COMPUTER MODELING AND OPTIMIZATION OF OBOGS WITH CONTAMINANTS

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SUMMARY

This report covers the first year of a two year project dealing with the development of an OB0GS computer model to aid in design and specification of these oxygen generation systems for the Army's in-flight, medivac, and field hospital use. A model which predicts the performance of a two bed system for O2 - N2 separation has been delivered and installed on the U.S. Army Aeromedical Research Laboratory (USAARL) VAX computer. A model to predict the propagation of contaminants in these beds is currently under development.
STATEMENT OF PROBLEM

The ultimate goal of this research is to insure proper design of molecular sieve oxygen generation systems for the U.S. Army's in-flight, medivac, and field hospital use. Specifically the research involves further development of an OBOGS model to include the effects of contaminants in the feed air. This OBOGS model can be used to optimize and design OBOGS systems with respect to system parameters such as cycle time and bed and valve dimensions.
BACKGROUND

The elimination of the need for liquid oxygen storage for in-flight and portable ground use by means of oxygen generation equipment is an especially attractive goal to the military. Such an accomplishment would not only increase safety, but would relieve the logistics requirements of LOX supply which is costly and can restrict mission durations. Although other means are available, the molecular sieve method of generating enriched oxygen breathing gas is the most feasible for in-flight usage. The molecular sieve system weighs little, and has the potential of high reliability.

A molecular sieve system utilizes the process of physical adsorption to separate air into its components. Although a detailed discussion of adsorptive phenomena is beyond the scope of this report, a brief overview of the process is in order.

Adsorption is the process by which particular types of molecules contained in a liquid or gas are selectively collected onto a solid surface. The term "adsorbent" refers to the collecting material while the "adsorbate" is that material which is collected. In physical adsorption (as opposed to chemical adsorption), Vander Waal's forces create the bonds between adsorbent and adsorbate; thus, the interaction is weak. The solid adsorbent is typically a highly porous, granular material with interior pores of diameters on the order of .4nm, and with the total pore volume approaching 50% of that of the whole particle. Clearly, abundant internal storage space is available in the sieve material.

Adsorptive separation is the process by which the molecular sieve system would separate air into its components and thereby produce an enriched oxygen product gas.

To maintain continuous operation from an adsorption plant, molecular sieve beds must be periodically "regenerated" by a period of desorption in which the adsorbate is removed from the sieve material. There are several ways in which
desorption may be accomplished. "Thermal Swing" involves heating the bed to a
temperature at which the adsorptive capacity of the bed material is so low that
the adsorbate must leave the molecular sieve internal surfaces. "Pressure
swing" creates the same effect by reducing the adsorptive capacity at
essentially constant temperature. "Inert purge stripping" removes the
adsorbate at constant temperature and pressure by the passage of fluid
containing no adsorbate molecules, in which the adsorbate is soluble.
"Displacement desorption" occurs when a fluid containing a high concentration
of a more strongly adsorbed molecule is passed through the bed. The pressure
swing adsorptive cycle, PSA, is of primary concern in this work.

Two important technological developments of recent decades have created the
possibility of in-flight and portable air separation systems. Firstly, the
domestic development and production of synthetic zeolites, a molecular sieve
material, affords the availability of reproducible adsorbents. Secondly, the
inception and development of the pressure swing adsorption cycle (PSA) has been
found to yield a satisfactory production system.

The PSA process usually employs two or more molecular sieve beds and cycles
them in a manner such that a continuous flow of enriched oxygen product gas is
attained. Sufficient gas is produced to meet demand and to regenerate
exhausted beds via pressure swing method. By use of an appropriate zeolite,
oxigen or nitrogen (for fuel tank inerting) can be concentrated to almost any
value up to 95% for O2 and 99.8% for N2. The product gas can be delivered
at normal room temperature and at some nominal pressure as desired. The
process cost is basically the cost of air compression for the feed gas.

Traditionally, PSA systems have found applications in industry and have
been very large systems which were relatively insensitive to the various rate
phenomena of the adsorption process. In the development of a scaled-down
system for portable applications, knowledge of transient behavior becomes
exceedingly important due to the vastly increased sensitivity of system output
to rate phenomena and the requirements of minimal size and weight.
Additionally, the effects of potentially harmful contaminants and chemical
agents which might be encountered during usage must be better understood.
APPROACH TO THE PROBLEM

CONTAMINANT MODEL

As a first step in the modeling of an OBOGS system, an experimentally verified model of a single bed system containing a zeolite molecular sieve with contaminants in the inlet air is being developed. A model that has been previously developed for two component O2 - N2 gas mixtures is described in appendix A. Preliminary work with O2 - N2 - CO and O2 - N2 - CO2 mixtures indicates that a similar model with a third component might be effective for contaminant studies. USAARL is presently conducting single bed experiments with contaminants such as CO2, CO, C2H60 (ethanol), NH3 (ammonia), C5H12 (pentane), CH3Br (methyl bromide), NO2, N204, O3 (ozone), CH4 (methane), CCl2F2 (freon 12), acrolein, oil breakdown products, and other battlefield products. These experiments are essentially column breakthrough experiments which will be used to validate the computer model.

Once the dynamics of a single bed are correctly modeled, an overall system model for a two bed system with valves and mixing plenum will be developed. This modeling has been done for O2 - N2 mixtures. A description is contained in appendix B. A similar model is being developed for contaminant studies.
RESULTS AND CONCLUSIONS

A computer program of the OBOGS model described in appendix B has been delivered and installed on the VAX* computer at USAARL. This program is menu driven for ease of operator use and has REGIS* graphical output for use with VT125* or VT240* graphical terminals. The operator has a choice of output of on-line plotting of oxygen mole fraction or inlet/outlet mass flowrate versus time or off-line plotting of a dynamic simulation of OBOGS for one cycle. The operator can also select and change a variety of geometric and material parameters in order to aid in design studies. Sample inputs and outputs of the program are given in appendix C.

A preliminary 3 component OBOGS has been developed for contaminant studies. Before any further development on this program can continue the results of the experimental single bed data generated by USAARL is necessary. As soon as this data is available, it will be incorporated into a single bed model. Then a two bed OBOGS system model will be developed and experimentally verified.
A Dynamic Model of a Molecular Sieve Bed With Nonlinear and Coupled Isotherms

A mathematical model of the O$_2$-N$_2$ separation process in a molecular sieve bed was developed and experimentally verified. Oxygen and nitrogen breakthrough experiments were performed on a single bed packed with molecular sieve 5A. In these experiments, the bed had initially adsorbed either pure oxygen or nitrogen and then a constant inlet flow of nitrogen or oxygen was switched on the bed. The outlet oxygen mole fraction and mass flowrate were then recorded. This was done at several pressures and flowrates. The model predictions agreed with the experimental data when a linear oxygen isotherm and a nonlinear Langmuir isotherm for nitrogen were used and when these were coupled. The numerical scheme presented in this study to solve the system equations makes efficient use of computation time.

1 Introduction

The elimination of the need for liquid oxygen for crew breathing requirements in aircraft is an especially attractive goal. A means of accomplishing this goal is now available through the use of a molecular sieve, OBOGS (On-Board Oxygen Generation System). Molecular sieves are in widespread use industrially [1], but the special problems associated with an OBOGS have led to the need for a reliable computer-based simulation tool that would model the relatively rapid transient response of such systems.

One promising system uses a synthetic zeolite to adsorb nitrogen from engine bleed air, thereby producing oxygen enriched breathing gas. This system uses a "pressure swing" adsorption cycle [2] in order to achieve gas separation. In this cycle, nitrogen is adsorbed from engine bleed air at high pressure (producing oxygen enrichment) and then desorbed and exhausted to the atmosphere at low pressure in order to replenish the sieve material. While large scale industrial systems are in commercial use, size and weight optimized units for airborne applications are still in the development stage.

In order to better understand the operation and scaling laws of the OBOGS, a computer model of this system has been developed. As a first step in this development, a model of a single molecular sieve bed with identified parameters is needed. This paper addresses the formulation and verification of such a model for predicting the transient response of gas flow rate and gas concentration at the bed outlet to sudden changes in gas composition at the bed inlet.

Previous work in this area has treated the diffusion process to be instantaneous [3, 4] or has considered one component at the trace level [5]. This work considers a complete "washout" of one gas type using another. In other words, mole fractions at the inlet undergo step changes from 0 to 1 and vice versa, while the bed back-pressure and inlet flows are essentially constant.

II Theoretical Model

Figure 1 shows a schematic of the experimental single bed which was used to validate the molecular sieve bed model, where component A is oxygen, B is nitrogen, x is oxygen mole fraction.
Oxygen is almost immediately washed out, is constant for a while, and finally trails off to its equilibrium value. The outlet mole fraction was measured with a respiratory mass spectrometer. Experimental data were taken for various inlet mole fractions of oxygen.

Pressure transducers were located at the bed inlet and outlet. These transducers were located at the bed inlet and outlet. These transducers served as a check on the isobaric assumption. The amount of pressure drop across the bed was on the order of 3 percent of inlet pressure. A mass flow meter was located just beyond the bed outlet to measure outflow. Outlet oxygen mole fraction was measured with a respiratory mass spectrometer. Experimental data were taken for various inlet pressures: 1 atm, 1 atm, 2 atm, and 3 atm. A hypobaric chamber was employed for the 1 atm test, while a hyperbaric chamber served as the plenum chamber for the 2 and 3 atm tests. For more information on the tests see Werlin [17].

Figure 3 shows the general nature of the oxygen and nitrogen "breakthrough" experiments where the symbols refer to experimental data. Figures 1 to 16 seconds an oxygen breakthrough is shown. As seen in this figure, the output mass flow rate rises to approximately twice the inlet flow rate and slowly trails off to its equilibrium value. The outlet mole fraction concentration starts at pure nitrogen and rises slowly to pure oxygen. At 16 seconds, the inlet flow is suddenly switched to pure nitrogen. As this point the outlet flow drops immediately, is constant for a while, and finally rises back to its equilibrium value as the concentration "front" propagates through the bed. The concentration time profile is much sharper than the oxygen breakthrough case, and at approximately 24 seconds the oxygen has completely washed out.

This general behavior can be explained by the fact that SA sorbent has a larger affinity for nitrogen than oxygen, so, when oxygen is washed out, more nitrogen is desorbed than oxygen is given up. Therefore, the flow rate will be reduced ahead of the concentration front. The concentration front remains sharp due to the fact that the velocity of the front is smaller than that behind it.

For oxygen breakthrough, the effect is reversed. In this case, more nitrogen is desorbed than oxygen is adsorbed. There is a higher flow rate ahead of the front, and oxygen and nitrogen will tend to be convected away from this region, leading to a broader concentration front.

IV Identification of Model Parameters and Comparison With Experimental Data

Effect of Model Parameters. A quantitative assessment of the effect of the model parameters on the characteristic flow rate and mole fraction time plots can be made by writing Equations (5) through (8) in nondimensional form as

\[ \frac{\partial \omega}{\partial t} + 1 = g \]  
\[ \frac{\partial \eta}{\partial t} + \frac{x}{u_0} = g \]  
\[ \frac{\eta_0}{\partial t} = g \]  
\[ \frac{\partial \omega}{\partial t} = g + x \]

where

\[ \omega = \frac{u}{u_0}, \eta = \frac{\eta}{\eta_0}, \tau = \frac{\tau}{\tau_0}, \gamma = \frac{\gamma}{\gamma_0}, \] 
\[ \eta_0 = \frac{\eta_0}{\eta_0}, \tau_0 = \frac{\tau_0}{\tau_0}, \gamma_0 = \frac{\gamma_0}{\gamma_0} \]

The single component isotherms of (18) and (19) can be expressed as

\[ g_\omega = g_\eta \]  
\[ g_\eta = (1 - \mu) \eta_\eta / (1 - \alpha \eta_\eta) \]

where \( \mu = 1 - K_\eta / K_\omega \) and \( \alpha = \eta_0 / \eta_\eta \). The ideal adsorption method is then used to couple these isotherms. For a nitrogen breakthrough, the initial and boundary conditions become

\[ \omega(0, \tau) = 1 \]  
\[ x(0, \tau) = 0 \]  
\[ \omega(\tau, 0) = 1 \]  
\[ \eta(\tau, 0) = 1 \]

Equations (24) through (28) with these conditions can then be solved numerically, as discussed previously, for values of the two parameters \( \mu \) and \( \alpha \). These simulations indicate that the nondimensional distance down the bed is related to nondimensional travel time by

\[ \tau = (1 - \mu \alpha r_{50} - 0.7) \]

where \( r_{50} \) is the nondimensional time for the outlet oxygen

\[ 268/\text{Vol} \ 105, \text{DECEMBER} \ 1983 \]
droop data was used to find values of flow rate and transfer coefficient for oxygen.

Identical at the same pressure), a least squares fit of all the oxygen data in Fig. presented. Since more than the minimum two different are presented. The match between the nitrogen data and breakthrough data to simulation predictions. and the Langmuir isotherm identified in this work. In Fig. interpretation of equation (29).

Identification of Model Parameters. The values of $K_A$, $K_B$, $b$, and $d$ can be effectively found by using breakthrough data and the results of the preceding section. The steps to obtain these parameters from a nitrogen breakthrough are:

1. Obtain values of $\mu - \alpha$ from flowrate droop data, i.e., $\mu - \alpha = 1 - \omega_0$, for at least two different bed pressures. This allows calculation of $\mu$ and $\alpha$.
2. Use (29) to obtain a value of $K_A$ from the time for 50 percent breakthrough. The value of $d$ is superfluous to the calculation since $\beta = d(1 - \tau)/\tau$ and $\tau \geq 0.70$ for the system under study. Using these two relations, (29) yields

$$K_A = L(1 - \tau) / \omega_0 (1 - \mu + \alpha) \lambda_{50}$$

(30)

(4) From dimensional analysis, one sees that $x$ is a function of $\lambda$ and $\tau$ and therefore

$$\frac{dx}{d\tau} = \frac{dx}{d\tau} = K_A \frac{dx}{d\tau}$$

This implies that the slope or tangent of $x(L, \tau)$ is directly proportional to $d$. This fact can then be used to adjust $d$ to match the mole fraction slope.

This resulting identification procedure can be checked by comparing oxygen breakthrough data and additional nitrogen breakthrough data to simulation predictions.

In Table 1, the experimental results of nitrogen breakthrough experiments of 1/2, 1, 2, and 3 atmospheres are presented. Since more than the minimum two different pressures are available (theoretically all droop data should be identical at the same pressure), a least squares fit of all the droop data was used to find values of $\mu$ and $\alpha$. Note $\omega_0 = W_{0d} M_{0A} / M_{0B}$, where $M_{0A} = 28$ for nitrogen and $M_{0B} = 32$ for oxygen. A value of $K_A$ is then found from step 2 as

$$K_A = L(1 - \tau) \rho_0 A_f / W_{0d} (1 - \mu + \alpha)$$

where $\rho_0$ is the bed inlet gas density. From step 3, $K_B = (1 - \mu) K_A$. Using slope adjustment as indicated in step 4, the mass transfer coefficient $d$ was set at a value of 90 s$^{-1}$ at 1/2 atm and $W_{0d} = 4.28$ gm/s. This value is adjusted for pressure and flow rate by using a correlation due to Lightfoot [18] which indicates that $d$ is proportional to $W_{0d}^2/P$ where $W$ is mass flow rate and $P$ is pressure. In any case, the value of $d$ did not have a large effect on the characteristic response. The result of this identification procedure gave the following parameter identification:

$$K_A = 0.153 \quad \sigma_{KA} = 0.0185$$
$$K_B = 0.0506 \quad \sigma_{KB} = 0.00611$$
$$b = 2.59 \quad \sigma_b = 0.31$$

The $\sigma$'s are the predicted standard deviations of the parameters.

As a validation of this procedure for identifying isotherm parameters a comparison with published isotherms and correlations is shown in Figs. 4 and 5. Plotted in Fig. 4 are the nitrogen isotherm data of Peterson [19], the correlation of Ruthven [10] based on a statistical thermodynamic model, and the Langmuir isotherm identified in this work. In Fig. 5, the oxygen isotherm data of Wright [20], the correlation of Ruthven [10], and the linear isotherm identified in this work are presented. The match between the nitrogen data and the model isotherm is excellent. The difference in the two sets of oxygen data in Fig. 5 is probably due to the relatively small amount of oxygen absorbed on zeolite 5A, which requires a very accurate gravimetric measurement. The model identified isotherm bisects both sets of given oxygen data.

Comparison of Simulation and Experiment. Comparisons of the model, using the identified parameters, with the experimental data are shown in Fig. 3 and in Figs. 6 through 10. Shown in Fig. 3 are the data and simulation for bed pressure at 1/2 atm for both oxygen and nitrogen with linear isotherms. As can be seen here for low pressure, a linear isotherm is adequate for predicting the time responses. The same values of $K_A$ and $K_B$ were then used for the 3 atm.
SINGLE BED MODEL TECHNICAL DESCRIPTION

APPENDIX A

**Fig. 6.3 Atmosphere breakthrough data and simulation – linear isotherms**

<table>
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<tr>
<td>KA</td>
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<tr>
<td>KB</td>
<td>.859</td>
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<tr>
<td>d</td>
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**Fig. 6.1 Atmosphere breakthrough data and simulation – nonlinear isotherms**

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<tr>
<td>b</td>
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<td>d</td>
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**Fig. 7. Atmosphere breakthrough data and simulation – nonlinear coupled isotherms**

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<td>.8586</td>
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<tr>
<td>b</td>
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<td>d</td>
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**Fig. 9.2 Atmosphere breakthrough data and simulation – nonlinear coupled isotherms**

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</table>

mosphere data, with the results of this simulation shown in Fig. 6. As can be seen, the match with experimental data is very poor. This indicates nonlinear isotherms are necessary.

Comparisons of the model using the nonlinear nitrogen isotherm with the experimental data are presented in Figs. 7 through 10. As seen in these figures, the data match has been greatly improved over the linear parameter model. Discrepancies between model and experiment can be attributed to experimental error and inaccurately assumed isotherms. The data indicate that a nonlinear oxygen isotherm may be appropriate, but this improvement is left for future work.

V Conclusions

A dynamic model of the O₂ - N₂ isobaric breakthrough process in a molecular sieve bed was developed and validated experimentally. This model includes nonlinear and coupled isotherms. The proposed model accurately predicts the outlet mole fraction and outlet mass flow. In addition, isotherms for oxygen and nitrogen were identified which are in agreement with previously obtained isotherms.

This model is presently being used in an overall system model for a pressure swing adsorption process to generate oxygen from aircraft engine bleed air.

References

Fig. 10. Atmosphere breakthrough data and simulation—non-linear coupled isotherms

A Dynamic Model of a Pressure Swing Oxygen Generation System

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1 Introduction

As mentioned in [1], a promising system for generating breathing oxygen for aircraft crew uses a synthetic zeolite material to physically adsorb nitrogen from engine bleed air. One such system is based on a "pressure swing adsorption cycle" in which nitrogen is adsorbed at high pressure and then desorbed at and exhausted to low pressure. The total process produces oxygen enrichment of air in a cyclical fashion. As a first step in the modeling of such systems, an experimentally verified model of a single bed system containing a zeolite molecular sieve bed was developed in [1]. The model developed in [1] provides predictions of the bed's transient outlet flow rate and mole fraction for a given inflow and mole fraction. The model was tested for pressures from 1/2 to 3 atmospheres and inlet mass flow rates of 3.21 g/s to 8.56 g/s.


Molecular sieve zeolite separation processes are in widespread use industrially, but OBOGS (acronym for On-Board Oxygen Generation System) units are much smaller in scale and are called on to respond to a much more variable demand as determined by the aircraft crew's breathing requirements. These special requirements have led to the need for a reliable computer-based simulation tool that would model the relatively rapid transient response in OBOGS. This model will be useful for both design modification and control development.

2 Description of System

Shown in Fig. 1 is a schematic of a two bed OBOGS developed by Bendix Corporation for use in military aircraft. The object of the system model is to simulate the transient oxygen concentration delivered to the pilot given the pilot's time varying breathing mass flow rate. This is accomplished by mathematically modeling the rotary valve, purge orifice, the two zeolite beds, and the breathing plenum, and coupling these separate models into an overall system model.

The pressure swing adsorption cyclic operation of the beds can be described as:
1. The inlet of bed 1 is supplied air at supply pressure through the rotary valve, while bed 2 is being purged to exhaust pressure through the valve. During this stage breathing flow is obtained from bed 1.
2. As the rotary valve turns, the inlet of bed 1 is switched to exhaust pressure and the inlet of bed 2 is switched to supply pressure. During an initial transition stage, the pressure in bed 1, P₁, is still higher than the pressure in bed 2, P₂. In this case, there is flow out of both sides of bed 1 and into both sides of bed 2. Breathing flow will come from the higher pressure bed 1.
3. As the pressure drops in bed 1 due to outflow and builds in bed 2 due to inflow, P₂ will become greater than P₁. This is the identical case of (1) above, but with bed 2 the higher pressure side. The stages 1, 2, and 3 above describe 1/2 of a production cycle. The other half cycle is symmetric to the first half cycle.

The components of the system are the zeolite molecular sieve beds, rotary valve, bypass or purge valve between the two beds, and the breathing plenum. These components are modeled as discussed below.
changes in the free stream concentration, and isobaric beds (the pressure drop across the beds is small), the oxygen/nitrogen adsorption in the beds can be modeled as

\[ \frac{\partial (\gamma A)}{\partial z} = A \beta (\gamma / C - 1) \]  

(1)

\[ \frac{\partial (\gamma A)}{\partial t} = A \beta (\gamma_A - \gamma / u) \]  

(2)

\[ \frac{\partial n}{\partial t} = - \delta (\gamma - C) \]  

(3)

\[ \frac{\partial n_A}{\partial t} = - \delta (\gamma_A - C_A) \]  

(4)

where

A = bed cross-sectional area

\( d \) = overall mass transfer coefficient

\( \beta = d (1 - e) / e \)

\( \epsilon = \text{void fraction of gas volume to total volume} \)

C = total gas phase concentration

\( C_A = \text{oxygen gas phase concentration} \)

\( C_A = \text{oxygen adsorbed phase concentration} \)

\( \gamma = \gamma_A + \gamma_B \) total interface concentration

\( \gamma_A = \text{oxygen interface concentration} \)

\( u = \text{convective velocity} \)

\( n = n_A + n_B \) adsorbed phase concentration

\( n_A = \text{oxygen adsorbed phase concentration} \)

Due to the relatively fast heat transfer, it was observed that

2.1 Zeolite Bed Model. Concentric beds were used in the experimental study and one is depicted in Fig. 2. As discussed in [1], if we assume an one-dimensional flow, negligible axial diffusion, diffusion into the zeolite described with a mass transfer coefficient, convective terms dominate temporal

Nomenclature

\[ A = \text{bed cross-sectional area, m}^2 \]

\[ A_d = \text{orifice area, m}^2 \]

\[ A_i = \text{inner annulus area, m}^2 \]

\[ A_o = \text{outer annulus area, m}^2 \]

\[ C = \text{gas concentration, kmole/m}^3 \]

\[ C_v = \text{valve discharge coefficient} \]

\[ C_p = \text{breathing plenum gas concentration, kmole/m}^3 \]

\[ d = \text{total mass transfer coefficient, 1/s} \]

\[ k = \text{ratio of specific heats} \]

\[ L = \text{bed length, m} \]

\[ M = \text{average molecular weight of gas in plenum, kg/kgmole} \]

\[ n = \text{adsorbed phase concentration, kmole/m}^3 \]

\[ P, P_o, P_r, P_f = \text{supply, Bed 1, Bed 2, exhaust pressures, (N/m}^2\) \]

\[ Q = \text{volume flowrate, m}^3/s \]

\[ t = \text{time, s} \]

\[ u = \text{convective velocity, m/s} \]

\[ W = \text{mass flowrate, kg/s} \]

\[ \gamma = \text{molecular flux of oxygen, kmole/m}^2\cdot s \]

Superscripts

\(- = \text{denotes property just before } z = L/2 \)

\(+ = \text{denotes property just after } z = L/2 \)
the experimental beds remained at essentially constant temperature during a cycle even though the adsorption process is not intrinsically isothermal. A more detailed study of the thermal properties of the system is the subject of ongoing research. In the isothermal case, \( \gamma_1 \) and \( \gamma_2 \), the interfacial concentrations of oxygen and nitrogen, respectively, are related to \( n_1 \) and \( n_2 \), the adsorbed oxygen and nitrogen concentrations, by the equilibrium adsorption isotherms [8]. As discussed in [1], these isotherms can be expressed as

\[
\gamma_1 = \gamma_1(n_1, n_2) \\
\gamma_2 = \gamma_2(n_1, n_2)
\]

for nonlinear coupled isotherms. The pure component isotherms were identified as

\[
\gamma_1 = K_1 n_1 \\
\gamma_2 = K_2 n_2 (1 - n_2 / h) 
\]

with \( K_1 = 0.153 \) kg/mole gas phase/kmole adsorbed phase, \( K_2 = 0.0506 \) kg/mole gas phase/kmole adsorbed phase, and \( h = 2.59 \) kg/mole adsorbed phase. The coupling is predicted by using an ideal adsorption method [1].

The diffusion coefficient \( d \) was empirically chosen as 200 L in order to best match the data. This value is higher than the values identified in [1]. This is probably due to the high velocities in the beds during exhaust and initial intake of air.

2.2 Valve Model. The orifices of the rotary valve and the purge orifice are modeled as standard compressible flow pneumatic orifices as described in [9]. The basic equation for the flow of a gas through an orifice is of the following form

\[
W = C_d A_d f \left( P_o, T_o, \frac{P_d}{P_o} \right)
\]

where

- \( W \) = mass flowrate
- \( A_d \) = orifice area
- \( C_d \) is a dimensionless discharge coefficient
- \( T_o \) = upstream stagnation temperature
- \( P_o \) = upstream stagnation pressure
- \( P_d \) = downstream pressure
- \( f \) = a function of \( P_o, T_o, \) and \( P_d / P_o \).

For pressure ratios \( P_d / P_o \) greater than the choked flow ratio and less than 1, the function \( f \) can be expressed as

\[
f = C_d \left( \frac{P_d}{P_o} \right)^{1/2} \left( 1 - \left( \frac{P_d}{P_o} \right)^{k-1} \right)^{1/2};
\]

for pressure ratios less than the choked flow ratio,

\[
f = C_1 \left( \frac{P_d}{P_o} \right)^{1/2},
\]

where \( C_1 \) and \( C_d \) are functions of \( k \), the ratio of specific heats, and the gas constant. These parameters are taken as constants for this study. For the rotary valve the orifice areas are cyclic functions of the rotation angle of the valve. The discharge coefficients were chosen between values of 0.6 and 1.0 in order to best match the measured experimental flow.

2.3 The Breathing Plenum. The breathing plenum is modeled as an ideal isobaric two stage mixing chamber. The transfer function between inlet mole fraction and outlet mole fraction can be expressed as:

\[
x_o = \frac{1}{(\tau + 1)^2}
\]

where

\[
\tau = \frac{C_v V_{ac} M}{W_{in}}
\]

The plenum remained at approximately constant pressure and therefore constant \( C_p \). This is probably due to the high pressures in the check valve/plenum system as described in the study.

The diffusion coefficient \( d \) was empirically chosen as 200 L in order to best match the data. This value is higher than the values identified in [1]. This is probably due to the high velocities in the beds during exhaust and initial intake of air.

The causality described above and shown on the graph is integral causality for the beds if they are treated as capacitive devices. Using other causality techniques, the spatial molecular interaction can be modeled as a boundary value problem in space with the interfacial gas phase concentrations as the boundary conditions.

3. Solution Techniques

3.1 Causal Considerations. The overall system model can be depicted by the bond graph [10] shown in Fig. 3. Besides the physical interconnections, the graph also indicates the important causal relationships in the system model. The causality shown in the graph can be read as:

1. \( P_0 \) and \( P_1 \) are inputs to the rotary valve while the valve determines the flowrate \( Q_{01} \) from these two pressures.
2. \( P_2 \) is determined from \( Q_{01} \) which has inputs the flow \( Q_{01} \) and the flow \( Q_{12} \).
3. \( P_1 \) and \( P_2 \) are the inputs to the purge valve and the valve supplies the flowrates \( Q_{12} \) and \( Q_{2a} \) to the system.
4. \( Q_{2a} \) is determined by the breathing flow and bed pressure in the check valve/plenum system as described in the next section.
5. \( P_2 \) is determined by bed 2 which has inputs the flows \( Q_{02} \) and \( Q_{12} \).

In addition to these causal statements, the spatial molecular concentration of the two gases in the beds is determined in the direction of the flowrate i.e., the concentration must be determined from upstream conditions. This will be discussed more thoroughly in the next section.

The causality described above and shown on the graph is integral causality for the beds if they are treated as capacitive fields [11] or mass storage devices. Using other causal arrangements is possible but will result in complicated and computationally time consuming iteration.

3.2 Solution Algorithm. Given input supply pressures \( P_0 \) and \( P_{in} \), breathing flow \( W_{in} \), and initial adsorbed phase concentrations \( n(t, 0) \) and \( n(t, 0) \) in the two beds, the system equations can be solved as a boundary value problem in space and a marching problem in time. The solution technique consists of:

1. Given \( n(t, 0) \) and \( n(t, 0) \), the interfacial gas phase concentrations \( \gamma(t, 0) \) and \( \gamma(t, 0) \) can be calculated from the equilibrium isotherms (5). Equation (6) can then be integrated along the entire length of the bed as

\[
Q_i = Q_{0i} + A_i \int_{0}^{\infty} \frac{A_{iL}}{2C_i} \left( A_i \int_{0}^{\infty} \frac{A_{iL}}{2C_i} \right) \frac{\partial \gamma_i}{\partial z} dz
\]
For bed 1, \( Q_1 = Q_{in}(P_1, P_2) \) where \( P_1 \) is proportional to \( C_1 \), the gas phase concentration in bed 1, for isothermal beds and assuming a perfect gas, and \( Q_1 = Q_1(P_1, P_2) = Q_{BA1} \) where \( P_1 \) is proportional to \( C_1 \), the gas concentration in bed 2 and \( Q_{BA1} \) accounts for the volume flow out of bed 1 due to crew breathing. For product flow out of bed 1, \( Q_{BA1} \) is proportional to \( H_{BA} \) for an isobaric and isothermal phenom. For bed 2, \( Q_2 = Q_{in}(P_1, P_2) = Q_{BA2} \) and \( Q_2 = Q_2(P_1, P_2) \) where \( Q_{BA2} \) accounts for breathing flow out of bed 2. Note that either \( Q_{BA1} \) or \( Q_{BA2} \) will be zero depending on which bed had the lower pressure. Equation (10) written out for both beds represents two coupled nonlinear algebraic equations for the two unknowns \( C_1 \) and \( C_2 \). These equations can be solved by an iteration procedure consisting of (1) assuming concentration \( C_1 \) and solving the resultant single nonlinear algebraic equation for \( C_2 \) using a modified false position algorithm, (2) using this value of \( C_2 \) to calculate a new value of \( C_1 \), (3) iterate until the solution procedure converges. Convergence of this procedure requires on the order of three to four iterations. The integrations involved in (10) are performed numerically by a trapezoidal rule, and are only done once per step. This iteration procedure amounts to a solution of the boundary value problem in the system.

(iii) Spatially integrate equation (11) numerically as

\[
 u = u_{n} + \beta(\gamma_{n} + \gamma_{n+1})/2C - \beta_{z}z, \tag{11}
\]

where \( n \) is the index for the space dimension, \( z = l_{2} \) and \( \Delta z \) is the space lump size. This integration is done in two steps from 0 to \( l/2 \) and then from \( l/2 \) to \( l \) with condition \( w_{1}(z) = \Delta z w_{1}(1/4)(z) \) at \( z = l/2 \) to account for the area change in the outer annulus and inner cylinder of the bed. Note that the starting velocity \( u_0 = Q_{in}(0) \) is known from step (i).

(iv) Using the velocity distribution calculated in (iii), equation (2) is a first order linear ordinary differential equation in space for fixed time. Approximate the velocity \( u \) and the interfacial concentration \( \gamma_{4} \) over a space lump as

\[
 u = r_0 + r_1 z - (r_0 - r_1) \Delta z < z < (r_1 + r_4) \Delta z
\]

where

\[
 r_0 = u_{n} + , r_1 = (u_{n} - u_{n+1})/\Delta z
\]

\[
 r_1 = r_{n+1} - (\gamma_{n} - \gamma_{n+1})/\Delta z
\]

Using these approximations, equation (2) can be integrated in closed form as shown in [1]. The direction of the integration will always be in the direction of the velocity flow. Which, as described in Section 2, might be (1) flow in one side of the bed and out the other, (2) flow into both sides of the bed, or (3) flow out of both sides of the bed. In cases (2) and (3), there will be at least one point in the bed that has zero flow. As the velocity in the bed is found as described in (i) above, the point of zero velocity is stored. For case (1), the integration will proceed in the direction of flow, for case (2) the integration will proceed from the sides of the bed to the point of zero flow, and for case (3) the integration will start at the point of zero velocity and proceed out the two sides. Although physically possible, multiple points of zero flow will not occur.
in normal operation of OBOGS and this case is not included at present in the computerized solution.

The ability to solve equation (2) in closed form is an important numerical result. The oxygen profiles in the beds can be very steep, and if a completely numerical procedure is applied to (2), it will require small increments for \( dz \) in order to be stable and accurate. This will result in very long computation times even on a high-speed computer.

Equations (3) and (4) are then integrated in time via a simple Euler method as

\[
\begin{align*}
n_{i+1} & = n_i - d_i (n_i - C_i) \Delta t \\
n_{k+1} & = n_k - d_i (n_k - C_k) \Delta t
\end{align*}
\]  

where \( i \) is the time index, \( t = t_{i+1} \), and \( \Delta t \) is the time step.

The input oxygen mole fraction at the breathing plenum is found from bed 1 at \( z = 0 \) or bed 2 at \( z = 0 \) depending on which bed has higher pressure. The mole fraction from the higher pressure bed is computed as \( C_i/C \). This input mole fraction is used with equation (9) and the breathing flow \( W_{ib} \) to solve for the output mole fraction, \( x_o \). Equation (9) is solved as two coupled ordinary differential equations via a simple Euler method.

March in time by proceeding to step (i) for the next time level.

The step and space lumps were chosen by performing numerical experiments to ensure accuracy and stability of the solution procedure. The model simulation time is approximately twice that of real time when computed on a CDC Cyber 170/150.

4 Comparison of Model With Experiment

The prototype experimental system is depicted in Figs. 1 and 2. The concentric molecular sieve beds have an inner area of 36.5 cm² and an effective outer area of 136 cm². The effective flow length of a bed is 39.4 cm. The beds are loaded with Linde 4A sorbent with zeolite particles of approximately 140 to 833 microns in diameter. The void fraction of the beds is \( \approx 0.3 \) All experiments were run at room temperature of 21°C. No noticeable variation in temperature was observed during the system operation which implies the isothermal assumptions is valid for the system under study. The fully open supply pressure valve has an effective diameter of .78 cm and a discharge coefficient of 0.8. The fully open exhaust pressure valve has an effective diameter of 1.12 cm and a discharge coefficient of 0.8. The purge orifice has a diameter of 0.191 cm and a discharge coefficient of 0.75. The breathing plenum volume is .0018 m³ and an additional volume of .0006 m³ is added to this quantity to account for mixing in the connections.

In this paper, comparison with of the model is made with three basic types of experiments: (1) transient startup, (2) cycle time variation, and (3) change of active volume of zeolite in the beds.

4.1 Transient Startup of OBOGS. Shown in Figs. 4 through 7 are the results from the experimental data and the simulation model for the OBOGS at normal atmospheric pressure. The results are shown for four different constant breathing flowrates of 0.214, 0.642, 1.08, and 1.50 liters/min (10, 30, 50, and 70 standard liters-min). As can be seen in these figures, the model does an excellent job of matching the transient experimental data for the breathing oxygen mole fraction over the range of breathing flowrates.

The increased ripple in the data and simulation for increased flow is due to less time for complete mixing in the plenum as the breathing flow goes up. The model describes this effect very well.

These plots indicate a method for controlling the outlet mole fraction. This is desirable since both high and low oxygen mole fraction can cause physiological problems [12] to the aircraft crew. By dumping product gas to artificially increase the breathing flow, the outlet mole fraction can be lowered if too high. If the mole fraction is too low, product gas dumping can be decreased.

4.2 Effect of Cycle Time Variation. In Fig. 8, the experimental and simulation results for a variation in cycle time are shown. As can be seen, the model does a good job of describing changes in oxygen output with cycle time variation. The results in this figure also demonstrate a method for controlling the outlet oxygen. By simply varying the cycle time of the process, control of oxygen output is possible. The cycle
time variation can be easily implemented by using a variable speed drive for the rotary valve. This control scheme has the advantage of not using any extra product gas which might be desirable for the contaminant filtering properties of the beds. The study of this control scheme is the subject of ongoing research and these results will be presented at a later date.

4.3 Bed Volume Variation. Figure 9 shows the effect of changing the volume of the beds, this was done experimentally [13] by filling the beds with fractional amounts of molecular sieve which had been deactivated with water. From simulation results, it was found that only bed volume and not shape is of importance for oxygen output. This might be an important design result, for it implies that the shapes of the beds are not critical. This means that the beds could be shaped for space considerations in the aircraft.

Another interesting result, is the relative insensitivity of the beds to volume changes until a critical volume is reached (around 75 percent for these beds). This also has important design implications. It means that sizing the system for increased flow is not just a simple increase in bed size, but a combination of volume changes and other design parameters. In particular, the valve areas and discharge coefficients are important design values.

In addition, these results indicate a potential problem in operation. If the beds were to become contaminated with water, which has the effect of decreasing the effective volume of the beds, there would be no outward indication of performance degradation until a critical volume were reached, and at that point the beds would rapidly lose performance with any further contamination.

5 Conclusions

A relatively simple model of a pressure swing oxygen generation system was developed in this study. The compartmented model includes the zeolite beds, valves, and plenum breathing chamber in the system. The model predictions compare favorably with detailed experimental data. Ongoing work in this area include the prediction of temperature and contaminant effects and control of output breathing oxygen.

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References

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APPENDIX C

COMPUTER MODEL FLOWCHART

1. Governing Equations

(1) \[
\frac{\partial (U \gamma C)}{\partial Z} = \beta (\gamma - C)
\]

\[
\beta = \frac{d - (1 - \varepsilon)}{\varepsilon}
\]

(2) \[
\frac{\partial (U \gamma A)}{\partial Z} = \beta (\gamma_A - C_A)
\]

\[
\eta = \eta_A + \eta_B
\]

(3) \[
\frac{\partial \eta_A}{\partial t} - d(\gamma_A - C_A)
\]

\[
\gamma = \gamma_A + \gamma_B
\]

(4) \[
\frac{\partial \eta}{\partial t} = d(\gamma - C)
\]

(5) \[
\frac{\partial C}{\partial Z} = 0
\]

(6) \[
W = \frac{C_d A \sqrt{\frac{2k}{R(k-1)}}}{\sqrt{T}} \left[ \left( \frac{P_d}{P_u} \right)^{1/k} \right]^{1/k} \left( 1 - \left[ \frac{P_d}{P_u} \right]^{k-1/k} \right)
\]

II. Procedures

(1) Initial guess \( P(1) \) and \( P(2) \)

(2) Use adsorption isotherms to calculate \( \gamma_A \) and \( \gamma_B \)

(3) Integrate equation (1) to get \( C \):

\[
(U \omega \zeta - U \omega A_i) C = \beta \int (\gamma - C) \, dz
\]

\[
C = \frac{1}{(U \omega \zeta - U \omega A_i)} \beta \int (\gamma - C) \, dz
\]
In Loop 1 and Loop 2, use False Position Method to find $C_1$ and $C_2$ so that these
values will be consistent with the supply pressure and exhaust pressure at each time step.

(5) Substitute $P(1)$ and $P(2)$ (calculated in step 4) into the valve eq. can get $w(1)$, $w(2)$, and $w(3)$

(6) Since $U_1 = W / (C_1 A_1 M_1)$, where $M_1$ is the molecular weight, $U_{01}, U_{11},$ and $U_{02}$ and $U_{12}$ can be calculated.

(7) Assume velocity is linear along the bed length. By integrating eq. (2), $CA(z)$ can be obtained.

(8) Use eq. (3) and eq. (4) to get new values for $\eta_A, \eta_B$ and $\eta$ for each time step.

(9) $T = T + dT$
    Get a new valve area and repeat the procedure again.

III. Flowchart of the computer program

(1) Sign Convention

(2) Flowchart

Please see attached.
START

CALL TIMEF

CALL BEDS

CALL INITIAL

CALL CONCENTRATION

CALL CONCA

is output option=4?

yes

write XA(1), XA(2), and ReGIS plotting commands to the graphics file

no

on-line ReGIS plotting for XBR, and w's

T = T + 1

yes

update time to calculate new n_A and n

sets initial values for P(1), P(2), w(1), w(2), w(3), x(1), x(2), x(3), n1 and n2

solves for w(1), w(2), w(3), P(1), P(2), U_01, U_02, U_02, and U_22 where U_01 and U_02 are the velocities at the end of bed #1. U_02 and U_22 are referred to bed #2.

solves for velocity distribution, U(Z,t), and mole fraction CA(Z,t) of each bed
APPENDIX C

is output=4?

yes

rewind and write the graphics file for off-line plotting

no

STOP

program returns to the MENU and is ready for the next run
APPENDIX C

The inputs to the program are, as in the menu:

SYSTEM PARAMETERS
1. supply pressure = 40.00 PSIA
2. outlet pressure = 15.00 PSIA
3. final observation time = 30.00 SEC.
4. cycle time = 10.70 SEC.
5. breathing flowrate = 10.00 STD LIT/MIN

GEOMETRIC PARAMETERS
6. by-pass valve diameter = 0.0750 IN.
7. supply valve diameter = 0.3062 IN.
8. outlet valve diameter = 0.4387 IN.
9. bed length = 15.50 IN.
10. outer bed diameter = 5.7300 IN.
11. inner bed diameter = 2.1800 IN.

BED PARAMETERS
12. KA = 0.1530 KGMOLE O2 ABSORBED/KGMOLE GAS
13. KB = 0.0490 KGMOLE N2 ABSORBED/KGMOLE GAS
14. B = 2.6500
15. diffusion coefficient = 200.00 1/SEC
16. void fraction = 0.37

The user has the following options after he has reviewed the menu:

1. change parameters
2. insert a step change in the breathing flowrate, or
3. exit the program

First, changing the parameters is done by entering the corresponding parameter number appeared in the menu. The program then prompts, for example:

ENTER THE PARAMETER AND PRESS "RETURN"

CURRENT VALUE

SUPPLY PRESSURE (PSIA) 40.00

Once the new value has been assigned, the program goes back to the menu with modified parameter(s) and waits for the next input.

If, on the other hand, the user wishes to insert a step change in breathing flowrate, he enters the number for that option (which is "59" in this program). The program will ask for the starting and ending time, as well as the value for the step change and again goes back to the menu.

After the completion of modifications on the parameters, the user enters "0" to run simulation. The program responds with:
COMPUTER MODEL FLOW CHART AND SAMPLE INPUT AND OUTPUT

APPENDIX C

THE FOLLOWING PLOTS ARE AVAILABLE TO YOU ON THE TERMINAL

1 MOLE FRACTION OF OXYGEN VS. TIME (DATA FILE=MOLEFRAC.DAT)
2 INLET MASS FLOW RATE VS. TIME (DATA FILE=FLOWRATE.DAT)
3 OUTLET MASS FLOW RATE VS. TIME (DATA FILE=FLOWRATE.DAT)
4 A DYNAMIC SIMULATION FOR ONE CYCLE (OXYGEN VS. TIME, DATA FILE=PROFILE.DAT)

PRESS THE CORRESPONDING # TO HAVE THE OUTPUT SHOWN AS THE SIMULATION TRANSPRIRES

The user chooses the desired output, and the program gives the following:

1 ENTER "0" TO RUN SIMULATION.
2 ENTER "19" TO CHANGE THE PARAMETERS
3 ENTER "99" TO EXIT PROGRAM.

ENTER THE CORRESPONDING # AND PRESS "RETURN"

and waits for the decision from the user. That is, it is still possible for the user to go back to the menu before he runs the simulation.

Finally, the program asks for a last item:

DO YOU WISH TO DOUBLE THE NUMBER OF SPACE LUMPS IN THE SIMULATION FOR BETTER ACCURACY? (CURRENT NUMBER USED 5000) (Y/N)

This is due to the fact that when using one hundred lumps the simulation is time consuming for the low breathing flowrate cases. The default is thus set to be 50 for faster simulation.
CURRENT SYSTEM PARAMETERS ARE:
1. SUPPLY PRESSURE = 40.00 PSIA
2. OUTLET PRESSURE = 15.00 PSIA
3. FINAL OBSERVATION TIME = 30.00 SEC
4. CYCLE TIME = 10.70 SEC
5. BREATHING FLOW RATE = 10.00 STD LIT/ MIN

CURRENT GEOMETRIC PARAMETERS ARE:
1. BY-PASS VALVE DIAMETER = 0.0750 IN
2. SUPPLY VALVE DIAMETER = 0.3062 IN
3. OUTLET VALVE DIAMETER = 0.4387 IN
4. BED LENGTH = 15.5000 IN
5. OUTER BED DIAMETER = 5.7300 IN
6. INNER BED DIAMETER = 2.1800 IN

THE CURRENT BED PARAMETERS ARE:
1. KA = 0.1530 KGMOLES O2 ABSORBED/KGMOLE GAS
2. KB = 0.0490 KGMOLES N2 ABSORBED/KGMOLE GAS
3. B = 2.6500
4. DIFFUSION COEFFICIENT = 200.00 1/SEC
5. VOID FRACTION = 0.370

ENTER CORRESPONDING PARAMETER # TO CHANGE PARAMETER
ENTER "0" TO SIGNIFY PARAMETERS ARE CORRECT--RUN SIMULATION
ENTER "59" TO INSERT A STEP CHANGE IN BREATHING FLOW RATE
ENTER "99" TO EXIT PROGRAM

**************************************************************************
ENTER THE PARAMETER AND PRESS "RETURN"

CURRENT VALUE

SUPPLY PRESSURE (PSIA) = 40.0000
CURRENT SYSTEM PARAMETERS ARE

- SUPPLY PRESSURE = 30.00 PSIA
- OUTLET PRESSURE = 15.00 PSIA
- FINAL OBSERVATION TIME = 30.00 SEC
- CYCLE TIME = 10.70 SEC
- BREATHING FLOWRATE = 10.00 STD LIT/MIN

CURRENT GEOMETRIC PARAMETERS ARE

- BY-PASS VALVE DIAMETER = 0.0750 IN
- SUPPLY VALVE DIAMETER = 0.3062 IN
- OUTLET VALVE DIAMETER = 0.4387 IN
- BED LENGTH = 15.5000 IN
- OUTER BED DIAMETER = 5.7300 IN
- INNER BED DIAMETER = 2.1800 IN

THE CURRENT BED PARAMETERS ARE:

- K_A = 0.1530 KMOLES O2 ABSORBED/KMOLE GAS
- K_B = 0.0490 KMOLES N2 ABSORBED/KMOLE GAS
- b = 2.6500
- DIFFUSION COEFFICIENT = 200.00 1/SEC
- VOID FRACTION = 0.370

Enter a corresponding parameter # to change parameter
Enter "9" to signify parameters are correct—run simulation
Enter "99" to insert a step change in breathing flowrate
Enter "99" to exit program

**"99"**

Enter the time at which the step change
in breathing flowrate is to occur

The final observation time is currently 30.00 SECONDS

**"99"**

Enter the time at which the step change
in breathing flowrate is to end

The final observation time is currently 30.00 SECONDS
APPENDIX C

ENTER THE NEW BREATHING FLOWRATE OCCURRING AS A STEP CHANGE FROM T = 10.00 TO T = 20.00 SECONDS

THE CURRENT BREATHING FLOWRATE IS 10.00 STD LIT/MIN

THE BREATHING FLOWRATE OF 30.00 STD LIT/MIN WILL BE INPUT AS A STEP AT T = 10.00 SECONDS AND WILL END AT T = 20.00 SECONDS

CURRENT SYSTEM PARAMETERS ARE:
1. SUPPLY PRESSURE = 30.00 PSIA
2. OUTLET PRESSURE = 15.00 PSIA
3. FINAL OBSERVATION TIME = 30.00 SEC
4. CYCLE TIME = 10.70 SEC
5. BREATHING FLOWRATE = 10.00 STD LIT/MIN

CURRENT GEOMETRIC PARAMETERS ARE:
6. BY-PASS VALVE DIAMETER = 0.0750 IN
7. SUPPLY VALVE DIAMETER = 0.3062 IN
8. OUTLET VALVE DIAMETER = 0.4387 IN
9. BED LENGTH = 15.5000 IN
10. OUTER BED DIAMETER = 5.7300 IN
11. INNER BED DIAMETER = 2.1800 IN

CURRENT BED PARAMETERS ARE:
12. KA = 0.1530 KGMOLES O2 ABSORBED/KGMOLE GAS
13. KB = 0.0490 KGMOLES N2 ABSORBED/KGMOLE GAS
14. R = 2.6500
15. DIFFUSION COEFFICIENT = 200.00 1/SEC
16. FRACITION = 0.370

0 = CORRESPONDING PARAMETER # TO CHANGE PARAMETER
0 = "NO" TO SIGNIFY PARAMETERS ARE CORRECT -- RUN SIMULATION
0 = "50" TO INSERT A STEP CHANGE IN BREATHING FLOWRATE
0 = "99" TO EXIT PROGRAM
COMPUTER MODEL FLOW CHART AND SAMPLE INPUT AND OUTPUT

APPENDIX C

THE FOLLOWING PLOTS ARE AVAILABLE TO YOU ON THE TERMINAL

1. MOLE FRACTION OF OXYGEN VS. TIME (DATA FILE=MOLEFRAC.DAT)
2. INLET MASS FLOWRATE VS. TIME (DATA FILE=FLOWRATE.DAT)
3. OUTLET MASS FLOWRATE VS. TIME (DATA FILE=FLOWRATE.DAT)
4. A DYNAMIC SIMULATION FOR ONE CYCLE (OXYGEN VS. TIME,
   DATA FILE=PROFILE.DAT)

PRESS THE CORRESPONDING # TO HAVE THE OUTPUT SHOWN AS THE
SIMULATION TRANSPIRES

1. ENTER "0" TO RUN SIMULATION
2. ENTER "19" TO CHANGE THE PARAMETERS
3. ENTER "99" TO EXIT PROGRAM.

ENTER THE CORRESPONDING # AND PRESS 'RETURN' 

0

DO YOU WISH TO DOUBLE THE NUMBER OF SPACE LUMPS IN
THE SIMULATION FOR BETTER ACCURACY? (CURRENT NUMBER USED
14, 50) (Y/N)
SAMPLE OUTPUTS

* OXYGEN MOLE FRACTION *

PSUP = 16.69 PSIA
POUT = 1.69 PSIA
WBRL = 9.00 STD LIT/MIN

PLEASE PRESS "C" TO CONTINUE:
APPENDIX C

SAMPLE OUTPUTS

*INLET MASS FLOW RATE*

PSUP = 40.00 PSIA
POUT = 15.00 PSIA
WRL = 10.00 STD LIT/MIN

Please press "C" to continue:
SAMPLE OUTPUTS

* OUTLET MASS FLOW RATE (KG/SEC) *

PSUP = 40.00 PSIA
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