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Analysis of Gas Purification by Pressure Swing Adsorption: Priming the Parametric Pump

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ABSTRACT

The transients during start-up of a pressure-swing adsorber lead to material and energy losses. A dynamic mathematical model is developed to analyze the PSA process to elucidate the conditions under which losses may be minimized. It is based on an ideal binary mixture comprised of components that have linear isotherms.

A processing alternative that virtually eliminates losses is suggested. The alternative is formulated by considering the PSA process as a specific type of parametric pump. It follows intuively that, as in an ordinary pump, the parametric pump will commence operation at steady-state if it is primed. In the case of PSA, that amounts to purging the initial adsorber contents with the less strongly adsorbed component.

Illustrations are provided of both single-bed and dual-bed processes. For a specific gas mixture and adsorbent, the effect of varying the ratio of the high and low pressures that occur in a cycle is examined. Results indicate that there is a significant advantage in priming the single-bed version because of the surge tank, which promotes backmixing. There is still an advantage in priming the dual-bed version, however, despite the absence of backmixing.

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INTRODUCTION

Of the class of cyclic sorption processes that are collectively known as parametric pumps, little attention has been paid to the proper method for commencing operation or to the constraints associated with initial transients. Despite that, it is useful to understand these concepts, in terms of the implications of operating conditions and process configuration, in order to improve the performance of the process.

The purpose of this work is to take the original viewpoint of Wilhelm(1), that is to consider the analogy of this cyclic separation process to a pump. The development is intended to illustrate that the initial performance of the process may be significantly improved by simply priming it. The incentives for reducing the initial transients to a minimum include conservation of energy, time, and materials. The last is especially relevent when a valuable impurity is to be recovered.

The specific version of the parametric pump is taken to be the pressure-swing adsorption (PSA) process, although the general concept is believed to be applicable to any version. Furthermore, the concept is shown to be valid for a simple, single column version of the PSA process, as well as those containing multiple beds. Although, in the latter case the number of beds has been restricted to two, as in heatless adsorption.

The present work is based on purification of a binary mixture in which both components adsorb according to linear isotherms. The topics covered are: general mathematical analysis, treatment of specific steps in a typical cycle, and particular conditions of both single column and dual column process configurations during start-up.

Since the middle 1960's there has been considerable progress in developing and refining PSA process layouts in applying the pro-process to laboratory and industrial-scale separations, and toward establishing theoretical understanding of both general and specific concepts. Lee and Stall (2) and Keller and Jones (3) have reported several process configurations and commercial applications. Doshi et al. (4) have discussed refinements in operating conditions. Khihara and Suzuki (5) and Knaebel and Hill (6) have developed mathematical analyses for steady-state operation. An excellent review of the general field of cyclic sorption separations has been presented by Wankat (7).

GENERAL ANALYSIS

In its most elementary form, the process is comprised of a packed bed of adsorbent material that has fixed cross-sectional area and porosity. The process operates in a series of four-step cycles; these steps are pressurization, high-pressure feed, blow-down, and purge. The basic concept is illustrated in Figure 1.

In the pressurization step, material having the mole fraction (of the more strongly adsorbed component), y_I, is injected into the column. The initial contents of the column are at the same composition. (At the outset of start-up this material is presumed to be at the feed composition.) As the step proceeds, however, the mole

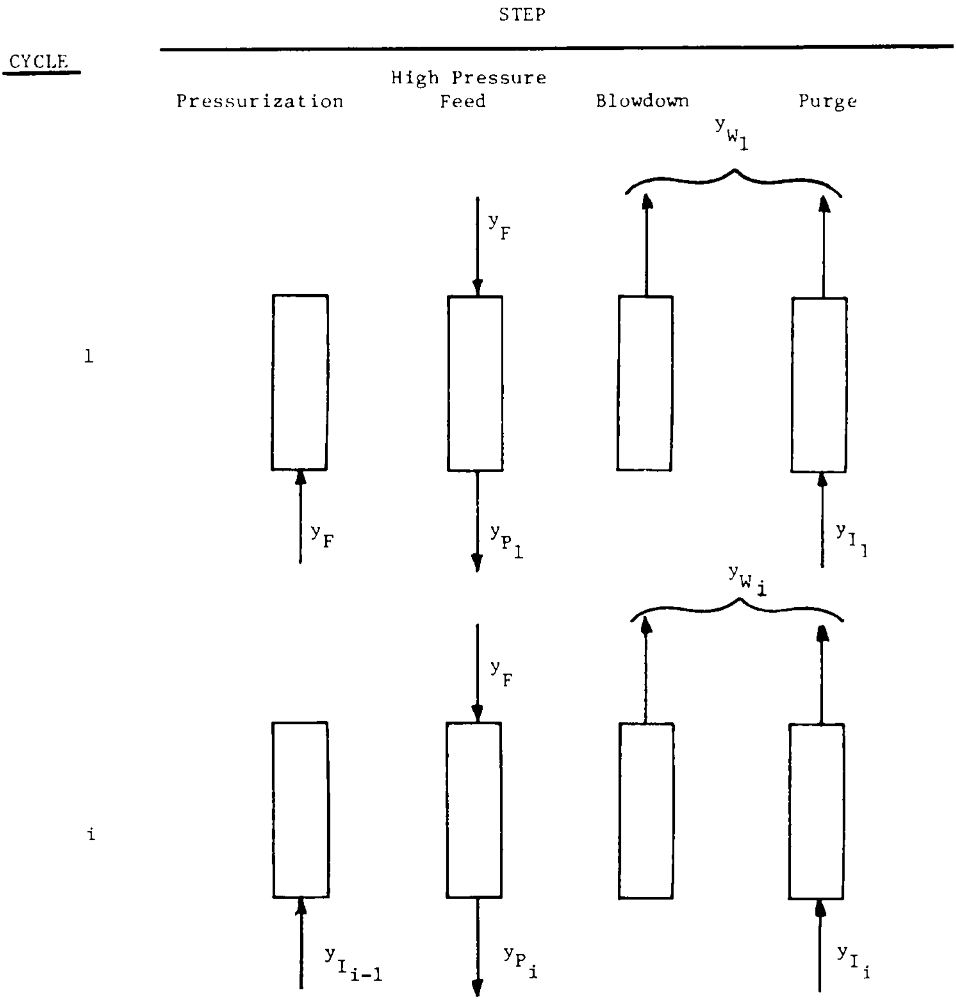

Figure 1. Schematic diagram of a pressure swing adsorber during start-up conditions. The source of y_I is the surge tank in the single bed version, while it is the product of the alternate bed in the dual bed process.

fraction may decrease because the more strongly absorbed component is selectively taken-up by the adsorbent. The mole fraction ultimately reached is y_U.

When the high pressure limit is attained, the feed and product lines are opened, and feed is supplied until the adsorbent is saturated with the more strongly held component. The product during this step has a composition that varies from y_I to y_U (assuming that conditions allow sustained operation). The average product mole fraction is denoted y_P.

Subsequently, the column is permitted to depressurize by opening the exhaust line. This material is enriched in the more strongly adsorbed species. Finally, part of the high-pressure product is recycled in order to purge the column. Actually, the composition of this material may be different from that of the product because it may have been mixed with the residual contents of the surge tank, as in a single-bed process, or it may be a portion of the product from an entirely different column, as in a dual column process. The combined effluent from the blowdown and purge steps is considered waste, having a mole fraction of y_W.

After several cycles, the product composition, y_P, decreases to zero and steady-state is attained.

It is important to note that the material used for pressurization and purging of the bed is assumed to be available. Subsequent analysis of the performance of the single column and dual column configurations will establish the limits of operability.

Much of the basic mathematical theory that pertains to this development has been presented elsewhere (6,8,9) and will be only sketched here. The purpose of the development is to establish values of crucial terms in material balance equations (such as flow rates and compositions) in order to describe the process performance. The process is assumed to operate isothermally with ideal gas-phase behavior, and all dissipative effects are neglected. Continuity of a binary mixture requires that

Component A

$$\varepsilon \frac{\partial p_A}{\partial t} + \frac{\partial u p_A}{\partial z} + RT\ (1-\varepsilon)\ \frac{\partial n_A}{\partial t} = 0 \qquad (1)$$

Total Mass

$$\varepsilon \frac{\partial P}{\partial t} + \frac{\partial u P}{\partial z} + RT\ (1-\varepsilon)\ \frac{\partial n}{\partial t} = 0 \qquad (2)$$

where p_A is the partial pressure of component A, p is total pressure, u is the interstitial velocity, ε is the porosity of the bed, and n represents the capacity of the adsorbent.

$$n = n_A + n_B = (k_A p_A + k_B p_B)/RT \qquad (3)$$

It is arbitrarily assumed that component A is preferentially adsorbed, i.e., $k_A > k_B$. The mole fraction in the remainder of this development refers to component A.

It is convenient to express the porosity and isotherm slope in a single parameter for each component,

$$\beta_A = \frac{1}{1 + (1-\varepsilon)k_A/\varepsilon} \qquad (4)$$

$$\beta_B = \frac{1}{1 + (1-\varepsilon)k_B/\varepsilon} \qquad (5)$$

and their ratio as,

$$\beta = \frac{\beta_A}{\beta_B} = \frac{\varepsilon + (1-\varepsilon)\ k_B}{\varepsilon + (1-\varepsilon)\ k_B} \tag{6}$$

Note that according to the constraint mentioned above, $0 \leq \beta < 1$. As a consequence, difficult separations are characterized by $\beta \approx 1$.

Assuming that the axial pressure gradient is negligible permits integration of the balance equations to get expressions for velocity within the bed

(a) Varying pressure; $u = o$ at $z = o$

$$u = \frac{-z}{\beta_B[1+(\beta-1)y]} \frac{1}{P} \frac{dP}{dt} \tag{7}$$

(b) Constant pressure (the sign is positive in the upwards direction, cf Fig. 1).

$$\frac{u_1}{u_2} = \frac{1+(\beta-1)y_2}{1+(\beta-1)y_1} \tag{8}$$

Solving the material balance equations by the method of characteristics yields

$$\frac{dz}{dt} = \frac{\beta_A u}{1+(\beta-1)y} \tag{9}$$

$$\frac{dy}{dP} = \frac{(\beta-1)(1-y)y}{[1+(\beta-1)y]P} \tag{10}$$

These provide the composition change due to a pressure shift in the characteristic directions. These may be integrated along with eq. (7) to get definite results

$$\frac{y}{y_0} = \left(\frac{1-y}{1-y_0}\right)^{\beta} P^{\beta-1} \tag{11}$$

$$\frac{z}{z_0} = \left[\frac{y}{y_0}\right]^{\frac{\beta}{1-\beta}} \left[\frac{1-y_0}{1-y}\right]^{\frac{1}{1-\beta}} \left[\frac{1+(\beta-1)y}{1+(\beta-1)y_0}\right] \tag{12}$$

where $z = 0$ at the closed end and $z = 1$ at the open end of the column, y is the ultimate concentration and y_0 is the feed concentration, and P is the pressure ratio $= P_H/P_L$.

A conclusion reached in earlier work was that pressurization with product was more efficient than pressurization with feed (6). Accordingly, the remainder of the analysis is oriented toward the former approach. For that case, a shock-wave is created during the high-pressure feed step of a cycle because the feed is richer in the preferentially adsorbed component. The rate of propagation of the shock-wave in the bed is given by

$$u_S = \left.\frac{dz}{dt}\right|_S = \frac{\beta_A\ u_1}{1+(\beta-k)y_2} = \frac{\beta_A\ u_2}{1+(\beta-1)y_1} \tag{13}$$

where the subscripts 1 and 2 refer to leading and trailing edges of the shock-wave, respectively, and S refers to the shock-wave. Those compositions are related by

$$y_2 = \frac{K\ y_1}{1+(K-1)y_1} \tag{14}$$

$$K = \frac{y_{2_o}\ (1-y_{1_o})}{y_{1_o}\ (1-y_{2_o})} \tag{15}$$

in which y_{1_o} represents the initial composition of the gas in the bed, and y_{2_o} represents the feed composition, i.e., y_F.

SPECIFIC STEPS

Pressurization

The pressurization step for any cycle involves adding gas to the column from the bottom (cf. Figure 1), while it is closed at the opposite end. Since the feed and initial contents of the column have identical compositions, the characteristics described by eqs. (9) and (10) do not intersect or diverge. Hence, there is no shock-wave created.

The ultimate composition reached during pressurization by the initial column contents is given by eq. (11). During an arbitrary cycle, i, the pressurizing gas composition is y_I, so the ultimate composition, y_U, becomes

$$\left.\frac{y_U}{(1-y_U)^{\beta}}\right|_i = \frac{y_I}{(1-y_I)^{\beta}} \, P^{\beta-1} \tag{16}$$

During n successive cycles, if the product is not mixed with other material before being reinjected, the ultimate composition is

$$\left.\frac{y_U}{(1-y_U)^{\beta}}\right|_n = \frac{y_F}{(1-y_F)^{\beta}} \, P^{n(\beta-1)} \tag{17}$$

Unfortunately, however, the product will (probably) be mixed with the material "beneath" it in the column, because that material evolves first during the high-pressure feed step.

The penetration of the feed into the bed is determined from eq. (12), in which y_0 and y are replaced by y_F and y_U, respectively. Note that z is the distance from the closed end, so $z_0 = 1$. From the penetration it is possible to assess the molar contents of the column by a material balance.

For a differential length of column, the total number of moles present is

$$dN = [\beta + (1-\beta)y] \frac{A_{cs}\ P}{RY\ \beta_A} dz \tag{18}$$

where A_{cs} is the cross-sectional area of the bed.

The total number of moles in the column is given by

$$N = \int_0^N dN = \int_0^1 [\beta + (1-\beta)y] \frac{A_{cs}\ P}{RT\ \beta_A} dz \tag{19}$$

or

$$N = \frac{A_{cs}\ P}{RT\ \beta_A} [\beta + (1-\beta) \int_0^1 y\ dz] \tag{20}$$

By symmetry the integral may be split and restated as

$$\int_0^1 y\ dz = \int_0^{y_U} (1-z_U)dy + \int_{y_U}^{y_I} (1-z)\ dy \tag{21}$$

The first term is a constant, since $z_U \equiv 0$. Furthermore, the first integral may be combined with the first term of the second integral to give

$$\int_0^{y_U} (1-z_U)dy = \int_{y_U}^{y_I} dy - y_I \tag{22}$$

The second term, however, is more complicated. It may be restated, and combined with eq. (23) to give

$$\int_0^1 ydz = y_I - \int_{y_U}^{y_I} \left[\frac{y}{y_I}\right]^{\frac{\beta}{1-\beta}} \left[\frac{1-y_I}{1-y}\right]^{\frac{1}{1-\beta}} \left[\frac{1+(\beta-1)y}{1+(\beta-1)y_I}\right] dy \tag{23}$$

which may be integrated analytically when $\beta = 0.5$ and $\beta \equiv 0$, but only by quadratures for other cases. It is, however, possible to determine the number of moles that is present following pressurization by a material balance that accounts for the feeds, products and accumulation in the remaining steps of a cycle. The result is:

$$\int_0^1 y\ dz = \frac{y_I}{P} [1 + \frac{\beta(P-1)}{1+(\beta-1)y_I}] \tag{24}$$

Similarly a component balance (for species A) yields

$$dN_A = \frac{A_{cs}\ P}{\beta_A\ RT}\ y\ dz \tag{25}$$

$$N_A = \frac{A_{cs}\ P}{RT\ \beta_A} \int_0^1 y\ dz \tag{26}$$

The integral may be evaluated as previously described.

High-Pressure Feed

Following the pressurization step, the process feed is introduced to the column from the top and the product is withdrawn from the bottom (cf. Figure 1). Since the feed concentration of the preferentially adsorbed component is higher than (or equal to) that of the column contents, a shock-wave is formed. When the adsorbent is exploited to the maximum possible extent, the shock-wave propagates to the product end during this step.

In spite of that, the column contents at the outset of this step are not unifrom. Therefore, it is necessary to examine the possibility of the shock-wave interacting with the material that has concentrations between those of the feed and the contents prior to pressurization. This is resolved by comparing the propagation rate of the characteristic that corresponds to the ultimate penetration of the pressurization material (i.e., from the bottom of the column), with that of the shock front that is formed by intersecting characteristics of the initial column contents (i.e., following the purge step) and the feed material (i.e., from the top of the column). That is, when these curves intersect, the conditions correspond to an implausible operation because insufficient product is generated to meet the requirements of the purge and pressurization steps.

From eqs. (8), (9), (12) and (13) the following inequality results

$$\left[\frac{y_U}{y_I}\right]^{\frac{\beta}{1-\beta}}\left[\frac{1-y_I}{1-y_U}\right]^{\frac{1}{1-\beta}}\left[\frac{1+(\beta-1)y_U}{1+(\beta-1)y_I}\right]+\left[\frac{1+(\beta-1)y_F}{1+(\beta-1)y_U}\right]\geq 1 \qquad (27)$$

When the inequality holds, the process performs satisfactorily.

As in the pressurization step, the overall results of the high pressure feed step can be evaluated by material balances. In this case, the initial state is described by eqs. (21-(26). Conversely, the final state corresponds to the instant at which the shock-wave reaches the bottom of the column. Thus, the contents of the column are uniform at the composition of the feed. Therefore, eqs. (21) and (26) reduce to

$$N = \frac{A_{cs}P_H}{\beta_A RT}\left[\beta + (1-\beta)\ y_F\right] \qquad (28)$$

$$N_A = \frac{A_{cs}P_H}{RT\ \beta_A}\ y_F \qquad (29)$$

In addition, the molar quantities supplies in the feed and removed in the product may be determined from the relation for the total number of moles supplied during the high-pressure feed step

$$N_{in} = \frac{-A_{cs}}{RT}\ u_H\ t_H\ P_H \qquad (30)$$

Combining this with the integrated form of eq. (13), based on complete displacement of the shock-wave over the length of the column, yields

$$N_{in} = \frac{A_{cs}}{RT}\ \frac{1 + (\beta-1)y_U}{\beta_A}\ P_H \qquad (31)$$

The corresponding number of moles in the product may be determined from eqs. (21- 24) and (31) through an overall material balance.

An equivalent procedure may be used to determine the quantities of species A, i.e., the preferentially adsorbed component.

Blowdown

After the shock-wave has reached the bottom of the bed, the product flow is stopped and the column is depressurized through the top. As this occurs, the shock-wave disintegrates and a simple-wave is formed which is described by the diverging characteristics, as in eqs. (9-12). As the pressure declines the composition within the column becomes increasingly enriched in the selectively adsorbed component. The product from the blowdown step, accordingly, has a time-dependent composition. Typically, the analysis of the net change that occurs during this step is more readily obtained by evaluating the other steps and applying overall material balances. This will be expanded upon in the next section.

Purge

Finally, the column contents that are rich in the preferentially adsorbed component are exhausted by essentially recycling a portion of the purified product. Again, since the material being supplied is leaner than the effluent, a simple-wave is formed. The step is complete when the characteristic that defines the trailing edge of that wave reaches the top of the column. That result may be obtained from eq. (9). The purging material or low-pressure feed is assumed to have a fixed concentration, viz. y_I.

As indicated in Figure 1, the net changes during the blowdown and purge steps are combined. The initial state is identical to the final state of the high-pressure feed step, while the final state corresponds to the initial state of the pressurization step. The latter case is the result of sufficient purified product being recycled to fill the column. This step proceeds according to eqs. (8) and (9). The ultimate molar contents of the bed are given by eqs. (21) and (26), which become

$$N = \frac{A_{cs}P}{PT\beta_A}\,[\beta + (1-\beta)y_I] \tag{32}$$

$$N_A = \frac{A_{cs}P}{RT\,\beta_A}\,y_I \tag{33}$$

As in the high-pressure feed step, the total number of moles supplied during the low-pressure pruge step may be evaluated

$$N_{in} = \frac{-A_{cs}}{RT}\,u_L\,t_L\,P_L \tag{34}$$

which may be combined with eq. (9) to give

$$N_{in} = \frac{A_{cs}}{RT}\,\frac{1 + (\beta-1)y_I}{\beta_A}\,P_L \tag{35}$$

Again, the quantity expelled during the blowdown and low-pressure purge steps may be found by an overall material balance, based on eqs. (29), (32) and (35). Similarly, the net flows of species A may be determined by the same procedure.

TRANSIENT PERFORMANCE OF A SINGLE-COLUMN SYSTEM

The single-column configuration of the PSA process is clearly the simplest both in terms of equipment and because limited synchronization is necessary. Nevertheless, upon start-up the process may be rather slow to attain steady-state, because the surge tank that is available for retaining the purified product is subject to backmixing. In addition, a portion of the purified product has intermediate composition, approaching that of the product from the previous cycle.

Two measures of the approach to steady-state are the ratios of the concentrations of: the average high-pressure product to that of the high-pressure feed, and the average high-pressure product to that of the recycled product, which is contaminated by backmixing. These concentration ratios may be determined from material balance relationships. For this development, the concentration of the gas used for purging then pressurizing the column is y_I, which is greater than or equal to the average composition of the purified product, y_P, because the latter mixes with the contents of the surge tank. Therefore, the performance of the process may be assessed by applying the equations provided in the previous section.

The permissible ranges of the two measures of approach to steady-state are from 1 to 0, and from 0 to 1, respectively. Nevertheless, it is unclear whether the latter is necessarily monotonic, and the ultimate values of both the numerator and denominator vanish, leaving a mathematically indeterminate result. Consequently, the former concentration ratio is used. The result, obtained by combining eqs. (21), (26), (28), (29) and (31), is

$$\frac{y_P}{y_F} = \frac{\frac{y_I}{P}\left[1 + \frac{(P-1)}{1+(\beta-1)y_I}\right] + (\beta-1)y_F y_U}{1+(\beta-1)\left[y_F + y_U - \frac{y_I}{P}\left(1 + \frac{\beta(P-1)}{1+(\beta-1)y_I}\right)\right]} \tag{36}$$

The effect of backmixing is taken into account in the evaluation of y_U, by eq. (16), and the integral term, by eq. (24).

Now, in order to tie the steps within a cycle together (and subsequently to consider a sequence of cycles), it is necessary to account for the capacity of the surge tank. The capacity should be based on three factors: the number of moles of product required for pressurization, for purging (following depressurization), and a residual volume that corresponds to the contents at the lower operating pressure. The sum of these is

$$V_t = RT\,(N_{PR} + N_{PU})/(P_H - P_L) \tag{37}$$

where N_{PR} and N_{PU} represent the moles required for the pressurization and purge steps, respectively. These may be determined from eqs. (21), (32) and (35), with the following result

$$V_t = A_{cs}\,\{\beta(P-1) + (1-\beta)\left[P\int_0^1 ydz - 2y_I\right] + 1\}/(P-1)\beta_A \tag{38}$$

where A_{cs} is the cross-sectional area of the column, which has unit length. In effect, V_t/A_{cs} is the ratio of the volume of the surge tank to that of the column. For a particular application, the volume could be set by the initial or ultimate (steady-state) conditions.

Mixing within the tank can occur in two steps, first while the tank is being repressurized, and second (if and) when the high-pressure product continues to pass through the tank after it is pressurized. It is easy to take both steps into account, by means of simple material balances. Most of the features, however, can be examined by considering only the first step. For that case the composition of the contents will become

$$y_I = y_P + (y_I - y_P)/P \tag{39}$$

where y_I is the concentration for the next purge and pressurization steps, and y_i is the concentration from the preceding cycle or the initial concentration.

Illustration

There is substantial interest in P.S.A. for separating air to get nearly pure oxygen and/or nitrogen. The uses of oxygen and nitrogen are obvious, but the reasons for using P.S.A. instead of conventional air separation processes may not be. For example, it is relatively easy and inexpensive to build a P.S.A. process for small-scale applications. This may make it possible for consumers of small quantities to be self-sufficient rather than depending on delivery and storage. As a result, P.S.A. may be employed to greater extent in aricraft, hospitals, and wastewater treatment facilities. In addition, there may be economic incentives for using P.S.A. instead of cryogenic systems for larger scale industrial applications, possibly even for combustion in power generation.

The separation of air by P.S.A. contrasts with other applications, such as recovery of helium from natural gas and enrichment of hydrogen isotopes, because the feedstock is practically free. Nevertheless, the energy costs and lag-time associated with start-up are considered worth minimizing.

Several studies of equilibrium adsorption on 5A molecular sieve of oxygen and nitrogen have been reported. (8,10,11,12). The isotherms in these studies are shown to be nearly linear for partial pressures up to about 1 bar, near ambient temperature. Despite that similarity, however, the actual values of the slopes of the component isotherms vary somewhat from study to study. Accordingly, typical values were taken and are listed in Table 1, along with other properties and conditions. Note that argon and other minor constituents of air have been neglected.

Coincidentally, the values of the isotherm slopes and void fraction yield a value of β = 0.5. As a result, eq. (16) reduced to

$$y_U = \frac{[1 + 4P\,(1-y_I)/y^2]^{0.5} - 1}{2P(1-y_I)/y_I^2} \tag{40}$$

Furthermore, eqs. (16 and 22) simplify to

$$\int_0^1 y\,dz = \frac{y_I}{2-y_I}\left\{1 + \frac{1-y_I}{P}\right\} \tag{41}$$

TABLE 1

Adsorbent Properties and Operating Conditions

Molecular Sieve 5-A	
Isotherm Slope @ 20°C	
A. Nitrogen	7.70 m^3 N_2/m^3
B. Oxygen	3.35 m^3 O_2/m^3
Bulk Density	700 kg/m^3
Void Fraction (interstitial)	0.5 m^3/m^3
Temperature	20°C
Feed Composition	
A. Nitrogen	79. % (mol)
B. Oxygen	21. % (mol)
Pressure Range	0.2-1.0 bar*
Column	
Length	1.00 m
Inner Diameter	0.05 m

*Note: As long as the isotherms are practically linear, any absolute pressure range in which the ratio of high to low is 5.0 is equivalent.

The approach to steady-state may be followed through multiple cycles by an analytic expression obtained by inserting eq. (41) into eq. (36), which is omitted here. Unfortunately, the process produces less than the minimum gross product that is necessary for recycle (during the pressurization and purge steps) under low operating pressure ratios. This is illustrated by the critical recycle to product mole ratio. That ratio is unity when the breakeven point is reached. For this example, the ratio is plotted versus pressure ratio in Figure 2. It is observed that the net product is available at pressure ratios greater than about 5.

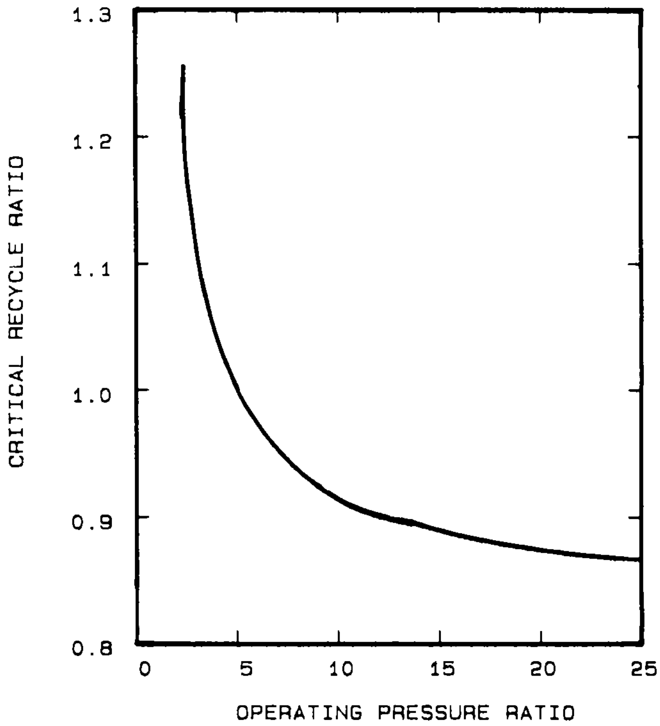

FIGURE 2. Critical recycle ratio for diversion of product. Based on BETA=0.5, YF=0.79, as for air with 5A molecular sieve. Single column process.

In order to assess the performance over several cycles, it is necessary to evaluate the size of the surge tank according to eq. (38). The results are shown in Figure 3, and are based on the data listed in Table 1.

Two scales of process performance are: the ratio of mole fractions of the high-pressure product to that of the feed, which depends on the number of elapsed cycles at a given operating pressure ratio, and the number of cycles required to attain steady-state,

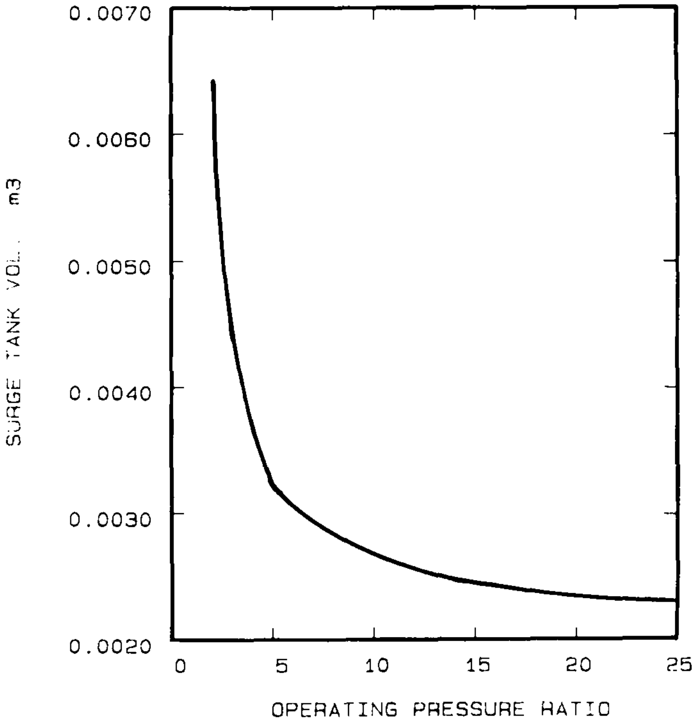

FIGURE 3. Minimal surge tank volume, cubic meters. Based on BETA=0.5, YF = 0.79, as for air with 5A molecular sieve.

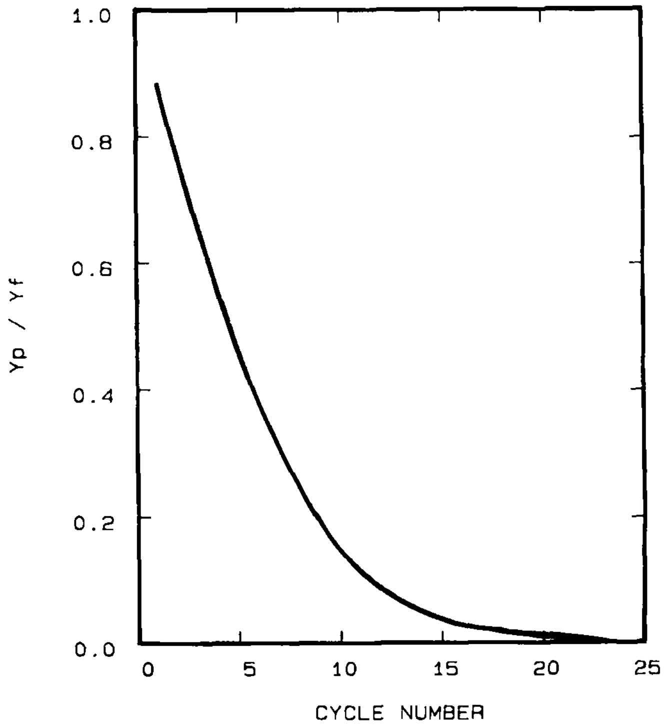

FIGURE 4. Ratio of product mole fraction to that of the feed, as steady stateis approached. Based on BETA=0.5, YF=0.79, as for air, with P=5.

which depends on the operating pressure ratio. These are illustrated in Figures 4 and 5, respectively.

In view of the preceding development, it is clear that the simple step of purging the column at the outset with pure oxygen (i.e., component B) would nearly eliminate the transient nature of the process. Furthermore, it is simpler to assess the appropriate size of the surge tank, because backmixing is not an issue. Finally, one feature that is not addressed above is the production rate of

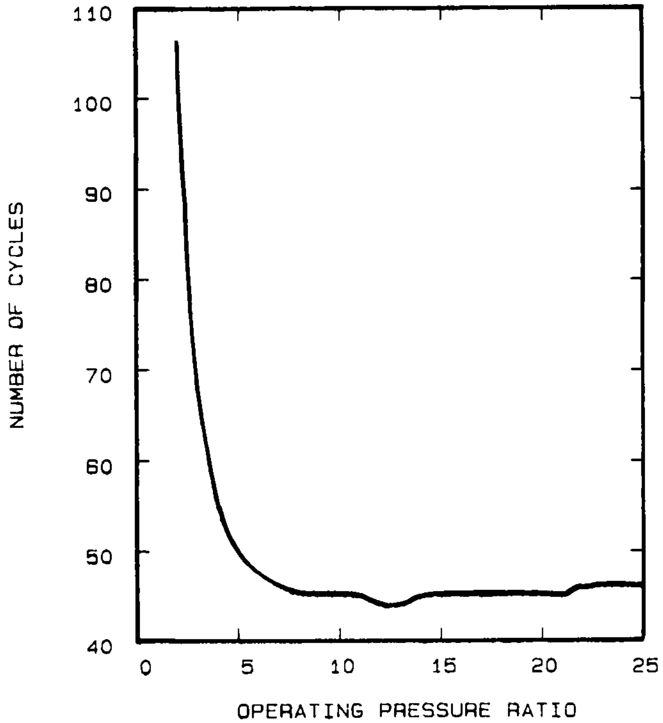

FIGURE 5. Number of cycles required to attain steady state. Based on BETA=0.5, YF = 0.79, as for air with 5A molecular sieve. Single column P.S.A. process.

the purified oxygen. Two effects reduce the production rate during transient start-up. First, the high-pressure product purity increases relatively slowly. Second, the quantity of purified product is reduced by the large surge tank capacity, which diverts potentially useful product. The only drawback is the necessity of another tank, which contains an initial charge that can be subsequently replenished during steady-state operation.

TRANSIENT PERFORMANCE OF A DUAL-COLUMN SYSTEM

Despite the simplicity of the single-column process, multiple-column configurations are more common (2). Two reasons for this are that such systems may not require significant capacitance, and by arranging columns in series higher purity levels may be obtained, while recovering a substantial fraction of the energy invested in compression. Furthermore, since columns normally are synchronized to be one-half cycle out-of-phase, each column is exposed only to alternate portions of recycled product. As a result, the purge and pressurization materials are at higher purity after a number of cycles than would be possible in a single, uncoupled column. The following development examines the effect of these concepts on a typical dual-column process, as shown in Figure 6.

Since the dead-volume between columns is small, the effect of backmixing is neglected. To estimate the transient development of steady-state, both columns will be studied, since the product of one is used to purge and to purify the other. Accordingly, the first cycle in the first column (i.e., the top one in Figure 6) is identical to the single-column case. The first cycle in the second column, however, resembles the second cycle in the single-column case. In fact, the performance is superior since backmixing is absent in the dual-column arrangement. During the second cycle, the first column resembles the single-column during its third cycle, and so on.

As a consequence, the analysis for a particular cycle involves only eqs. (16), (21), (24), (26), (29), (31), (33), and (35). The sequence calls for replacing y_P with y_I when advancing one half-cycle to the alternate column.

As in the single-column system, the performance of the process depends on the number of cycles to attain steady-state. According-

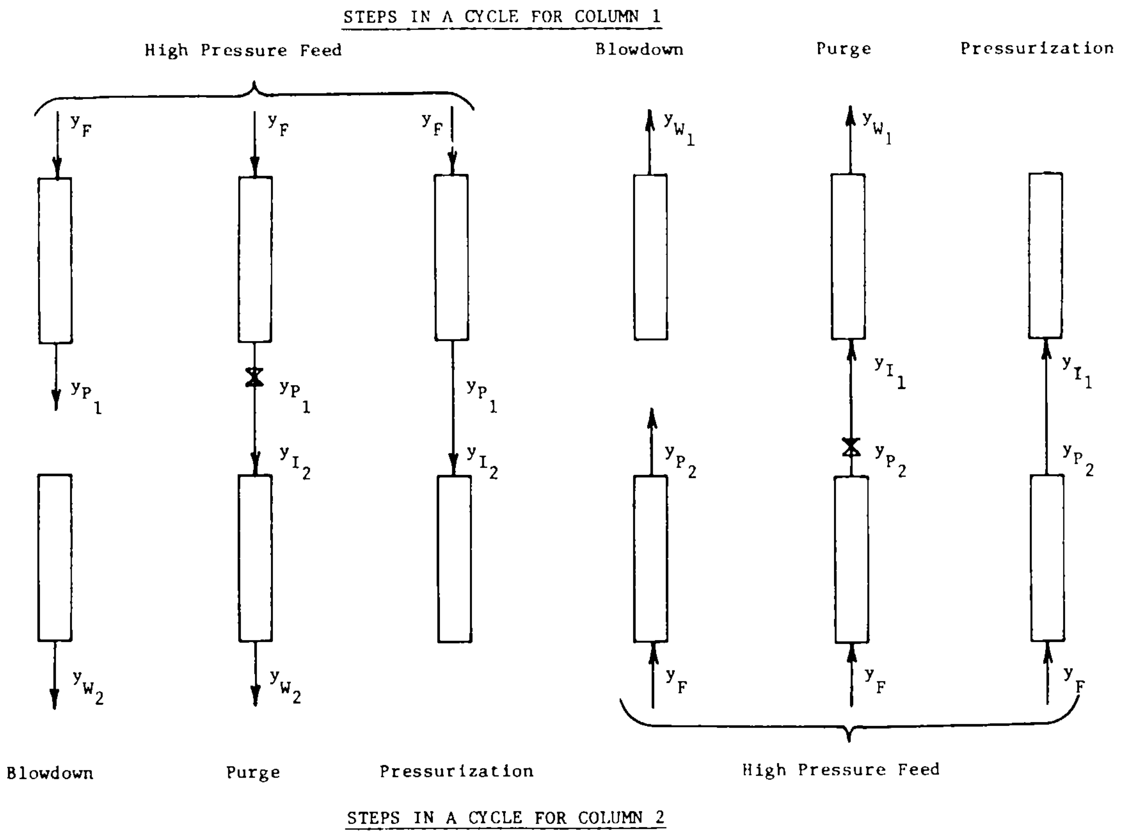

Figure 6. Schematic diagram of a dual-column pressure-swing adsorption process. The high pressure feed step is divided into three parts to indicate the disposition of the product.

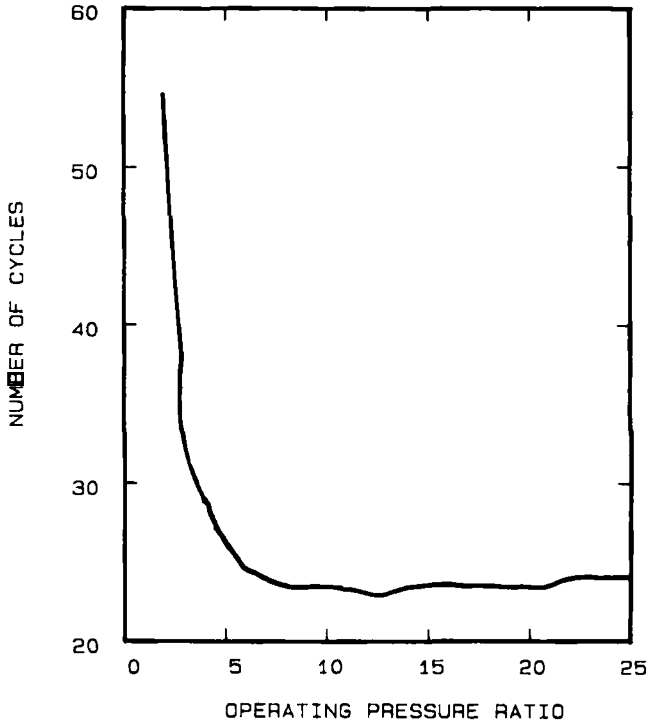

FIGURE 7. Number of cycles required to attain steady state. Based on BETA=0.5, YF = 0.79, as for air with 5A molecular sieve. Two-column P.S.A. process.

ly, the mole fraction ratio of the product to the feed, as defined in eq. (36), is employed again.

Illustration

This section is a continuation of the illustration given for the single-column process, viz. separation of air. In this case, however, the actual dimensions of the column, etc., are not relevant because production rates are not compared, and because mixing effects are neglected. Despite that, it is necessary that these two columns be identical. Other parameters and conditions are unaltered from the previous example, as listed in Table 1.

The results for those conditions have been determined from eq. (36), based on eq. (16) and (24). Sample numerical values are shown in Figure 7.

For this dual-column application it would be possible to essentially eliminate the delay of attainment of steady-state by initially purging and pressurizing the first column with oxygen (i.e., component B). Since the delay is relatively short, however, the savings may not compensate for the added complexity.

NOMENCLATURE

A_{cs}	column cross-sectional area
k	isotherm slope
n	moles adsorbed per unit volume
N	moles present or added
p	partial pressure
P	total pressure
$\mathcal{P}$	pressure ratio
R	gas law constant
t	time
T	temperature
u	interstitial velocity
V_t	surge tank volume
y	mole fraction (usually of the more strongly adsorbed component)
z	axial position

Subscripts

A	component A (more strongly adsorbed)
B	component B (less strongly adsorbed)
F	feed
H	high pressure step
I	recycled product
in	injected
L	low pressure step
P	product
PR	pressurization step

PU	purge step
S	shock-wave
U	ultimate value reached during pressurization
W	waste
1	leading edge
2	trailing edge

Greek Symbols

β_A	defined by eq. (4)
β_B	defined by eq. (5)
β	β_A/β_B
ϵ	void fraction of adsorbent bed

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