

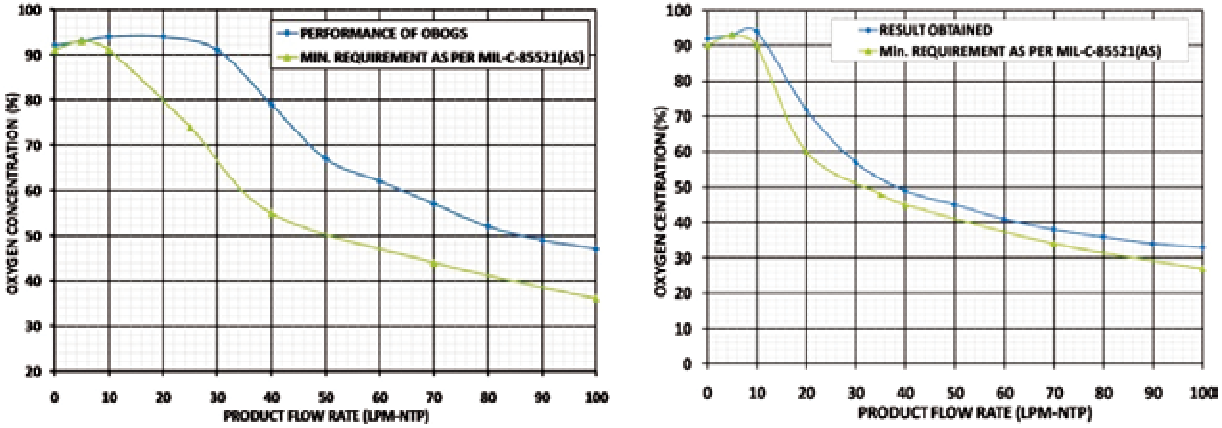

Figure 4. Comparison of performance of OBOGS with minimum O_2 concentration requirement as per MIL-C-85521(AS) at inlet pressure of (a) 3.0 bar (g) and (b) 1.7 bar (g).

at 21.1 °C and 1 bar(a). Here LPM refers to when no product flow is drawn at the outlet of the OBOGS. However, a flow of 400 cc/min - 600 cc/min is given to oxygen analyser (OA) for measurement of oxygen concentration.

3. RESULTS AND DISCUSSIONS

The OBOGS was operated at its optimal constant cycle time of 14 s while the step changes in product flow were induced by the flow control valve. The product flow was increased by steps of 10LPM (NTP). The experiments were conducted at 0, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 LPM(NTP). Average oxygen concentrations produced by OBOGS are shown in Fig. 4 at input pressure of (a) 3 bar (g) and (b) 1.7 bar (g). The product oxygen concentrations specified in Military Specification MIL-C-85521 (AS) are also depicted. The OBOGS was operated at its optimal constant cycle time of 14 seconds. Increasing the flow of product gas from OBOGS results in a progressive reduction of the concentration of oxygen. The increasing flow of product gas eventually causes the nitrogen wavefront to break through into the product gas. High oxygen concentrations are obtained by decreasing the flow of product gas, thereby allowing a sufficient quantity of purge gas to enter to the depressurised bed. Referring to Fig. 4 (a), at the low product flows (up to 30LPM) the oxygen concentration is about 90-94% and the concentration drops rapidly as the product flow increases. At both, a moderate flow rate of 30 LPM and the maximum flow rate of 100 LPM for dual crew requirement, the oxygen concentrations are above the desired minimum concentration level as specified in MIL-C-85521(AS). The maximum oxygen concentration specification is imposed to prevent acceleration at electasis[7]. To meet the oxygen concentration as per physiological requirements under various flight profiles, the OBOGS is operated with longer cycle time. Longer cycle times generally reduce the product oxygen concentration by allowing the nitrogen component to penetrate deeper into molecular sieve. Hence, a greater amount of nitrogen exits the bed with the product gas. Shorter cycle times increase the oxygen concentration but also significantly increase the air consumed and leads to a high concentrator failure rate.

The performance of the OBOGS at inlet pressures of 1.5, 1.75, 2.0, 2.5, and 3.0 bar (g) for product flows in the rage of 0 to 100 LPM-NTP is shown in Fig. 5. The oxygen concentration measured increased with inlet air pressure due to higher adsorption capacity of molecular sieves at higher pressures. The oxygen concentrations above 3 bar(g) inlet pressure did not increase due to the internal pressure regulating valve of OBOGS which limits the pressure to 3.0 bar (g).

The OBOGS was also tested for purity delivered at altitudes of 10, 20, 30, 40 and 50 thousand feet. The entire unit was exposed to the ambient pressures specified with the nitrogen enriched exhaust venting directly to these altitudes. Figure 6 shows oxygen concentration v/s product flow rate for constant inlet pressure of 1.7 bar (g) and with inlet air at ambient temperature at altitudes of 10 through 50,000 feet. As seen from these results oxygen concentration increases with altitude due to efficient bed cleaning at higher altitude. The venting of nitrogen to ambient is efficient and relatively less amount of it is retained in the sieve cages at higher altitudes.

The other critical factors affecting the performance of OBOGS are temperature of inlet air and molecular sieve activity. The oxygen concentration falls at higher temperatures

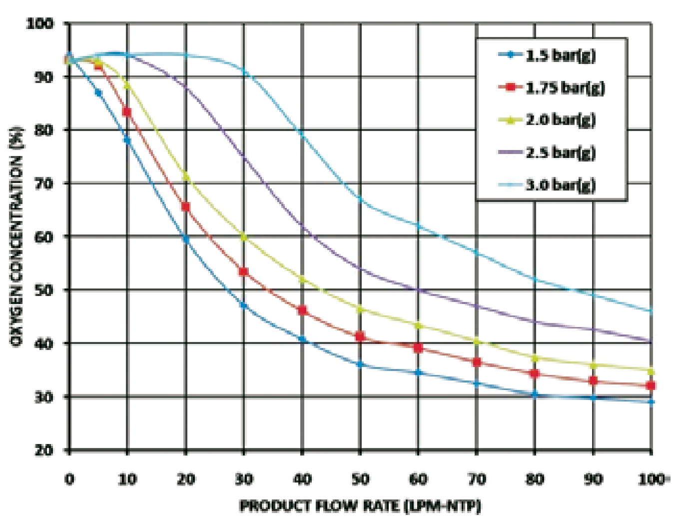

Figure 5. Performance of OBOGS at inlet pressure of 1.5, 1.75, 2.0, 2.5 and 3.0 bar (g) and product flows up to 100 LPM-NTP.

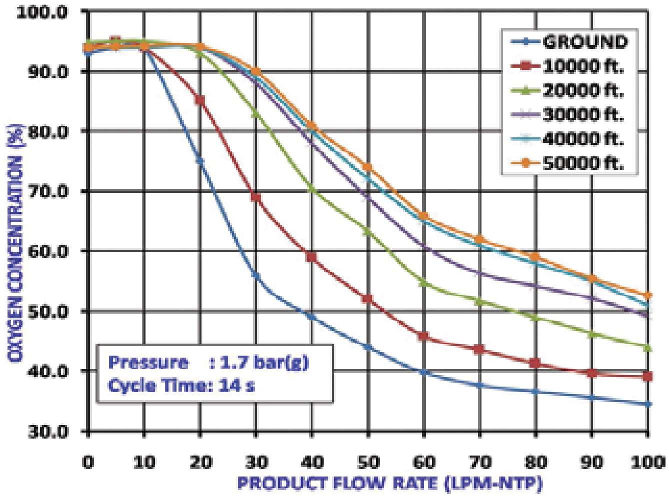

Figure 6. Performance of OBOGS at higher altitudes.

above 50 °C due to reduction in nitrogen adsorption capacity of molecular sieves[8]. This situation rarely arises as the temperature of air drawn from ECS does not exceed 35 °C. The loss of molecular sieve activity also reduces the concentration of oxygen in the product gas. The major cause of loss of activity is water adsorption. The coalescent filter traps and eliminates most of the water before it could enter the molecular sieve beds which emphasize the importance of this component of OBOGS. The water which enters the beds is eliminated from the beds by the purge during desorption phase of the PSA cycle.

4. CONCLUSIONS

The OBOGS developed in this work has demonstrated the ability to provide a sufficient quality and quantity of breathing gas for single crew and twin crew aircrafts. Laboratory testing proved the equipment and it meets the performance requirements specified in MIL-C-85521 (AS). The oxygen concentration generated by OBOGS increases with increase in inlet pressure and aircraft altitude but decreases with increase in product flow rate.

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