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(54) Title: ENGINEERED ADSORBENT STRUCTURES FOR KINETIC SEPARATION

(57) Abstract: Improved adsorbent sheet based parallel passage adsorbent structures for enhancing the kinetic selectivity of certain kinetic-controlled adsorption processes, such as PSA, TSA and PPSA processes, and combinations thereof, are provided. The enhancements in kinetic selectivity made possible through the implementation of the present inventive improved adsorbent structures may unexpectedly enable significant intensification of selected kinetic adsorption processes relative to attainable performance with conventional adsorbent materials in beaded or extruded form. Such process intensification enabled by the present inventive adsorbent structures may provide for increased adsorption cycle frequencies, and increased gas flow velocities within the adsorbent beds, which may increase the productivity and/or recovery of a kinetic adsorption system incorporating the inventive adsorbent



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ENGINEERED ADSORBENT STRUCTURES FOR KINETIC SEPARATION**CROSS REFERENCE TO RELATED APPLICATION**

This application claims the benefit of the earlier filing date of U.S.

- 5 Provisional Application No. 60/642,366, filed on January 7, 2005. The entire disclosure of Provisional Application No. 60/642,366 is considered to be part of the disclosure of the accompanying application and is incorporated herein by reference.

FIELD

- 10 The present invention relates to adsorbent structures for improved performance of pressure swing adsorption and other adsorptive gas separation processes based on kinetic selectivity.

BACKGROUND

- 15 Gas separation by pressure swing adsorption (PSA) and other adsorptive gas separation processes such as temperature swing adsorption (TSA) and partial pressure swing or displacement purge adsorption (PPSA) are achieved when a first gas component is more readily adsorbed on an adsorbent material compared to a second gas component which is relatively less readily adsorbed on the adsorbent
- 20 material. In many important applications, to be described as “equilibrium-controlled” processes, the adsorptive selectivity is primarily based upon differential equilibrium uptake of the first and second components. In another important class of applications, to be described as “kinetic-controlled” processes, the adsorptive selectivity is primarily based upon the differential rates of uptake of the first and
- 25 second components.

- In PSA processes, a feed gas mixture containing the first and second gas components is separated by cyclic variations of pressure coordinated with cyclic reversals of flow direction in a flow path contacting a fixed bed of the adsorbent material in an adsorber vessel. In the case of TSA or PPSA processes, cyclic
- 30 variations of temperature and/or partial pressure of the gas components may be coordinated with gas flow through a flow path to perform a separation. The process in any specific PSA application operates at a cyclic frequency characterized by its

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period, and over a pressure envelope between a first relatively higher pressure and a second relatively lower pressure. Separation in PSA is achieved by coordinating the pressure variations with the flow pattern within the flow path, so that the gas mixture in the flow path is enriched in the second component (owing to preferential
5 adsorptive uptake of the first component in the adsorbent material) when flowing in a first direction in the flow path, while the gas mixture is enriched in the first component (which has been desorbed by the adsorbent material) when flowing in the opposite direction in the flow path. In order to achieve separation performance objectives (i.e. product gas purity, recovery and productivity), process parameters
10 and operating conditions should be designed to achieve a sufficiently high adsorptive selectivity of the first and second components over the adsorbent material, at the cyclic frequency and within the pressure envelope.

In PSA processes designed to be equilibrium-controlled, the intrinsic adsorptive selectivity may typically be independent of cycle frequency, and depend
15 only on the intrinsic equilibrium adsorptive preference of the adsorbent material in question relative to the fluid components in the feed fluid. The actual separation performance may be degraded by dissipative effects including mass transfer resistance and axial dispersion. The deleterious effects of mass transfer resistances associated with film (such as resulting from fluid flow boundary layer effects),
20 macropore and micropore mass transport on equilibrium-controlled separation performance typically increase at higher gas flow velocities associated with higher cycle frequencies. Therefore the maximum practicable PSA cycle frequency which can be achieved for equilibrium-controlled separations may typically be limited by such mass transfer resistances. In order to maximize specific productivity for a
25 given adsorbent vessel volume, it is desirable to increase cycle frequency within the constraints set by (1) performance degradation associated with mass transfer resistance and (2) adsorbent degradation as fluidization velocities of typical conventional granular packed beds are approached. While smaller adsorbent pellets may typically have lower macropore and film mass transfer resistance, it is generally
30 impracticable to reduce pellet diameters below about 0.5 mm to about 1mm before encountering excessive flow friction pressure gradients and the risk of fluidization and associated adsorbent pellet degradation.

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As set forth in prior commonly assigned US Patent numbers 5,082,473, 6,451,095, 6,692,626, and US Patent Application number 10/041,536 (the contents of which are herein incorporated by reference), equilibrium-controlled PSA processes may be enhanced by configuring the adsorbers as layered “adsorbent laminate sheet” parallel passage contactor structures, with the adsorbent material formed into adsorbent sheets, with or without suitable reinforcement materials incorporated into such sheets. As described in the above references, such adsorbent sheets may preferably be separated by spacing means, such as exemplary expanded or woven metal mesh sheet spacers, or printed spacers, establishing generally parallel fluid flow channels between adjacent surfaces of adsorbent sheets. Such parallel passage adsorbent contactor structures may be assembled according to methods known in the art, such as by the exemplary forming of the adsorbent sheets and spacing means as stacked layers or as a multi-layer spiral roll. While parallel passage adsorbers fabricated as extrudate monoliths are also known in the art, the adsorbent structures formed from multiple layers of adsorbent sheets, as described above are particularly suitable for achieving high surface area and narrow flow channels desirable for cyclic adsorptive service.

It has been established that multilayer adsorbent sheet structures can achieve favourable performance in equilibrium-controlled PSA processes where macropore diffusion dominates mass transfer resistance. The adsorbent is fully immobilized in sheet form to avoid fluidization limits of conventional granular adsorbers. Flow friction pressure drop is reduced relative to conventional packed granular beds, while macropore mass transfer resistance may be reduced by using thin adsorbent sheets. Because mass transfer and pressure drop constraints can be reduced, equilibrium-controlled PSA processes can thus be operated at high cycle frequency, for example and without limitation, up to about one cycle per second for adsorbent sheets about 250 microns thick. Therefore, compared to conventional granular (beaded) adsorbent beds, the onset of separation performance degradation due to macropore mass transfer resistance in adsorbent sheet structures can be shifted to higher operating cycle frequencies (as determined by macropore kinetics), while the inherent selectivity of the equilibrium-controlled process remains substantially unaffected.

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In kinetic-controlled adsorption processes, separation over a given adsorbent material may be achieved between a first component which adsorbs and typically also desorbs relatively more rapidly at a particular cycle frequency, and a second component which adsorbs and typically desorbs relatively less rapidly at the cycle frequency. In the case of kinetic-controlled PSA processes, such adsorption and desorption are typically caused by cyclic pressure variation, whereas in the case of TSA, PPSA and hybrid processes, adsorption and desorption may be caused by cyclic variations in temperature, partial pressure, or combinations of pressure, temperature and partial pressure, respectively.

In the exemplary case of PSA, kinetic-controlled selectivity may be determined primarily by micropore mass transfer resistance (e.g. diffusion within adsorbent particles or crystals) and/or by surface resistance (e.g. narrowed micropore entrances). For successful operation of the process, a relatively and usefully large working uptake (e.g. the amount adsorbed and desorbed during each cycle) of the first component and a relatively small working uptake of the second component may preferably be achieved. Hence, the kinetic-controlled PSA process may preferably be operated at a suitable cyclic frequency, balancing between and avoiding excessively high frequencies where the first component cannot achieve a useful working uptake, and excessively low frequencies where both components approach equilibrium adsorption values.

Some established kinetic-controlled PSA processes use carbon molecular sieve adsorbents, e.g. for air separation with oxygen comprising the first more-adsorbed component and nitrogen the second less adsorbed component. Another example of known kinetic-controlled PSA is the separation of nitrogen as the first component from methane as the second component, which may be performed over carbon molecular sieve adsorbents or more recently as a hybrid kinetic/equilibrium PSA separation (principally kinetically based, but requiring thermal regeneration periodically due to partial equilibrium adsorption of methane on the adsorbent material) over titanosilicate based adsorbents such as ETS-4 (such as is disclosed in US Patent numbers 6,197,092 and 6,315,817 to Kuznicki et. al.). These known kinetic-controlled adsorptive separation applications may be characterized by relatively low cycle frequencies and gas flow velocities, where conventional beaded

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or extruded adsorbents may be used in granular packed beds without resulting in fluidization. Since the cycle frequency of kinetic-controlled PSA processes is typically determined by micropore and/or surface resistance kinetics, contrasting with equilibrium-controlled PSA processes whose cycle frequency is typically
5 limited by macropore kinetics, a system has been needed which can enable significant intensification (e.g. higher operating frequencies and gas flow velocities, and therefore resulting higher productivities and/or recoveries) of kinetic-controlled adsorption processes, such as PSA, TSA, and PPSA processes, and combinations thereof.

10

SUMMARY

The present invention comprises improved adsorbent sheet based parallel passage adsorbent structures for enhancing the kinetic selectivity of certain kinetic-controlled adsorption processes, such as PSA, TSA and PPSA processes, and
15 combinations thereof. The enhancements in kinetic selectivity made possible through the implementation of the present inventive improved adsorbent structures unexpectedly enables significant intensification of kinetic adsorption processes relative to attainable performance with conventional adsorbent materials in beaded or extruded form. Such process intensification enabled by the present inventive
20 adsorbent structures may provide for increased adsorption cycle frequencies, and increased gas flow velocities within the adsorbent beds, which may increase the productivity of a kinetic adsorption system incorporating the inventive adsorbent structures. In particular, increases in productivity may enable the reduction in adsorbent material inventory for a given system capacity, resulting in smaller, lower
25 cost adsorption systems, and potentially enabling the use of kinetic adsorption systems in cost and/or space sensitive separation applications for which adsorption systems were previously unviable. Alternatively, the increase in productivity resulting from kinetic process intensification may enable increased product recovery and resulting reductions in operating costs of adsorption systems incorporating the
30 inventive adsorbent structures. Further, the inventive kinetic adsorbent structures may enable kinetic separations that could not be achieved at all with conventional adsorbents in packed bed adsorbers, due to the freedom of the inventive adsorbent

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structures from some limitations in cycle frequency and/or gas flow velocity suffered by conventional adsorbent materials in packed adsorber beds.

The present invention provides a kinetic-controlled adsorption process, in which separation is achieved between a first component "A" (the "fast component")
5 which adsorbs and typically desorbs relatively more rapidly on a kinetically selective adsorbent in an adsorbent structure at a given cyclic frequency, and a second component "B" (the "slow component") which adsorbs and typically desorbs relatively less rapidly on the adsorbent at the given cycle frequency. The kinetic-controlled adsorption process may be achieved through the cyclic variation of
10 pressure in the case of PSA, temperature in the case of TSA, and partial pressure in the case of PPSA, or the cyclic variation of a combination of these variables.

The adsorbent sheets comprising the improved adsorbent structures in the present invention may be made according to any suitable method, such as those disclosed in the Applicant's previously published US Patent Application number
15 10/041,536, which is incorporated by reference as disclosed above. A desired adsorbent material may desirably be supported as adsorbent sheet layers of a characteristic thickness "X" contacting flow channels within the adsorber structure. In an exemplary embodiment, the flow channels are typically oriented tangentially with respect to the adsorbent sheet layers. Such flow channels may typically be
20 established by spacing means situated between adjacent adsorbent sheet layers, such as the mesh or printed spacing means disclosed in the above mentioned reference, or in other embodiments may be established by another typically sheet-like material situated between adjacent adsorbent layers, where the other material has a relatively higher fluid permeability compared to the adsorbent sheet layers, thus establishing a
25 fluid flow channel between adsorbent sheet layers. The adsorbent sheet layers may be flat, or may be curved with a radius of curvature which typically would be much larger than the layer thickness "X". The adsorbent layers may typically comprise a macroporous matrix of microporous adsorbent particles of a characteristic radius " r_c ", with the adsorbent macroporous matrix having a macropore void fraction " ϵ_p ".
30 The microporous adsorbent particles may typically be zeolite or titanosilicate or other crystalline molecular sieve crystals or crystallites of radius " r_c ", or alternatively could be particles or domains of an amorphous adsorbent material or

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gel, such as silica, alumina or carbon. Alternatively, other known adsorbent materials may be included in the adsorbent layers.

Adsorbents suitable for incorporation into the adsorbent layers of the adsorbent sheet structures according to the present invention designed for the kinetic-controlled separation of gases may be selected from any known crystalline or amorphous microporous solid exhibiting adsorbent properties, and typically having an average pore size on the order of one or more of the gas components desired to be separated.

For the separation of small molecules of similar size such as N_2/O_2 , or propane/propylene, small-pore zeolites such as chabazite, zeolite A, or other crystalline microporous molecular sieves having pores defined by 8-membered rings (as defined by the International Zeolite Association) may be used. The composition or structure of such suitable molecular sieve materials may be modified appropriately to reduce the pore size and generate a desired kinetic selectivity defined as the ratio of the diffusivities of the gas component species into the adsorbent material.

Titanosilicate molecular sieves such as ETS-4 may be used with additional advantage to the kinetic-controlled adsorptive system (particularly PSA) design, comprising the adsorbent structures of the present invention. Unlike conventional molecular sieves, the heat of adsorption of various components on such titanosilicate molecular sieve adsorbents can be modified independently of the pore size. Furthermore, the pore size of titanosilicate molecular sieves can be precisely controlled through synthesis and/or dehydration of the adsorbent which may desirably allow a high degree of "customization" toward the target gas separation. Being able to independently vary and thereby "tune" the diffusivity constants of the desired gas components to be separated through pore size reduction and values of the heats of adsorption (and/or Henry Law adsorption constants) through compositional modification may allow additional levels of optimization, particularly in kinetic-controlled separations, and particularly in the design of kinetic-controlled PSA cycles.

The adsorbent sheet layers in the inventive adsorbent structures may include a binder to immobilize the adsorbent particles, may contain a fibrous or filamentary

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material for structural reinforcement, and may be attached to a support sheet or mesh or grid to form an adsorbent sheet that may have adsorbent layers on one or both sides of the sheet, such as is described in the above mentioned references disclosing methods of making adsorbent sheet structures generally.

- 5 Kinetic-controlled adsorptive selectivity may be determined primarily by micropore diffusion internal to the adsorbent particles, such as for example and without limitation zeolite or other molecular sieve crystals or crystallites of radius “ r_c ” with an intracrystalline diffusivity for the fast component of “ D_{cA} ” and for the slow component of “ D_{cB} ”. Using a standard linear driving force approximation for
10 diffusive transport, time constants for diffusion of the fast and slow gas components are for this disclosure defined as:

$$t_{cA} = \frac{r_c^2}{15 \cdot D_{cA}} \quad t_{cB} = \frac{r_c^2}{15 \cdot D_{cB}}$$

- with the factor 1/15 reflecting the well known pulse response of approximately
15 spherical adsorbent particles.

- Alternatively, kinetic-controlled adsorptive selectivity may be determined primarily by surface resistance (for example and without limitation surface resistance due to a barrier coating or narrowed micropore entrances) of the internal adsorbent particles. With rate coefficients “ k_{sA} ” and “ k_{sB} ” for the fast and slow
20 components, their time constants are (for surface resistance on approximately spherical adsorbent particles of radius “ r_c ”) are in this case defined as:

$$t_{cA} = \frac{r_c}{3 \cdot k_{sA}} \quad t_{cB} = \frac{r_c}{3 \cdot k_{sB}}$$

- 25 With the above definitions of the time constants, they are given for the typical industrial kinetic-controlled PSA air separation over Bergbau-Forschung carbon molecular sieves, with oxygen comprising the fast component and nitrogen the slow component, as $t_{cA} = 25$ seconds and $t_{cB} = 1130$ seconds. The present invention and inventive adsorbent structures are particularly concerned with order of

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magnitude faster kinetic separations and rate constants where $t_{cA} < \text{about } 2.5$ seconds. The invention also addresses yet another order of magnitude faster kinetic separations and rate constants where $t_{cA} < \text{about } 0.2$ seconds, such separations having been impracticable to achieve with conventional granular adsorbent in
 5 packed beds, due to the fluidization limitation of gas flow velocities in the beds, which practically also limit the maximum cycle frequencies possible in such conventional systems to below the threshold for the fastest kinetic separations mentioned above.

Macropores in adsorbent materials have a characteristic typical tortuosity " τ "
 10 and pore diffusivity " D_p ". For the case of equimolar diffusion and with the pore diffusivity dominated by molecular diffusivity " D_m ",

$$D_p = D_m/\tau.$$

A viable kinetic-controlled adsorptive separation process provides that a usefully and relatively large working uptake (e.g. the amount adsorbed and desorbed
 15 during each cycle) of the first component and a relatively small working uptake of the second component may be desirably achieved at a given cyclic operating frequency for the process. The differential equilibrium uptakes are defined by the slopes of the adsorption isotherms as

$$K_A = \frac{dq_A}{dc_A} \quad K_B = \frac{dq_B}{dc_B}$$

For the kinetic-controlled separation, an ideal selectivity is defined as:

$$S_o = \frac{K_A \cdot t_{cB}}{K_B \cdot t_{cA}} \quad \text{or} \quad S_o = \frac{K_A \cdot D_{cA}}{K_B \cdot D_{cB}}$$

25 with $S_o \gg 1$.

The problem to be overcome by the present invention exists in adsorptive separation applications where the ideal kinetic selectivity is masked or nullified by macropore and external film mass transfer resistances. For the layered adsorbent

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sheet structures of the present invention, a semi-empirical kinetic selectivity is approximately defined in the linear driving force model as:

$$S = \frac{\frac{t_{cB}}{K_B} + \frac{X^2}{6 \cdot \varepsilon_p \cdot D_p}}{\frac{t_{cA}}{K_A} + \frac{X^2}{6 \cdot \varepsilon_p \cdot D_p}} \quad \text{or} \quad S = \frac{\frac{r_c^2}{15 \cdot K_B \cdot D_{cB}} + \frac{X^2}{6 \cdot \varepsilon_p \cdot D_p}}{\frac{r_c^2}{15 \cdot K_A \cdot D_{cA}} + \frac{X^2}{6 \cdot \varepsilon_p \cdot D_p}}$$

5

In the limit of vanishing macropore resistance (either $X \rightarrow 0$ or $D_p \rightarrow \infty$), $S = S_0$.

A figure of merit "F" may be defined so that a high value of "F" implies that $S \rightarrow S_0$.

The multi-layered kinetic-controlled parallel passage adsorbent structure of the present invention is characterized by the inequality

10

$$X^2 \leq \frac{6 \cdot \varepsilon_p \cdot D_p \cdot t_{cA}}{F \cdot K_A}$$

This expression may be restated, for the case of micropore diffusion kinetic control and with molecular diffusion dominating macropore diffusion, as

15

$$X^2 \leq \frac{6 \cdot \varepsilon_p \cdot D_m \cdot r_{cA}^2}{15 \cdot F \cdot \tau \cdot K_A \cdot D_c}$$

For $F < 1$, accordingly $S < 0.5 \cdot S_0$, which indicates substantial loss of kinetic selectivity. In a desirable range of parameters for enhanced kinetic selectivity according to several embodiments of the present inventive kinetic-controlled adsorbent structure which may enable effective kinetic-controlled separation, for $F > 3$, accordingly $S > 0.75 \cdot S_0$; for $F > 4$, $S > 0.80 \cdot S_0$; for $F > 9$, $S > 0.90 \cdot S_0$; and for $F > 19$, $S > 0.95 \cdot S_0$.

25

Accordingly, in an embodiment according to the invention it is desirable that "F" should be in excess of unity (1) for either of the above inequalities as applicable,

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so that preferably $F > 3$, more preferably $F > 4$, yet more preferably $F > 9$, and most preferably $F > 19$.

The adsorption and diffusion parameters K_A , k_{cA} and D_{cA} for the fast component are representative of process conditions over the adsorbent materials for the gas mixture being separated, within the working range of gas concentrations for the fast and slow components for a PSA cycle conducted at a nominal working temperature within the inventive kinetic-controlled adsorber structure and within a working pressure envelope (between an upper pressure and a lower pressure of the PSA cycle) at the cycle frequency. Owing to nonlinear concentration sensitivity of the isotherms and micropore diffusivities, adsorption and diffusional interactions between the fast and slow components, the adsorption and diffusion parameters may in general vary with time over the PSA cycle and with location along the flow channel in the inventive adsorbent structure. To avoid ambiguity in the definition of "F", the adsorption and diffusion parameters K_A , k_{cA} and D_{cA} in the above inequalities will correspond to the concentrations of the feed gas mixture and the upper pressure of the PSA cycle.

For given adsorption and diffusion parameters in the case of micropore diffusion control, and with the adsorbent structure design parameters of the invention grouped for visibility on the left side of the inequality, an embodiment of the invention provides that

$$\frac{\tau}{\varepsilon_p} \cdot \left(\frac{X}{r_c} \right)^2 \leq \frac{6 \cdot D_m}{15 \cdot F \cdot D_{cA} \cdot K_A}$$

With the adsorption and micropore diffusion parameters on the right side of the above expression corresponding to the choice of process conditions and the specific adsorbent within the inventive adsorbent structure, the geometrical parameters "X", " r_c ", " ε_p " and " τ " provide the basis for engineered adsorbent structures according to the invention. These geometrical parameters may desirably be similarly designed within the invention for the case of kinetic selectivity based on surface resistance control.

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In order to avoid the masking of kinetic selectivity by macropore mass transfer resistance, it is desirable that the macropore structure within the adsorbent layer be as open as possible. Hence, the macropore void fraction " ϵ_p " may desirably be relatively high, preferably in the range of about $0.5 > \epsilon_p > 0.3$ (where the lower
5 limit corresponds approximately to conventional zeolite adsorbent pellets), and the macropore tortuosity may desirably be as close to unity as possible ($\tau \rightarrow 1.0$). In some aspects of the invention, the macropore tortuosity will preferably be in the range $2.5 > \tau > 1.0$, and more preferably in the range $1.5 > \tau > 1.0$, comparing to a typical value of $\tau \sim 3$ for conventional zeolite adsorbent pellets.

10 In order to achieve a desirable high value of " F ", the adsorbent layer thickness " X " may desirably be relatively low, as enabled by the adsorbent structures of the invention which may enable attainment of a first approximate range $150 \mu\text{m} > X > 50 \mu\text{m}$ with grid, screen, mesh, cloth or fibrous supports, and of a second approximate range $50 \mu\text{m} > X > 5 \mu\text{m}$ with adsorbent coating or film-growth
15 techniques, such as are described in above mentioned references disclosing methods for making adsorbent sheet materials. The upper limit of the first approximate range is smaller than the smallest practical mean pellet radius in conventional granular adsorbent beds.

To achieve high " F ", a large radius " r_c " of the adsorbent particles or zeolite
20 crystals would be helpful. However, the objective of process intensification desirably requires high cycle frequency and gas flow velocity. For a micropore diffusion controlled kinetic PSA process, attainable cycle frequency will be inversely proportional to the square of crystal or particle radius " r_c ". Accordingly, and subject to attainment of a satisfactory value of " F ", a relatively small radius " r_c "
25 would facilitate process intensification. For an embodiment of the present invention, the adsorbent particle or crystallite size range may typically be between about $10 \mu\text{m} > r_c > 1 \mu\text{m}$, or preferably between about $4 \mu\text{m} > r_c > 1 \mu\text{m}$.

It may be noted that the dimensional ranges of the adsorbent layer in its second approximate range and the adsorbent particles or crystals overlap, so that the
30 present invention contemplates certain embodiments in which the adsorbent layer may be a monolayer coating of adsorbent particles such as zeolite crystals grown *in situ* on an inert support.

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The invention includes a kinetic-controlled adsorption process (particularly in embodiments employing PSA) comprising the inventive adsorbent structures. Such inventive kinetic-controlled adsorption process may be operated at a cyclic frequency suited to approximately relatively maximize the working adsorptive uptake of the fast component while minimizing the working adsorptive uptake of the slow component. While the invention allows wide latitude as to the adsorption cycle (particularly PSA, but may also comprise TSA, PPSA, or combinations of all three) steps employed and the partition of the cycle period between those steps, the cycle period "T" may typically be selected in the approximate range between about $10 t_{cA}$ $< T < 2 t_{cB}$.

In another embodiment of the present invention, the inventive kinetic-controlled parallel passage adsorbent structures may be used in adsorbent beds in a rotary PSA device. Suitable such rotary PSA devices may include such embodiments as disclosed in the commonly assigned US Patents numbered RE38,493, 6,051,050, 6,451,095, and 6,565,535, the contents of which are hereby incorporated by reference. Such suitable rotary PSA devices may preferably be capable to operate as rapid cycle rotary PSA, with cycle speeds preferably in excess of about 1 cycle per minute, and more preferably in excess of about 5 cycles per minute. In addition, such suitable rotary PSA devices may typically comprise at least one rotary valve to control pressure and fluid flow in the adsorbent beds comprising the inventive kinetic-controlled adsorbent structures. This combination of at least one rotary valve with the adsorbent structures of the present invention may advantageously provide for simple control of adsorption cycle speed through changes in speed of the rotary valve, such simple control facilitating fine-tuning of adsorption cycle speed to allow optimization of kinetic-controlled adsorption separation processes within the adsorbent structure.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG.1 shows the theoretical kinetic selectivity for air separation over a modified 4A zeolite in pellet form, indicating the dependences on pellet radius and crystallite diameter.

FIG. 2 is a sketch of an adsorbent laminate structure according to the invention.

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FIG. 3 shows the theoretical kinetic selectivity for air separation over a modified 4A zeolite in the adsorbent laminate of Example 2, indicating the dependences on adsorbent sheet thickness and crystallite diameter.

FIG. 4 shows the theoretical kinetic selectivity for the adsorbent laminate of
5 Example 3 indicating the dependence on adsorbent sheet thickness.

FIG. 5 shows the theoretical kinetic selectivity for the adsorbent laminate of Example 4 indicating the dependences on adsorbent sheet thickness and the adsorption isotherm slope.

10 **DETAILED DESCRIPTION OF SEVERAL EMBODIMENTS**

Example 1 (Prior Art)

Air separation for generation of nitrogen-enriched inert gas may be performed over carbon molecular sieves and over narrow pore zeolites such as a modified 4A zeolite. Such narrow pore zeolite may typically be modified to reduce
15 the equilibrium selectivity for nitrogen over oxygen, opposing the kinetic selectivity for oxygen as the fast component and nitrogen as the slow component. The modified 4A zeolite for this application may typically have more rapid micropore diffusion time constants than the previously commercialized carbon molecular sieves. It is of interest for the present invention, both for showing the limitations of
20 conventional pellet packed beds for kinetic-controlled PSA processes operating at higher frequency, and for demonstrating some advantages of the present invention relative to the prior art.

Table 1 below shows relevant adsorption and micropore diffusion parameters for modified 4A zeolite, as reported in the text "Pressure Swing Adsorption" by
25 Douglas M. Ruthven, S. Farooq and K. Knaebel, VCH Publishers, New York, 1993.

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Table 1

	D_{ci} (cm ² /sec)	K_i	r_c (microns)	t_{ci}/K_i (seconds)
oxygen	1.6×10^{-8}	2.10	1	0.0198
nitrogen	4×10^{-10}	4.26	1	0.3912
argon	3×10^{-11}	~2	1	11.11

FIG.1 shows the theoretical kinetic selectivity for air separation over a modified 4A zeolite in pellet form, indicating the dependences on pellet radius "R" and crystallite diameter $d_c = 2 r_c$. These calculations are based on the following semi-empirical linear driving force approximation for kinetic selectivity "S", with additive mass transfer resistance terms in the numerator and denominator for micropore diffusion, macropore diffusion and film resistance in the approximation of stagnant flow conditions.

$$S = \frac{\frac{r_c^2}{15 \cdot K_B \cdot D_{cB}} + R^2 \left(\frac{1}{15 \cdot \epsilon_p \cdot D_p} + \frac{1}{3 \cdot D_m} \right)}{\frac{r_c^2}{15 \cdot K_A \cdot D_{cA}} + R^2 \left(\frac{1}{15 \cdot \epsilon_p \cdot D_p} + \frac{1}{3 \cdot D_m} \right)}$$

The curves for "S" versus "R" are shown for crystal diameters of 1 μm , 2 μm and 4 μm . For granular adsorbent in the small size range of 20/40 mesh (pellet diameters between 420 and 821 μm), fairly good performance is predicted ($S/S_o \sim 0.9$) for crystal diameter 4 μm , dropping significantly ($S/S_o \sim 0.75$) for crystal diameter 2 μm , and with severe degradation ($S/S_o \sim 0.5$) for crystal diameter 1 μm . Clearly, superior performance may be achieved by using the larger zeolite crystals of about 4 μm diameter to obtain $F > 9$.

Conventional kinetic-controlled PSA systems using this granular adsorbent may employ a cycle frequency of about 10 cycles/minute. Such PSA systems are

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used in aircraft as “onboard inert gas generation systems” to generate nitrogen as a safety measure for inerting partly empty fuel tanks.

FIG. 2

5 FIG. 2 is a sketch of a multi-layer adsorbent sheet structure 10 according to an embodiment of the present invention. The structure 10 comprises adsorbent sheets 11 with adsorbent layers 13 of thickness “X” contacting flow channels 12 of height “h” between adjacent sheets 11, such flow channels defined by spacing means 15. The spacers establish the channel height accurately, while presenting minimal
10 obstruction to flow in the reversing flow direction 16. The adsorbent layers 13 consist of adsorbent particles (e.g. zeolite crystals) of diameter “ d_c ”. A support grid, mesh, cloth, fibrous, or other suitable reinforcement material may be included within or between the layers 13.

 In additional inventive embodiments, the adsorbent layers may be coated
15 onto an inert sheet, such as a foil for example, between two layers 13 each of thickness “X”, or onto wires, whose diameter may be substantially greater than “X”. In yet further embodiments of the invention, any suitable process for coating or otherwise forming an adsorbent sheet material such as are disclosed in the above mentioned references may be used to produce an adsorbent sheet structure for use in
20 the kinetic-controlled adsorbent structures according to the present invention.

Example 2

 FIG. 3 shows the semi-empirical theoretical kinetic selectivity for air separation over a modified 4A zeolite in the adsorbent laminate of Fig. 2, using the
25 adsorption and micropore diffusion parameters of Table 1, and indicating the dependences on adsorbent sheet thickness and crystallite diameter. These calculations are based on the following semi-empirical linear driving force approximation for kinetic selectivity “S”, with additive mass transfer resistance terms in the numerator and denominator for micropore diffusion, macropore
30 diffusion and film resistance.

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$$S = \frac{\frac{r_c^2}{15 \cdot K_B \cdot D_{cB}} + X^2 \cdot \left[\frac{1}{(6 \cdot \epsilon_p \cdot D_p)} + \frac{2}{8.235 D_m} \right]}{\frac{r_c^2}{15 \cdot K_A \cdot D_{cA}} + X^2 \cdot \left[\frac{1}{(6 \cdot \epsilon_p \cdot D_p)} + \frac{2}{8.235 D_m} \right]}$$

Adsorbent laminate structures according to the present invention, as shown in Fig. 2, may be readily manufactured in the first approximate thickness range of $150 \mu\text{m} > X$
 5 $> 50 \mu\text{m}$, such that $X = 100 \mu\text{m}$, $S/S_o > 0.9$ ($F > 9$) may be achieved for all crystal sizes in the range of $1 \mu\text{m}$ upward, while $S/S_o > 0.95$ ($F > 19$) may be achieved for all crystal sizes in the range of $2 \mu\text{m}$ upward. For particular embodiments of the present invention, it is preferred that the above properties of the inventive kinetic-controlled adsorbent structures be selected to maximize the value of S/S_o .

10 The unexpected advantages of the present invention in this exemplary application may now be made apparent with comparison to the conventional 20/40 mesh granular adsorbent bed of Example 1, recalling that crystal diameter below $4 \mu\text{m}$ in the 20/40 mesh adsorbent will result in significant macropore degradation of kinetic selectivity, and also recalling that cycle frequency can be intensified by a
 15 factor of substantially 4 when the zeolite crystal diameter is reduced by a factor of 4. In addition to the intensification of the cycle frequency, the gas flow velocity within the adsorbent structure of the present invention is not limited to the relatively low levels required to avoid fluidization as are conventional packed granular adsorbent beds. The combination of such increases in cycle frequency and gas flow
 20 velocity in the inventive systems and processes may provide desirable increases in productivity, and/or recovery.

The inventive adsorbent structures may use zeolite crystals of $2 \mu\text{m}$ diameter to achieve a 4-fold intensification (increasing cycle frequency from 10 to 40 cycles/minute), while also improving kinetic selectivity and thus separation
 25 performance with $S/S_o \sim 0.95$ ($F > 19$). Alternatively, the inventive adsorbent structure may use zeolite crystals of $1 \mu\text{m}$ diameter to achieve a 16-fold intensification (increasing cycle frequency toward 160 cycles/minute), while retaining approximately equal kinetic selectivity and thus separation performance with $S/S_o \sim 0.9$ ($F > 9$).

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It will be appreciated that a 4-fold or 16-fold intensification, proportionately reducing the volume and weight of the adsorbers, is extremely desirable for aviation onboard fuel tank inerting, and any other application where greater recovery and/or productivity (which may also contribute to smaller size and/or lower capital cost) is advantageous for an adsorptive separation system. The inventive adsorbent structure is also inherently more robust and tolerant of aircraft shock/vibration exposure than granular adsorbent, or physical shock or stress from any other application specific exposure.

10 Example 3

Example 3 considers a kinetic-controlled adsorptive separation with faster time constants and somewhat stronger equilibrium adsorption. The specific parameters used are

$$15 \quad t_{cA} = 0.025 \text{ seconds} \quad t_{cB} = 2.5 \text{ seconds}$$

$$K_A = 22 \quad K_B = 26$$

These adsorption and micropore kinetic parameters may apply to the industrially important application of propylene/propane separation. Useful kinetic and equilibrium data is provided for that separation over AIPO-34 and AIPO-18 adsorbents in U.S. Patent Nos. 6,730,142 and 6,733,572, both by Reyes et al. That data suggests that this olefin/paraffin PSA separation may best be conducted at elevated temperatures of 423 K or even higher, with the present model indicating the desirability of such elevated temperature to avoid excessively high values of K_A .

FIG. 4 shows the theoretical kinetic selectivity for the adsorbent laminate of Example 3 indicating the dependence on adsorbent sheet thickness for the above parameters. It is seen that adsorbent layer thicknesses in the second approximate thickness range of $50 \mu\text{m} > X > 5 \mu\text{m}$ may be necessary, as $S/S_0 \sim 0.5$ ($F \sim 1$) for $X \sim 50 \mu\text{m}$. For $S/S_0 > 0.9$ ($F > 9$), the adsorbent layer may be a thin crystal coating of $X \sim 15 \mu\text{m}$.

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Example 4

Example 4 generalizes similar cases to Example 3, exploring the sensitivity to changes of the isotherm slope. FIG. 5 shows the theoretical kinetic selectivity for the adsorbent laminate of Example 4 indicating the dependence on adsorbent sheet
5 thickness and the adsorption isotherm slope K . For simplicity, $K = K_A = K_B$, and again

$$t_{cA} = 0.025 \text{ seconds} \quad \text{and} \quad t_{cB} = 2.5 \text{ seconds.}$$

10 As seen in FIG. 5, the adsorbent layer thickness may be increased to e.g. $X \sim 50 \mu\text{m}$ for $K \sim 5$ if $S/S_o \sim 0.8$ ($F \sim 4$) is acceptable. Such low values of K_A may be achieved by operating at high temperature and high on the isotherm (approaching saturation), or indirectly by increasing ϵ_p .

Conversely, relatively high values of $K > 80$ may compel use of very thin
15 adsorbent layers down to the range of $10 \mu\text{m} > X > 5 \mu\text{m}$. Such thin layers may be provided as monolayer crystal coatings on an adsorbent sheet structure according to the present invention. In order to avoid excessive channel voidage in the adsorber, the equivalent channel height "h" may need to be in a comparable range, e.g. $20 \mu\text{m} > h > 5 \mu\text{m}$.

20 Some relief from the need for very thin adsorbent layer coatings (and corresponding narrow flow channels) on the adsorbent sheet comprising the inventive adsorbent structures may be provided by designing for surface resistance control rather than bulk micropore resistance control within the adsorbent crystals or particles. The bulk adsorbent crystal or particle may be a microporous material
25 having relatively fast micropore diffusivity, and with the micropores narrowed at the crystal or particle surface by hydrothermal treatment, silanation, or a thin overlay coating (e.g. $\sim 1 \mu\text{m}$ thick) of a micropore-selective material such as AlPO-34 for example.

30 Example 5

Example 5 represents a kinetic-controlled adsorptive separation using adsorbent structures according to the present invention. Modified zeolitic silicate

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type adsorbent materials with micropores in the size range of about 2-5 angstroms may show a molecular sieving effect, and may be suitable for use as a kinetic-controlled adsorbent material, for incorporation in the kinetic-controlled adsorbent structures of the invention. Using such modified zeolitic silicate type adsorbent materials in the inventive adsorbent structures, methane may be separated from carbon dioxide in a mixture of the two gases using a kinetic-controlled adsorptive separation process.

The macropore and film mass transfer resistances may be suitably reduced for enhancing kinetic-controlled adsorption in such materials by proper design of the inventive adsorbent structures incorporating the materials, and through adsorptive separation operation under appropriate process conditions. Under such circumstances, micropore resistance may be found to control the kinetic-controlled adsorptive separation process. Under such conditions and using inventive adsorbent structures comprising such zeolitic silicate materials and corresponding to such physical characteristics as shown in Table 2 below, the ideal kinetic-controlled adsorptive selectivity, S_0 may be as high as around 100 for the kinetic-controlled process for separation of carbon dioxide from methane, which may be very favorable for effective separation.

The diffusivity of CH_4 on such modified zeolitic silicate adsorbent materials may be relatively fast, resulting in very small values for the adsorption time constant of about ~ 0.1 seconds. The kinetic-controlled adsorption cycle may preferably be designed and operated in such a way that the longest time period of the adsorption cycle may be shorter in duration than the adsorption time constant of methane on the adsorbent material incorporated in the inventive adsorbent structure, to desirably reduce significant adsorption of methane in the adsorbent. Therefore the adsorption process cycle speed in this application may preferably be in the range of orders of magnitude faster than conventional beaded PSA systems, such that at such rapid cycle speeds CO_2 may adsorb on the adsorbent material based on its relatively rapid diffusion rate, but that adsorption of methane may be desirably minimized.

Table 2

	D_{ci} (cm ² /sec)	K_i	r_c (microns)	t_{ci}/K_i (seconds)
Carbon Dioxide	$\sim 5 \times 10^{-7}$	~ 40.0	2~5	0.001
Methane	$\sim 6 \times 10^{-9}$	~ 20.0	2~5	0.14
Nitrogen	$\sim 3 \times 10^{-7}$	~ 15.0	2~5	0.004

Example 6

Example 6 represents a further embodiment of the present invention directed toward enabling the kinetic-controlled adsorptive separation of CH₄ from N₂ using a structured adsorbent bed comprising the present inventive kinetic-controlled adsorbent structures. Silicate materials with modified micropore structures may desirably be used for this separation, in a case which is similar to that disclosed above in Example 5. The appropriate values for diffusivity, Henry's constant, and adsorbent material crystal sizes for such an application are shown above in Table 2. In such an application, an effective kinetic-controlled selectivity may be defined such that the inventive adsorbent structures may be optimized to enhance the separation of CH₄ from N₂ by the relatively more rapid adsorption of nitrogen, and relatively less rapid adsorption of methane on such suitable adsorbent materials.

As disclosed in the above examples, the inventive kinetic-controlled adsorbent structures may be applied to many different adsorptive separation processes, incorporating any suitable adsorbent materials, such as those known in the art.

The present invention has been described above in reference to several exemplary embodiments. It is understood that further modifications may be made by a person skilled in the art without departing from the spirit and scope of the invention which are to be determined by the following claims.

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We claim:

1. A multi-layer parallel passage adsorbent structure for implementing a rapid cycle kinetic-controlled adsorptive separation between at least a first more rapidly adsorbed gas component and a second less rapidly adsorbed gas component, such adsorbent structure comprising a multiplicity of adsorbent sheets comprising at least one adsorbent material wherein the at least one adsorbent material defines an ideal kinetic selectivity S_0 between the first and second components, wherein:
the multiplicity of adsorbent sheets are spaced apart by spacing means to form flow channels between adjacent adsorbent sheets, and wherein the adsorbent sheets comprise at least one adsorbent layer characterized by an adsorbent layer thickness X , wherein each adsorbent layer comprises particles of the at least one adsorbent material, characterized by an adsorbent particle radius r_c , and wherein the dimensions of the adsorbent layer thickness X and adsorbent particle radius r_c are selected to maximize the value of an effective kinetic selectivity S of the adsorbent structure for implementing the rapid-cycle kinetic-controlled adsorptive separation, relative to the ideal kinetic selectivity S_0 of the at least one adsorbent material.
2. The adsorbent structure according to claim 1 wherein the rapid cycle kinetic-controlled adsorptive separation is a rapid cycle kinetic-controlled PSA separation.
3. The adsorbent structure according to claim 2 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 , is at least 0.75.
4. The adsorbent structure according to claim 2 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 is at least 0.80.
5. The adsorbent structure according to claim 2 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 is at least 0.9.

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6. The adsorbent structure according to claim 2 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 is at least 0.95.
- 5 7. The adsorbent structure according to claim 2 wherein the at least one adsorbent material comprises a zeolitic silicate molecular sieve, the first more rapidly adsorbed gas component comprises carbon dioxide, and the second less rapidly adsorbed gas component comprises methane.
- 10 8. The adsorbent structure according to claim 2 wherein the at least one adsorbent material comprises a zeolitic silicate molecular sieve, the first more rapidly adsorbed gas component comprises nitrogen, and the second less rapidly adsorbed gas component comprises methane.
- 15 9. The adsorbent structure according to claim 7 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 , is at least 0.75.
10. The adsorbent structure according to claim 7 wherein the value of the ratio of
20 the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 is at least 0.80.
11. The adsorbent structure according to claim 7 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic
25 selectivity of the at least one adsorbent material, S / S_0 is at least 0.9.
12. The adsorbent structure according to claim 7 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 is at least 0.95.

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13. The adsorbent structure according to claim 8 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 , is at least 0.75.
- 5 14. The adsorbent structure according to claim 8 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 is at least 0.80.
- 10 15. The adsorbent structure according to claim 8 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 is at least 0.9.
- 15 16. The adsorbent structure according to claim 8 wherein the value of the ratio of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic selectivity of the at least one adsorbent material, S / S_0 is at least 0.95.
17. A rapid cycle rotary PSA device, comprising:
at least one rotary valve;
at least one multi-layer parallel passage adsorbent structure adapted for
20 implementing a rapid cycle kinetic-controlled adsorptive separation between at least a first more rapidly adsorbed gas component and a second less rapidly adsorbed gas component, such adsorbent structure comprising a multiplicity of adsorbent sheets comprising at least one adsorbent material wherein the at least one adsorbent material defines an ideal kinetic selectivity S_0 between the first and second
25 components, wherein the multiplicity of adsorbent sheets are spaced apart by spacing means to form flow channels between adjacent adsorbent sheets, and wherein the adsorbent sheets comprise at least one adsorbent layer characterized by an adsorbent layer thickness X , wherein each adsorbent layer comprises particles of the at least one adsorbent material, characterized by an adsorbent particle radius r_c ,
30 and wherein the dimensions of the adsorbent layer thickness X and adsorbent particle radius r_c are selected to maximize the value of an effective kinetic selectivity S of the adsorbent structure for implementing the rapid-cycle kinetic-controlled

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adsorptive separation, relative to the ideal kinetic selectivity S_0 of the at least one adsorbent material.

18. The adsorbent structure according to claim 17 wherein the rapid cycle
5 kinetic-controlled adsorptive separation is a rapid cycle kinetic-controlled PSA separation.

19. The adsorbent structure according to claim 18 wherein the value of the ratio
of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic
10 selectivity of the at least one adsorbent material, S / S_0 , is at least 0.75.

20. The adsorbent structure according to claim 18 wherein the value of the ratio
of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic
selectivity of the at least one adsorbent material, S / S_0 is at least 0.80.

15

21. The adsorbent structure according to claim 18 wherein the value of the ratio
of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic
selectivity of the at least one adsorbent material, S / S_0 is at least 0.9.

20 22. The adsorbent structure according to claim 18 wherein the value of the ratio
of the effective kinetic selectivity of the adsorbent structure to the ideal kinetic
selectivity of the at least one adsorbent material, S / S_0 is at least 0.95.

FIG. 1

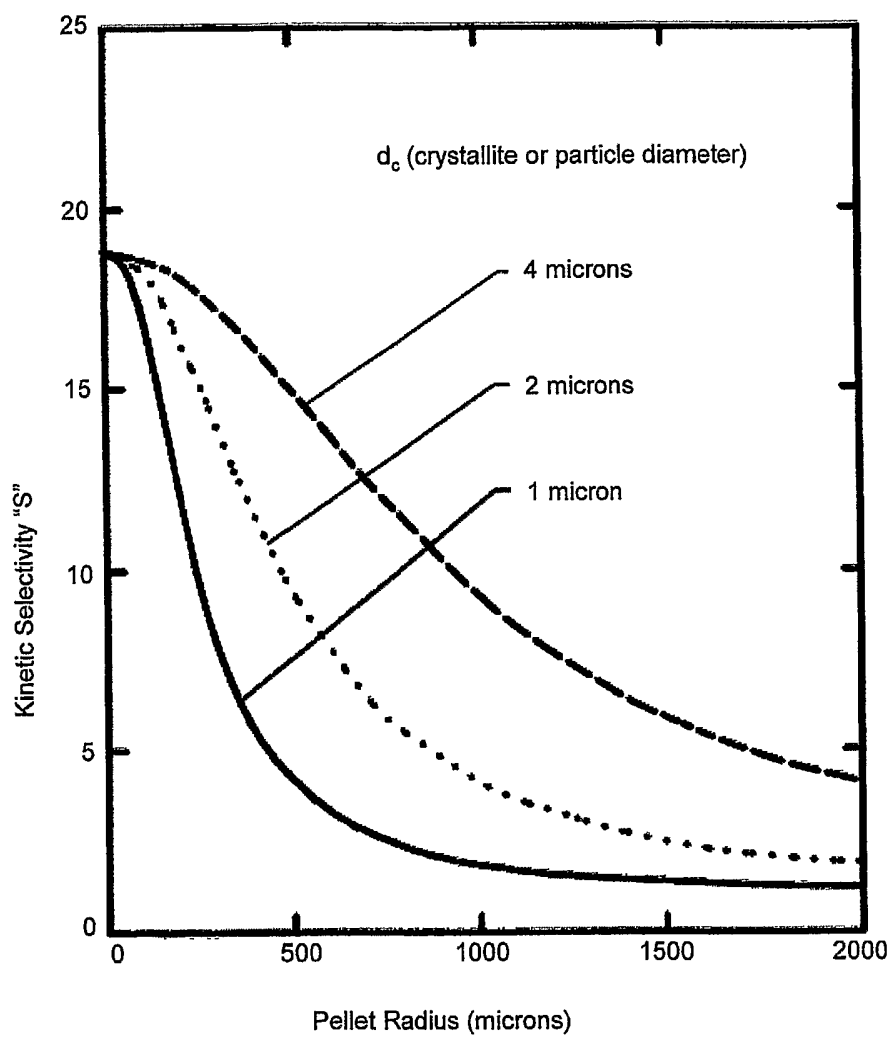


FIG. 2

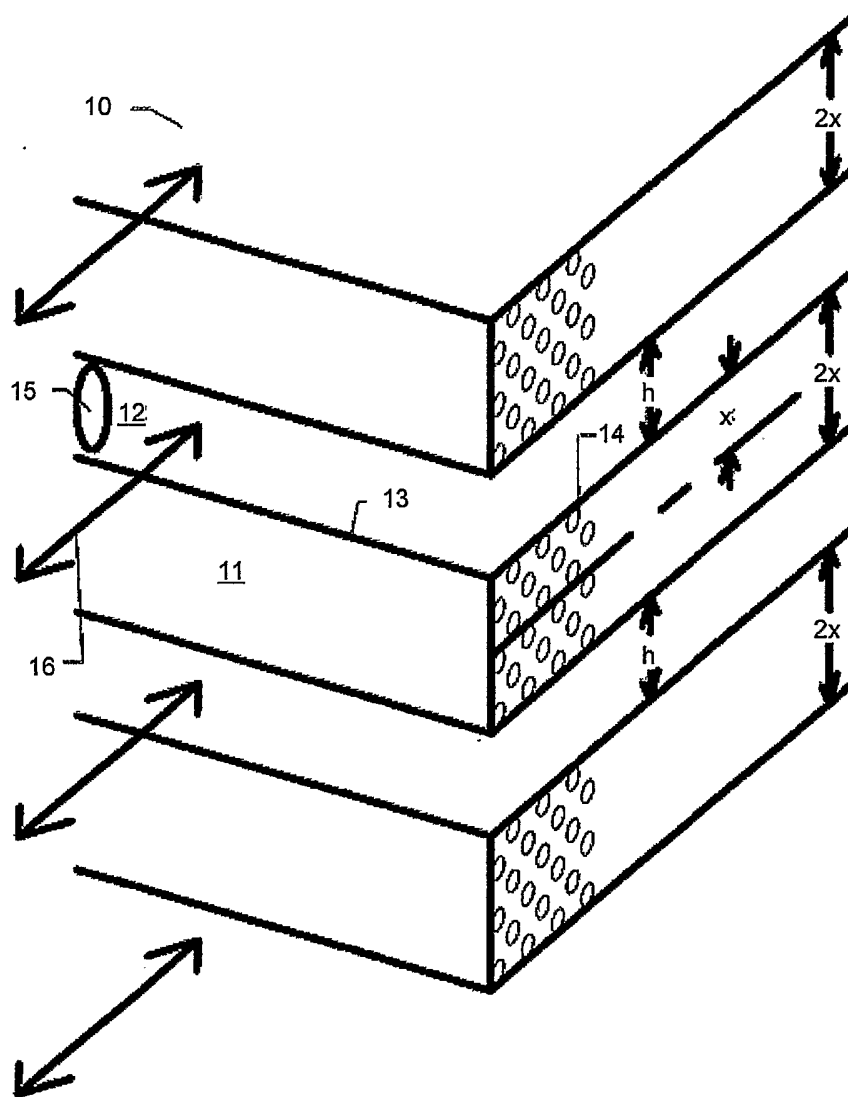
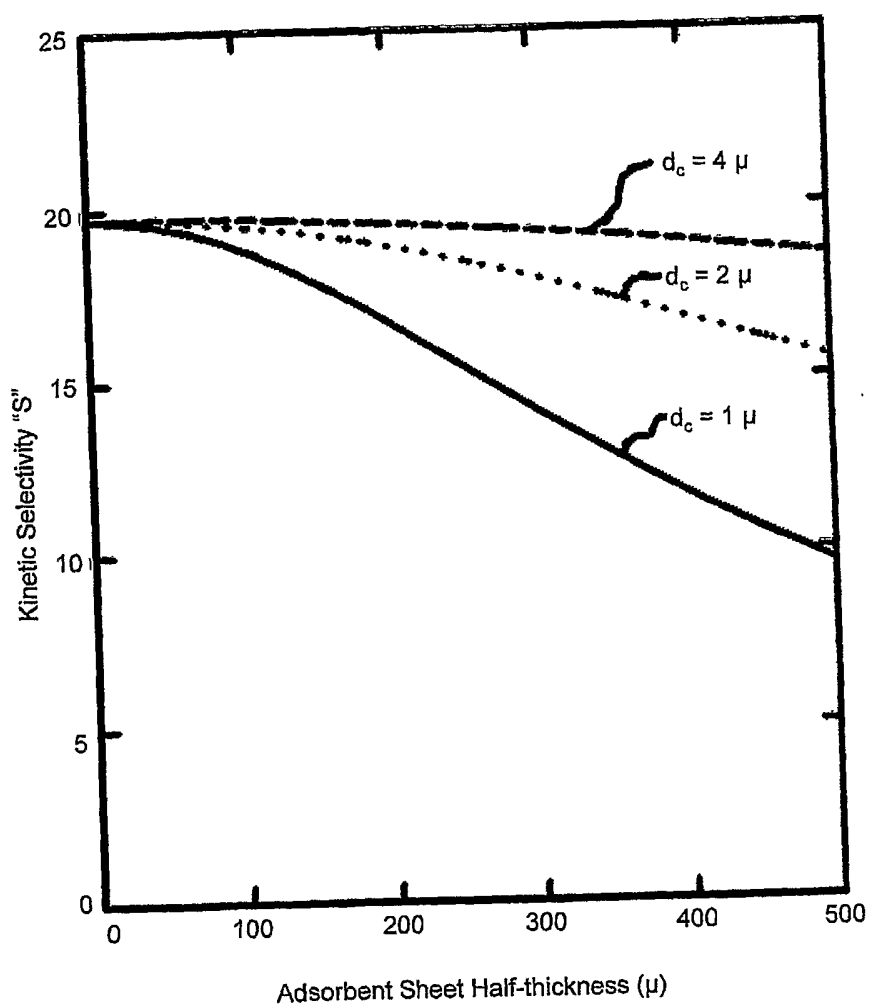


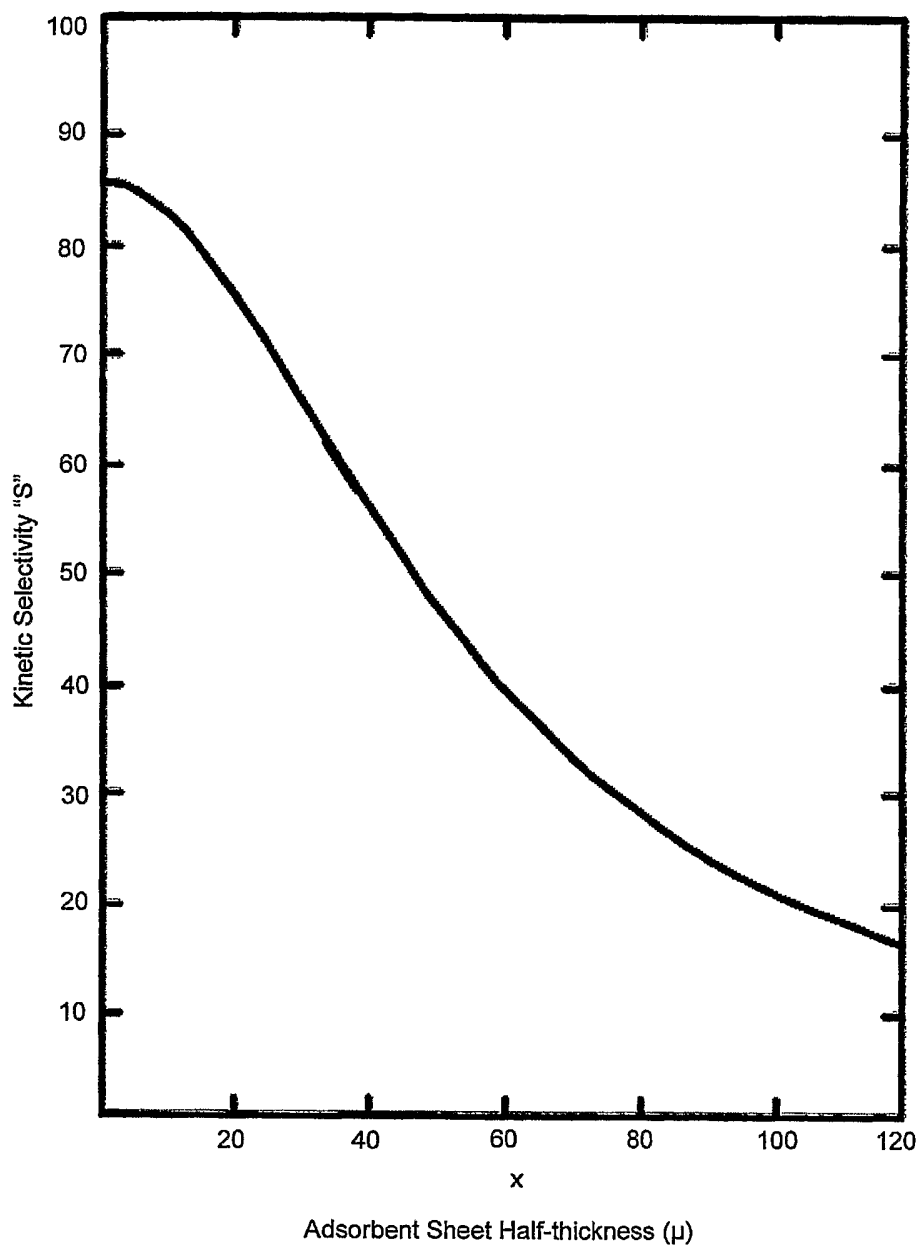
FIG. 3



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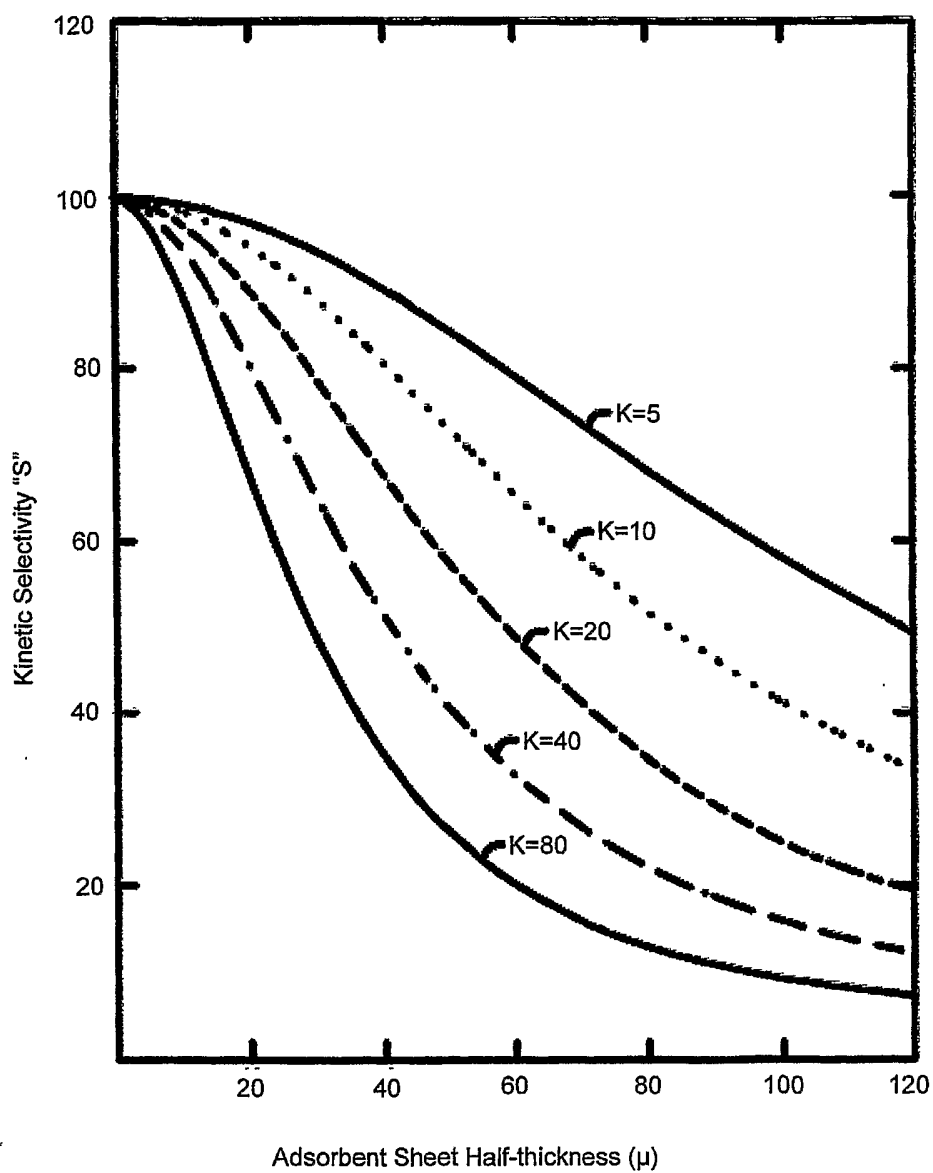
FIG. 4



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FIG. 5



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