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A Pressure Swing Adsorption Process for Production of 23-50% Oxygen-Enriched Air

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Abstract

A simple pressure swing adsorption process for direct production of low to medium purity (23-50%) O_2-enriched gas from ambient air is described. The process provides a high O_2 production capacity per unit amount of the adsorbent and a high O_2 recovery combined with a very low energy requirement for the separation. The performance of the process using three different air separation adsorbents is described.

INTRODUCTION

A large number of pressure swing adsorption (PSA) process concepts for the production of oxygen-enriched air from ambient air have been patented in the last 20 years, and several of these processes have been commercialized (*1-6*). Most of these processes are designed to produce a high-purity oxygen-enriched stream containing 80-95% O_2, which finds application in biological wastewater treatment, home medical use, paper pulp bleaching, etc. There are also certain industrial applications such as enhanced combustion of various kinds and improved oxidation in chemical and biochemical reactors where oxygen-enriched air containing oxygen concentrations on the order of 23-35% is needed for efficient operation. It may be cost effective to produce a low or medium-purity, oxygen-enriched air directly from ambient air by the use of PSA

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technology rather than by diluting the high-purity O_2 product for these applications.

An earlier PSA process was designed to produce ~30% O_2 enriched air (*7*) from ambient air by selective adsorption of N_2 on a zeolite adsorbent. The process consisted of six cyclic steps, and it required a source of bone dry, CO_2-free air for partial desorption of the adsorbed N_2 by purging the adsorbent with that gas. The production of such a purge gas can be expensive and will require additional equipment.

Recently, a very simple PSA process was developed by Air Products and Chemicals, which can be used to directly produce 23–50% O_2-enriched air from the ambient air (*8*). The process is a very efficient method of air separation with a very low energy requirement. It is called the Oxy-Rich process. The purpose of this paper is to describe this process and its performance using different N_2-selective adsorbents for air separation.

THE OXY-RICH PSA PROCESS

There are two modes of operation of this process. The first mode consists of only three cyclic steps as described below.

1. Adsorption Step

The ambient air is compressed and fed into an adsorber packed with a layer of a desiccant in the feed air end and a layer of a nitrogen-selective adsorbent in the product O_2 end. The valve at the product end of the adsorber is kept closed during this step so that the adsorber is pressurized to the highest pressure level (P_A) of the PSA cycle by air. The compressed air is cooled to near ambient temperature prior to its introduction into the adsorber. This removes a part of the moisture from the air by condensation. The remaining H_2O is removed by selective adsorption on the desiccant layer so that the nitrogen–oxygen separation in the subsequent N_2-selective adsorbent layer is not affected by the presence of water.

2. Cocurrent Depressurization Step

The introduction of air to the adsorber is stopped when its pressure reaches P_A. The adsorber is then depressurized to an intermediate superatmospheric pressure level of P_I by withdrawing gas through the product end (cocurrent to the direction of feed air). The effluent gas consists of the oxygen-enriched product gas which is dry and CO_2-free. The purity of the effluent gas can be varied by changing P_I.

3. Countercurrent Depressurization Step

At the end of Step 2, the adsorber is depressurized from P_I to a near ambient pressure level (P_D) by withdrawing gas through the feed end of the adsorber (countercurrent to the direction of feed air). The desorbed gas contains N_2, O_2, H_2O, and CO_2 which is wasted.

The adsorber is now ready to undergo a new cycle starting from Step 1.

This simple PSA cycle can be used to produce a 23–26% O_2-enriched air from ambient air very efficiently. This mode of operation is, however, not very useful if a higher purity (26–50%) O_2 product is desired because the O_2 recovery decreases significantly. In that case, the second mode of operation of this process can be practiced, which introduces the following additional step in the above-described PSA cycle.

4. Countercurrent Purge Step

At the end of Step 3 of the first mode of operation, the adsorber is purged with a part of the O_2-enriched product gas from Step 2 by introducing the gas through the O_2 product end (countercurrent) at near ambient pressure level. The remainder of the effluent gas from Step 2 is withdrawn as the O_2 product. The effluent from the adsorber during this step contains further desorbed N_2 along with H_2O, CO_2, and O_2 which is wasted. The quantity of the purge gas used in this step determines the purity of the O_2 product by this process.

The cycle is then repeated starting from Step 1.

The O_2 enriched product gas is produced at a pressure varying between P_A and P_I in either mode of operation of this process. Thus the product gas can be delivered at a positive pressure (e.g., 5 psig) without further compression.

A three-column PSA system, as shown in Fig. 1, is necessary for operation of this process by the first mode in order to have a continuous product O_2 withdrawal and continuous operation of the feed compressor. A four-column PSA system, as shown by Fig. 2, will be necessary for the second mode of operation of this process. A product O_2 surge tank may

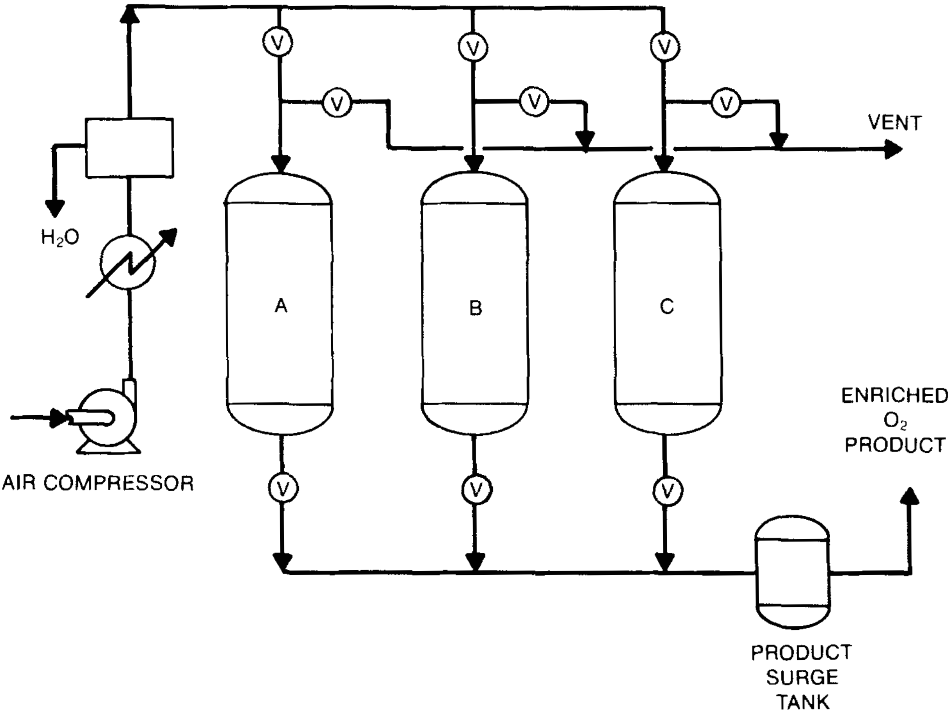

FIG. 1. Schematic flow diagram for the Oxy-Rich process: First mode of operation.

be required to smooth out the flow rate and concentration fluctuations of the O_2-enriched product gas.

PROCESS PERFORMANCE

A multicolumn pilot unit was used to evaluate the performance of the Oxy-Rich process by both modes of operation. The columns were 4 inches in diameter and 144 inches long, and they were externally insulated. Three different types of zeolites (mordenite, A, and X) were tested as the N_2 selective adsorbent in the process.

Figure 3 shows the pure N_2 and O_2 adsorption isotherms on these zeolites, and Table 1 reports their thermodynamic selectivities (S) for adsorption of N_2 (Component 1) over O_2 (Component 2) as a function of temperature (T). The selectivity is defined by $S = (n_1 y_2/n_2 y_1)$, where n_i and y_i are, respectively, the specific amounts adsorbed and the equilibrium

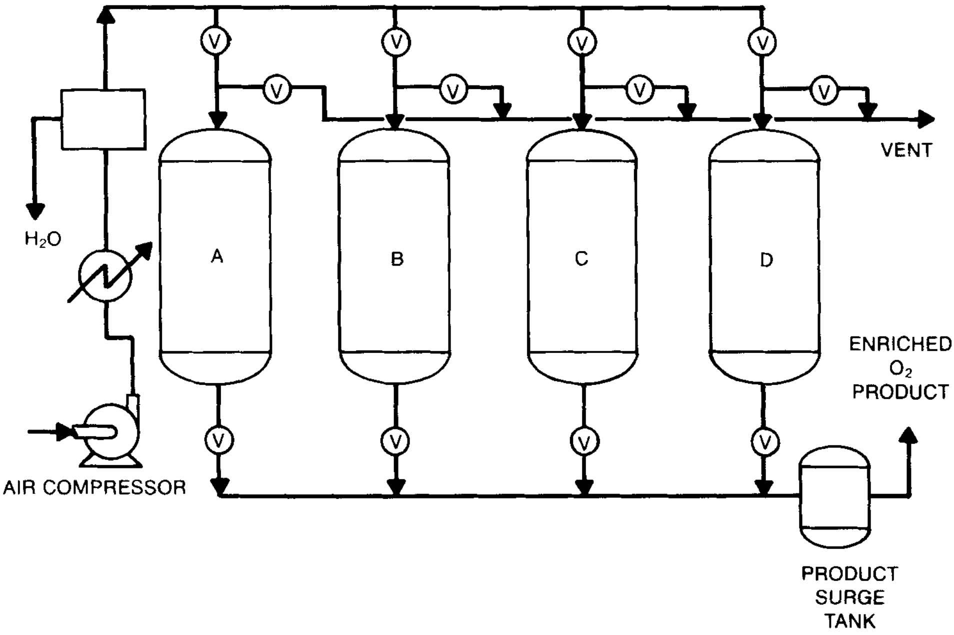

FIG. 2. Schematic flow diagram for the Oxy-Rich process: Second mode of operation.

gas phase mole fractions of Component i (= 1, 2). S decreases with increasing temperature, but it is practically independent of the gas pressure (P) and composition in the pressure range of 0-5 atm for these adsorbents. The table also shows the isosteric heats of adsorption of pure N_2 and O_2 on these adsorbents.

These data show that the N_2 and O_2 adsorption capacities from air and the selectivities of N_2 adsorption over O_2 decrease for these adsorbents in the order mordenite > A > X. The strengths of adsorption of N_2 and O_2 on these zeolites also follow the same order as indicated by the isosteric heats of adsorption.

The kinetics of ad(de)sorption of N_2 and O_2 in the pelletized forms of these zeolites are relatively fast because they are controlled by diffusion through the macroporous binder matrix used for bonding the small (1-5 μm) zeolite crystals. The typical diffusional time constants for both N_2 and O_2 were in the range of 0.2-1.0 s^{-1}, depending on the conditions of operation.

The Oxy-Rich process steps were carried out in a continuous cyclic manner and the process data were measured after the cyclic steady state

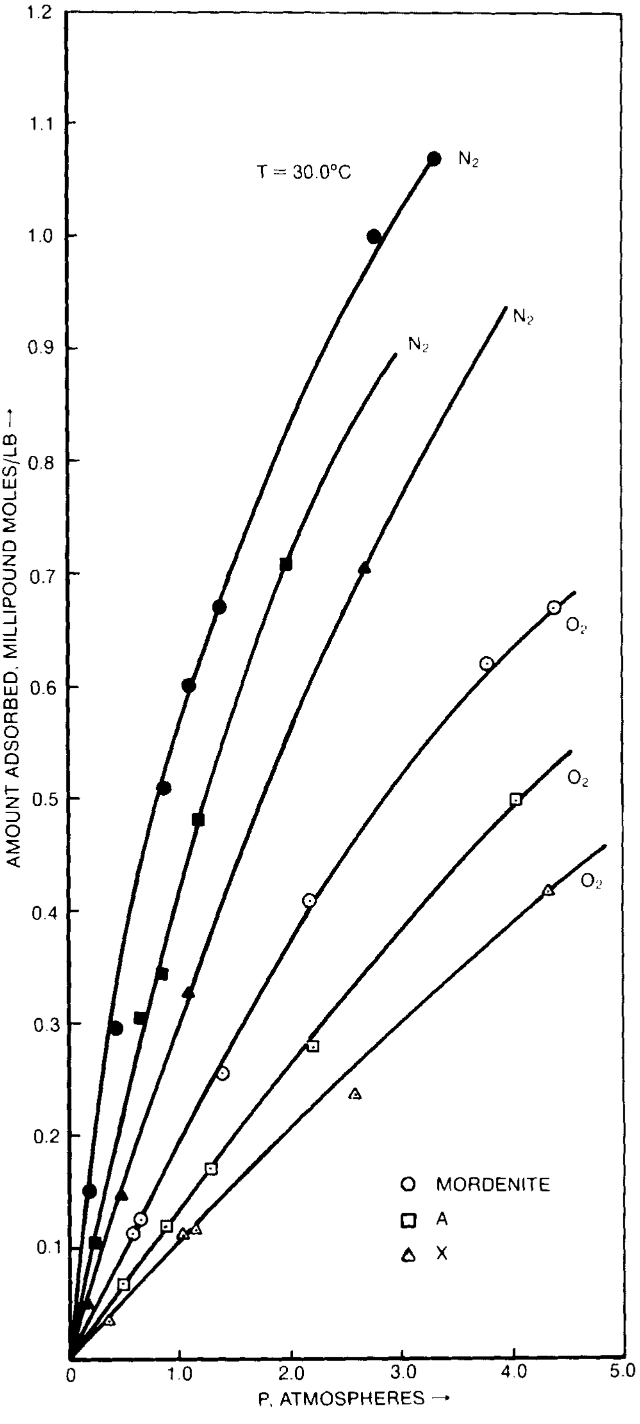
T = 30.0°C
N$_2$
N$_2$
N$_2$
O$_2$
O$_2$
O$_2$
○ MORDENITE
□ A
△ X
AMOUNT ADSORBED, MILLIPOUND MOLES/LB →
P, ATMOSPHERES →
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.0
2.0
3.0
4.0
5.0

TABLE 1
Selectivity of Adsorption of N_2 over O_2 and Isosteric Heats of Adsorption of Pure Gases

	Selectivity of adsorption of N_2 over O_2 (S)			Isosteric heat of adsorption (kcal/mol)	
	20°C	30°C	50°C	N_2	O_2
Mordenite	3.89	3.63	3.15	6.22	4.90
A	3.76	3.47	2.95	5.38	3.87
X	3.30	3.13	2.86	4.43	3.54

was achieved. Figure 4 shows the overall performance of the process by the first mode of operation using an adsorption pressure (P_A) of 3.72 atm. The figure shows the O_2 production capacity by the process as a function of O_2 product purity (y_{O_2}) which was varied by changing the value of P_I.

The O_2 product capacity is defined by the amount (millipound moles) of contained O_2 in the product per unit amount (pound) of zeolite in the adsorber per cycle. Thus, if the total amount of O_2-enriched product gas was B lb-mol/lb of zeolite/cycle having an O_2 mole fraction of y_{O_2}, then the contained oxygen production capacity was By_{O_2} (lb-mol/lb of zeolite/cycle).

Figure 5 shows the net O_2 recovery from the feed air as a function of y_{O_2} corresponding to the performance described by Fig. 4. The O_2 recovery (R) is defined by $By_{O_2}/0.21F$, where F is the amount (millipound moles) of air feed used per unit amount of the zeolite adsorbent per cycle.

It may be seen from Figs. 4 and 5 that both the O_2 production capacity and the O_2 recovery decrease as the O_2 purity of the product is increased. However, the first mode of operation of the process can provide a large O_2 production capacity and recovery if the O_2 purity in the product is between $0.22 \leqslant y_{O_2} \leqslant 0.26$. This is particularly true for the X zeolite, where the O_2 recovery from the feed air can be higher than 80%, and the O_2 production capacity is more than 0.09 millipound moles/lb when y_{O_2} is less than 0.26.

This high O_2 recovery and capacity by the Oxy-Rich process to produce the low-purity, O_2-enriched product gas directly makes this process very

FIG. 3. Pure N_2 and O_2 adsorption isotherms on mordenite, A, and X zeolites at 30°C.

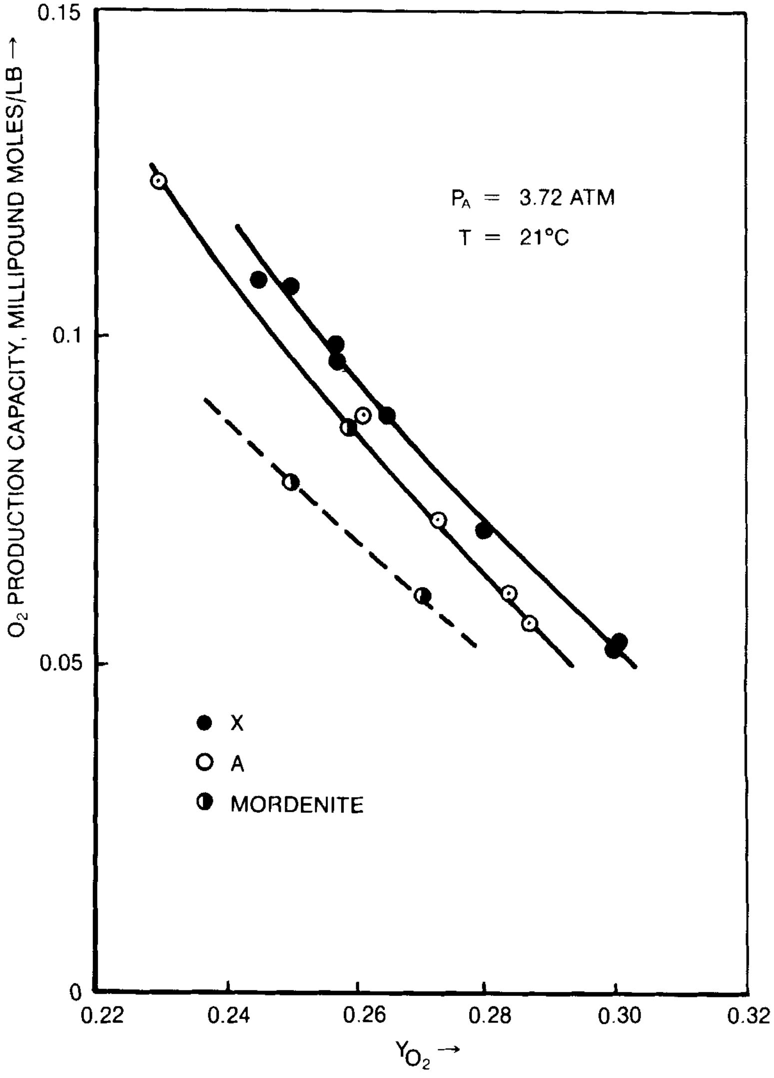

FIG. 4. O_2 production capacity as a function of O_2 product purity by the Oxy-Rich process: First mode of operation.

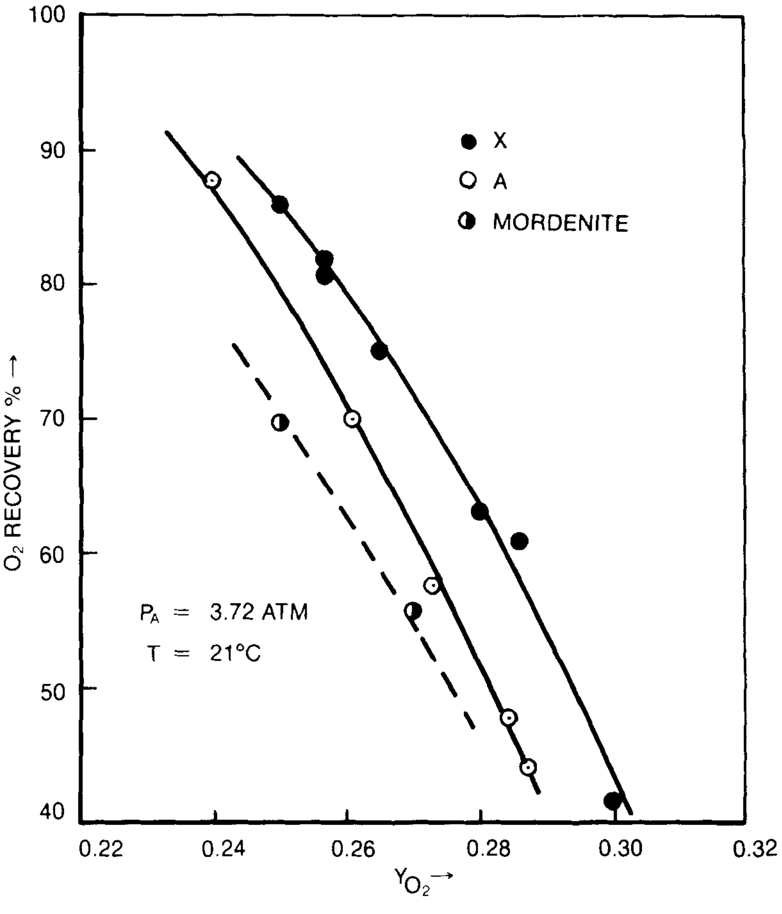

FIG. 5. O_2 recovery as a function of O_2 product purity by the Oxy-Rich process: First mode of operation.

attractive economically. The high O_2 recovery translates into a lower energy of separation because higher O_2 recoveries require smaller amounts of feed air to be compressed per unit amount of contained O_2 in the product ($F/By_{O_2} = 1/0.21R$). On the other hand, the high O_2 production capacity means that a small adsorbent inventory is required for the process. By comparison, it should be mentioned that a typical O_2 production capacity for producing a 90% O_2-enriched stream by a conventional PSA process, operating between a super atmospheric adsorption pressure and a near-ambient desorption pressure, is 0.015

millipound moles/lb of zeolite, and the corresponding O_2 recovery is only between 35–50% (*6*).

A very interesting feature of the process performance described by Figs. 4 and 5 is that the X zeolite gave the highest O_2 production capacity and recovery for a given O_2 purity among the three zeolites tested. The O_2 production capacities of the X zeolite were about 10 and 35% more than those for the A and the mordenite, respectively, in the entire y_{O_2} range of 0.23–0.28. The absolute values of O_2 recovery for the X zeolite were also about 10% more than that of the A zeolite, and about 15% more than the O_2 recovery by the mordenite. This trend may be surprising because the capacity and selectivity of adsorption of N_2 from O_2 decreased on these zeolites in the order mordenite > A > X. The reason for the observed performance is that the desorption of N_2 in the first mode of operation of the Oxy-Rich process is achieved by a mild pressure reduction from P_I to P_D, and the adsorbent which holds the N_2 most weakly (X in this case) is cleaned best under these conditions. This provides a larger working adsorption capacity for N_2 which, in turn, increases the O_2 production capacity by this process. The selectivity of adsorption for N_2 is not very critical in this process because of the low purity of the O_2 product gas. In contrast, both high N_2 adsorption capacity and selectivity are preferred when a high-purity O_2 product is required (*6*).

Figures 4 and 5 show that both the O_2 production capacity and recovery, by the first mode of operation of this process, decrease substantially when y_{O_2} is increased. This can be remedied by using the second mode of operation of the Oxy-Rich process. Figure 6 shows the performance of this mode of operation (open circles) using the X zeolite. The figure also shows the performance by the first mode of operation (filled circles) for comparison. It may be seen that a significant improvement in the O_2 production capacity and recovery in the y_{O_2} range of 0.26–0.50 was obtained by introducing the purge desorption step in the process, which provides better regeneration (desorption of N_2) of the adsorbent. A decent O_2 production capacity (0.065 millipound moles/lb) and O_2 recovery (55%) can be obtained even at an O_2 product purity level of 40.0%.

Figure 7 shows the effect of the highest adsorption pressure level (P_A) on the process by both modes of operation using the X zeolite. The dashed lines represent the process performance for a P_A of 3.04 atm while the solid lines (reproduced from Fig. 6) describe the performance for a P_A of 3.72 atm. It may be seen that the O_2 production capacity increases significantly when P_A is increased, but the O_2 recovery is affected very little by the change in P_A. Thus, increasing P_A decreases the adsorbent

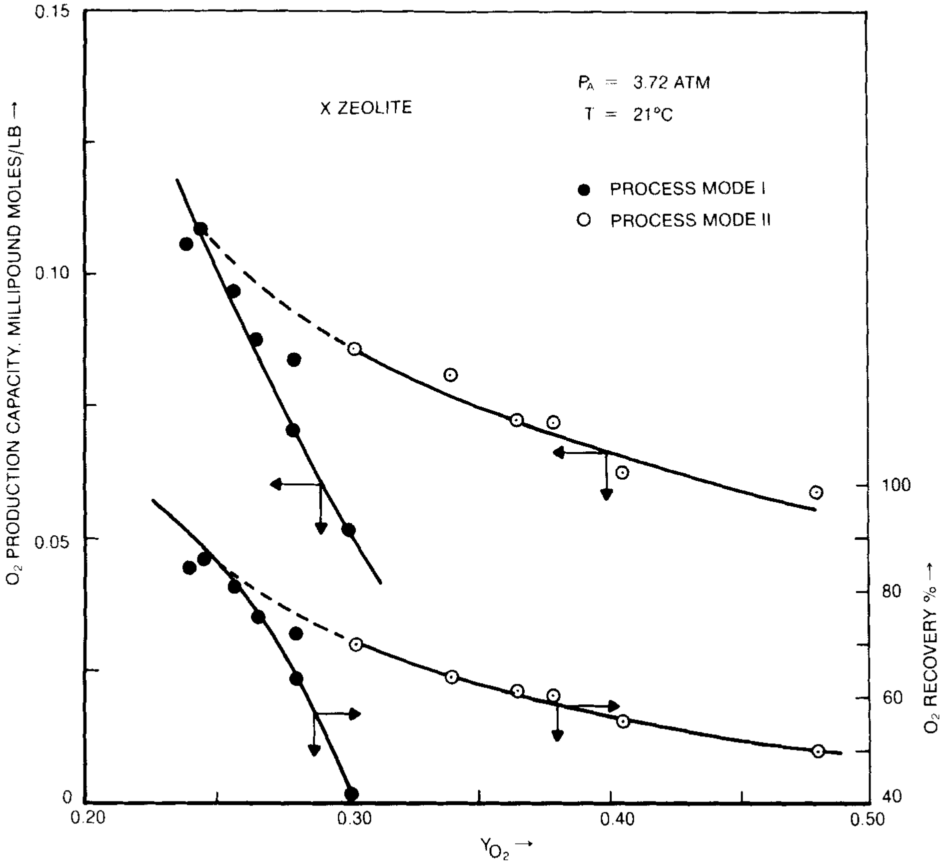

FIG. 6. O_2 production capacity and recovery as a function of O_2 product purity by the Oxy-Rich process: Comparison between the first and second modes of operation.

inventory for the process, but it increases the compression energy for the separation.

ENERGY OF SEPARATION

The energy of separation for the Oxy-Rich process is supplied through the feed air compressor. However, the entire air feed to the adsorber is not compressed to the highest pressure level (P_A) of the PSA cycle. The compressor discharge pressure varies between 1 atm and P_A during the

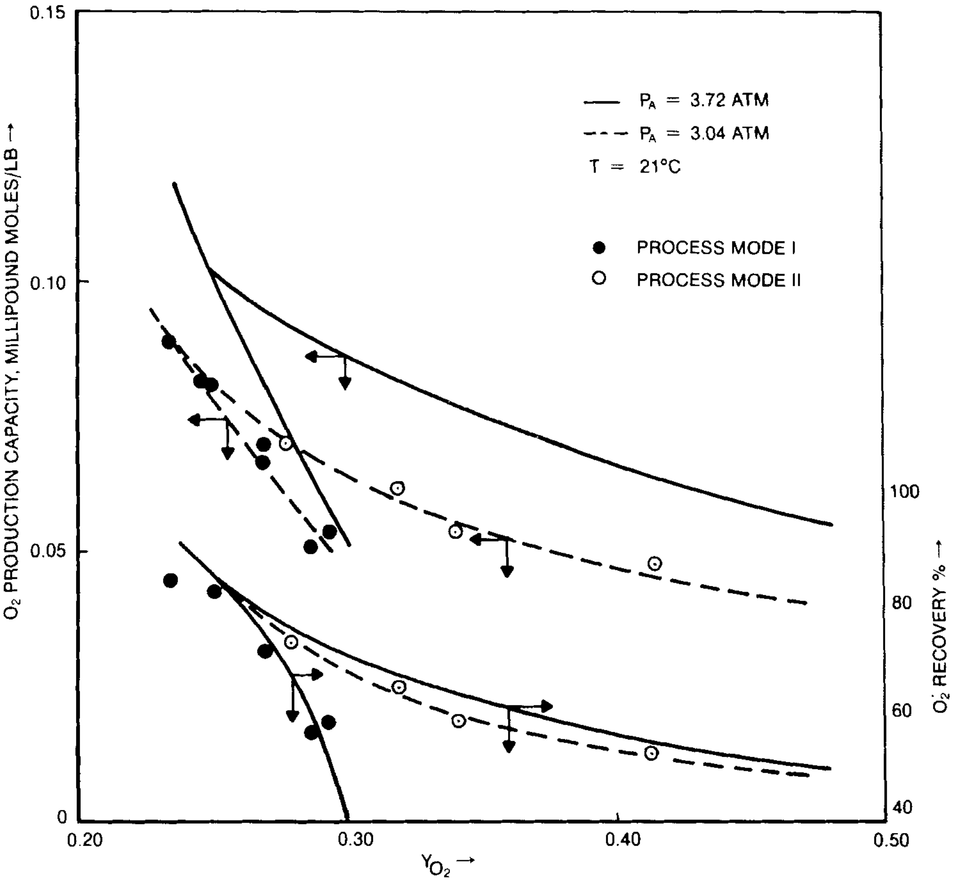

FIG. 7. Effect of adsorption pressure on the performance of the Oxy-Rich process.

adsorption step. This reduces the total energy required for the compression of the feed air.

The differential energy, dE (kWh), required to compress a differential amount, dQ (lb-moles), of air adiabatically from the ambient pressure to a pressure level of P (atm) may be written as (9):

$$dE = 1.384(P^{0.286} - 1)dQ \tag{1}$$

Equation (1) assumes that the feed air is at 70°F and the efficiency of the compressor is 78%.

Equation (1) may be integrated to obtain the total energy required (E, kWh) for the compression process:

$$E = 1.384 \int_0^{Q_A} (P^{0.286} - 1)dQ \tag{2}$$

where Q is the cumulative amount (lb-moles) of air compressed and fed to the adsorber per cycle when its pressure is raised from 1 atm to P (atm). P_A is the highest pressure level in the PSA cycle and Q_A is the total amount of feed air introduced into the adsorber per cycle.

It was found that Q was a linear function of P for the X zeolite, so that

$$Q = Q_A \frac{(P - 1)}{(P_A - 1)} \tag{3}$$

Q_A is related to the contained O_2 production capacity (By_{O_2}) by

$$Q_A = \frac{(By_{O_2})W}{0.21R} \tag{4}$$

where R is the O_2 product recovery at a purity of y_{O_2} and W is the total amount (lb) of zeolite adsorbent in the adsorber. Equations (2)–(4) may be combined to obtain the specific energy of separation. ($\bar{E}$, kWh/lb-mole) for the Oxy-Rich process per unit amount of contained O_2 product $[\bar{E} = E/(By_{O_2})W]$ as

$$\bar{E} = \frac{6.59}{R(P_A - 1)} \left[\frac{(P_A^{1.286} - 1)}{1.286} - (P_A - 1) \right] \tag{5}$$

Equation (5) shows that $\bar{E}$ decreases with decreasing P_A and increasing R.

An example of the specific energy of separation required by the Oxy-Rich process was calculated for an O_2 product at 5 psig containing 25% O_2 using the data of Fig. 7. The X zeolite gave an O_2 recovery of 83% for this product purity using an adsorption pressure of 3.04 atm. Equation (5) shows that $\bar{E}$ for this condition of operation is only 1.7 kWh/lb-mol of contained O_2 product.

A comparable energy of separation for a PSA process to make 90% O_2 product, operating between an adsorption pressure of 3 atm and a desorption pressure of 1 atm, is between 6–9 kWh/lb-mol of contained O_2 product (*10*). Thus, the net energy required to produce an O_2 product at a pressure of 5 psig containing 25% O_2 by diluting a 90% O_2 contained gas with ambient air compressed to 5 psig is 2.0–2.7 kWh/lb-mol of containing O_2 product. This shows that the direct production of low purity O_2 product by the Oxy-rich process can save considerable energy.

CONCLUSIONS

The Oxy-Rich PSA process provides a very efficient means of directly producing a low to medium purity (23–50%) oxygen-enriched product gas from ambient air. It is a low capital, low energy separation process. The first mode of operation of the process, using a three-bed PSA system, is best suited when the desired O_2 product purity is between 23–26%. The second mode of operation of the process, using a four-bed PSA system, is necessary when the O_2 product purity is between 26–50%.

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