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(54) **Title**: A METHOD OF MANUFACTURING A STRUCTURED ADSORBENT BED FOR CAPTURE OF CO2 FROM LOW PRESSURE AND LOW CONCENTRATION SOURCES

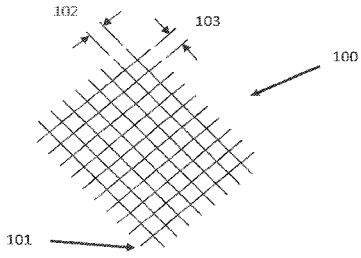

Figure 1a

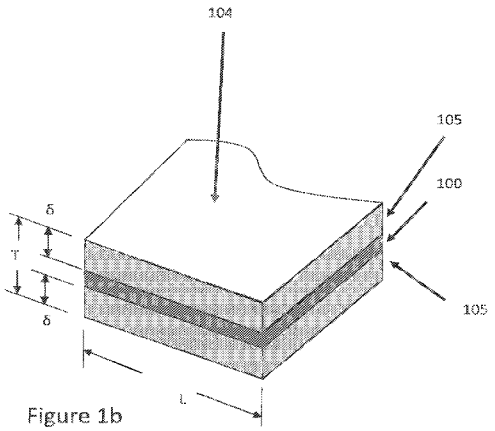

Figure 1b

(57) **Abstract**: A method of forming a structured adsorbent sheet is provided. The method includes, combining a nano-adsorbent powder and a binder material to form an adsorbent material, and sandwiching a porous electrical heating substrate between two layers of adsorbent material. The nano-adsorbent powder may be a nano-particle adsorbent. The nano-adsorbent powder may be selected from the group consisting of crystal zeolite, activated carbon, activated alumina, silica gel, and metal organic framework (MOF).

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A METHOD OF MANUFACTURING A STRUCTURED ADSORBENT BED FOR CAPTURE OF CO2 FROM LOW PRESSURE AND LOW CONCENTRATION SOURCES

Background

Interest in recovery CO2 from various CO2 containing gas mixture is propelled by multiple factors. the merchant CO2 market, enhanced oil recovery (EOR) and greenhouse gas emissions reduction. However, majority of CO2 sources are from low pressure gas mixtures having relatively low concentration of CO2. Such sources, for example, include the flue gas from a fossil fuel-fired power plant, an industrial furnace, a cement kiln, or an oxy or air combustion facility, or the exhaust gas of an engine or lime kiln. Typically, the flue gas is obtained at near ambient pressure (< 3 bara). The concentration of CO2 in the flue gas ranges from approximately 5 to 25%, with a balance of mostly nitrogen. The flue gas flow rate is numerous.

Conventionally, most commercial CO2 recovery plants use processes based on chemical absorption with a monoethanolamine (MEA) solvent. MEA was developed over 60 years ago for removing CO2 and H2S from natural gas streams. However, the process suffers large equipment costs and high regeneration energy requirements. Recently, a CO2 CPU (compression and purification unit) process was proposed to capture the CO2 from SMR (steam methane reforming) plant H2 PSA (pressure swing adsorption) off gas. The benefit of the process is that the waste gas from the CPU plant, which normally contains significant amount of H2 at high pressure, can be recycled back to the PSA for additional H2 production credit. But the CPU process requires high compressing and cold temperature operation, especially, when the CO2 concentration in the feed to CPU process is low, such as in the case of flue gas. The application of the CPU process in CO2 capture is economically adjustable only when the feedstock contains relative higher amount CO2 concentration, for example 50%.

Recovery CO2 from flue gas sources by using adsorption technologies was proposed earlier. Paul Webley's group used vacuum swing adsorption (VSA) process to recover CO2 from power plant exhaust gases by applying conventional 13X adsorbent. However, the use of a vacuum pump limits the process to be operated at a very fast cycle time and therefore the productivity remains relatively low. Energy consumption is high due to the necessity of vacuum. On the other hand, thermal swing adsorption (TSA) processes were also proposed by many groups to remove CO2 from air or flue gases. For example, there are studies in operating TSA at relative short cycle by designing adsorbers as a heat exchanger type (including heat exchange tubes inside adsorbent bed or coating adsorbent onto surface of heat exchange tubes) to increase heat transfer in and out of adsorbents. But the amount of adsorbent loading per unit volume is low leading to large and costly adsorber even at reduced cycle time. Therefore, there is an urgent need for developing a technology which can capture CO2 from low pressure sources having CO2 concentration in a range of 5 to 30% more economically.

The proposed invention is to design a rapid cycle thermal swing adsorption process to capture CO2 from low pressure and low concentration CO2 sources utilizing the novel structured adsorbent bed configuration with electric energy to regenerate the adsorbent bed. This new compact design allows operating the thermal swing adsorption process at a much faster cycle speed than the conventional pellet-loaded adsorbent bed, therefore to significantly increase CO_2 production yield. The design of new rapid cycle thermal swing adsorption (RTSA) process has advantages of the same or even higher overall adsorbent loading per volume compared with beaded materials in enough mass transfer rate, but with much lower pressure drop and in much fast heat transfer rates by reducing characteristic lengths of the transport distances at all scales of the adsorption and desorption process steps. As a result, the proposed technology ideally suits applications that involve large gas flow and are sensitive to pressure drop. Success of this technology for CO_2 capture application will open up many other opportunities, such as driers for conditioning, natural gas upgrade, etc.

Summary

A method of forming a structured adsorbent sheet is provided. The method includes, combining a nano-adsorbent powder and a binder material to form an adsorbent material, and sandwiching a porous electrical heating substrate between two layers of adsorbent material. The nano-adsorbent powder may be a nano-particle adsorbent. The nano-adsorbent powder may be selected from the group consisting of crystal zeolite, activated carbon, activated alumina, silica gel, and metal organic framework (MOF).

The size of nano-adsorbent powder may be less than 1 micron, preferably less than 0.1 microns, preferably less than 0.01 microns. The size of nano-adsorbent powder may be between 0.1 and 1 micron, preferably between 0.02 and 0.5 micron.

The porous electrical heating substrate may be a wire mesh. The wire mesh may have a wire diameter of less than or equal to 1000 microns, preferably less than or equal to 500 microns. The wire mesh may have a center to center spacing of greater than 500 microns, preferably less than 5000 microns, preferably less than 1000 microns. The porous electrical heating substrate may be nichrome, copper, aluminum, stainless steel, or carbon, alone or in combination.

The adsorbent material may have a thickness δ of between 50 and 1000 microns, preferably between 100 and 1000 microns, preferably 400 microns.

The nano-adsorbent powder may be modified by ion exchange or impregnated with promoters to enhance CO2 adsorption. The promoter may be amine.

Brief Description of the Drawings

The invention may be understood by reference to the following description taken in conjunction with the accompanying drawings, and in which:

Figures 1a and 1b illustrate schematic representations of a structured adsorbent sheet in accordance with one embodiment of the present invention.

Figured 2a and 2b illustrate schematic representations of a structured adsorbent module in accordance with one embodiment of the present invention.

Figures 3a, 3b, and 3c illustrates a schematic representation of a mass transfer zone and its position in different cases in accordance with one embodiment of the present invention.

Figure 4 represents estimated characteristic parameters for structured adsorbent.

Figure 5 illustrates a schematic representation various sheet spacers in accordance with one embodiment of the present invention.

Figure 6 illustrated a schematic representation of the various shapes of corrugations that may be used in accordance with one embodiment of the present invention.

Figure 7 illustrates a schematic representation of the relationship between an adsorbent sheet, adsorbent module, adsorbent bed, and adsorbent unit in accordance with one embodiment of the present invention.

Figure 8 illustrates a schematic representation of a structured adsorbent bed in accordance with one embodiment of the present invention

Description of Preferred Embodiments

Illustrative embodiments of the invention are described below. While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the description herein of specific embodiments is not intended to limit the invention to the particular

forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developer's specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

As used herein, and as indicated in Fig 6, the following terms are defined:

Structured Adsorbent Sheet is the basic adsorbent, binder, mesh assembly.

Structured Adsorbent Module is an assembly of individual Structured Adsorbent Sheets.

Structured Adsorbent Bed is an assembly if individual Structured Adsorbent Modules.

Structured Adsorbent Unit is an assembly of individual Structured Adsorbent Beds.

In conventional cyclic adsorption process, the cycle time is determined by the mass and heat transfer rates of targeted gases into pores of adsorbent pellets or beads. These mass and heat transfer rates are a primary limiting fact for increasing bed productivity. Due to low heat transfer in and out of granular adsorbent, conventional TSA operation normally prohibits its cycle process from operating at much short time. Besides, the maximum gas space velocity inside the bed is restricted by the pressure drop and often by the bed fluidization limit. These are

long-standing problems with the conventional adsorbent bed, and much pronounced when applied to large volume of process streams at near ambient pressure.

The ways to overcome these problems described above are to use a structured adsorbent packing. Structured adsorbents are well known in the art. For example, a thin laminated adsorbent sheet structures was fabricated by web coating slurried adsorbent mixture onto suitable support materials for PSA applications. But it is limited in the density of adsorbent material achievable in the laminate as a result of the search of high kinetics, meaning very small thickness as explained below.

In general, the characteristic heat and mass transfer time is proportional to the square of distance of mass and thermal transfer:

$$t_h \propto h^2 / D_h$$
$$t_m \propto L^2 / D_m$$

Where t_h and t_m are characteristic heat and mass transfer time. D_h and D_m are thermal and mass diffusivities, and h and L are transport distances. Therefore, reducing the thickness of adsorbent layer improves heat and mass transfer rates.

The mass and heat transfer rates increase in the structured adsorbent are not only due to the use of a thin layer of coated adsorbent but are also contributed by lowing gas flow boundary layer thickness along the channels. The mass transfer of adsorption molecules and heat flow from a gas phase to an adsorbed phase controlled by several steps, which include (1) diffusion in gas phase; (2) resistance from boundary layer; (3) macro-porous diffusion inside adsorbent; and (4) micro-porous diffusion in adsorbent. In conventional adsorption process, boundary layer resistance and macro-porous diffusion resistance are the primary mass transfer controlling steps.

Typically, the macro-porous inside adsorbent is created by the binder material which is normally used to form a different shape of adsorbent from crystal particle for an easy handling. The diffusion distance of molecules travelling inside

macro-pores before them reach the micro-pore surface is dependent on the radii of beaded adsorbent or thickness of the coated layer. Conventionally, the particle size used in the adsorption processes is between 2 to 6 mm in diameter, therefore, the travelling distance of molecules diffusion inside the pores is around 1 to 3 mm. In the structured adsorbent technology for TSA application, the coating thickness of adsorbent layer can be less than 1 mm with the use of binder material to create macro-pore diffusional passage inside the thin adsorbent layer.

Referring now to Figures 1a, 1b, 2a, and 2b, the instant invention is discussed. The binder material should be selected to exhibit a strong adhesive capability to bind crystal adsorbent particles together on the metallic wire mesh **100** and creates super macro-pore passage inside the layer. For example, with 1 mm thickness **H** of structured adsorbent sheet **104**, the molecular diffusional path reduces 50% and then its corresponding characteristic heat and mass transfer time increases 4 times in comparison with conventional beaded particle of 2 mm diameter. In addition, the gas space velocity in the structured adsorbent bed is much higher than it is in a conventional beaded bed because bed fluidization is not an issue in structured packing. Therefore, thickness of the boundary layer is much lower, which enhances transfer rates of both mass and heat through boundary layer and into the adsorbent.

The structured adsorbent sheet **104** is made by casting or coating adsorbent slurry which consists of adsorbent crystal and selected binder material **105** onto substrate material **100**. The substrate material 100 is an electric conducting metallic heating wire mesh or screen with an appropriate mesh size **102,103** of pore opening. The wire diameter **101** can be for example around 0.05 mm or higher dependent on the electric energy and heating requirement. The substrate material can also be selected from thin metallic membrane, porous metallic sheet, metallic monolith…etc.

The adsorbent casting process is similar to the process of making cement concrete blocks for building construction with the substrate material as a support structure as shown in Figures 1a, 1b, 2a, and 2b. The shape of each adsorbent

sheet **104** can be designed to fit special requirement. For example, it can be cast on a flat substrate sheet or a folded or curved shape. The flat adsorbent sheet **201, 203** and folded or curved adsorbent sheet **202** stacking together form a structured adsorbent module **200** in which straight flow channels **204** are designed and created for gas flow through the structured adsorbent module **200** at much less pressure resistance. The actual size of channel opening **204** can be designed based on process requirement.

The thickness δ of the structured adsorbent layer **105** for TSA application is preferred to be high to increase amount of adsorbent loading in comparison with PSA application. It can be approximately the same order of magnitude as the wire diameter **101** or higher, i.e. both being approximately in the range 50 to 1000 microns. The relative adsorbent volume load (adsorbent volume / adsorber volume) is dependent on the actual thickness δ of adsorbent layer **105** on each structured adsorbent sheet **104** and pore opening **102,103** on the wired mesh screen **100.** For example, with wire mesh of wire diameter **101** of 100 microns and adsorbent coating thickness δ of 400 microns, the adsorbent loading can be reached is approximately 60% with fluid flow channel **204** opening 0.5 mm. This value of adsorbent loading is equivalent to a bed loading for standard beaded adsorbent material (~60%). The effective adsorbent load of the structured adsorbent bed, taking into account of 20% inert volume of the binder material necessary to maintain together the powder or crystals and to stick them onto the substrate is therefore in the order of 48% with is the same as the actual loading of conventional beaded adsorbents achievable. The adsorbent loading may decrease slightly if it is necessary to increase the channel opening **204** in order to reduce the pressure drop across the fluid flowing channel **204** for capturing CO2 from low pressure CO2 sources. With the 400 microns thickness δ of the structured adsorbent layer **105**, the molecular diffusion distance has reduced 7.5 times compared with 3 mm diameter conventional beaded adsorbent. As a result, the characteristic heat and mass transfer time of molecules traveling inside the adsorbent layer decreases 56 times.

The above mentioned structured adsorbents were normally targeted to be used in a pressure swing adsorption operation, where enhancement of mass transfer rate for adsorbate diffusing into adsorbent pore network was a key factor. For thermal (electrical) swing adsorption process, improvement of adsorbent loading density per unit structured bed and of heat transfer rate during regeneration is a primary concern, transfer mass should remain fast enough but is not as critical as in PSA process for the CO2 capture application.

In this particular application, it is typically not necessary to remove all CO2 from the CO2 containing gas, such as maintaining the CO2 mass transfer zone inside the bed. This is for instance in the case for air purification in front of an ASU. Typically the CO2 is removed down to 0.1 ppm , thus decreasing the inlet CO2 content (from 400 to 500 ppm) by a factor more than one thousand.

In the case of CO2 capture from its low concentration and low pressure sources, a recovery of 95, 90 even 85% will be a valuable target. This means we can afford to allow a small amount of CO2 to break through; therefore, a very high CO2 adsorption kinetics may not be necessary. Figures 3a, 3b and 3c show the mass transfer zone and its position in different cases. Fig 3a shows schematically an adsorber bed **1** with a feed gas inlet **2** and outlet **3**; the mass transfer front **4a** and the saturation zone **5a**. The area of **6a** represents the adsorbent which is not saturated with adsorbate. Figure **3a** represents a case where the targeted adsorption species are completely captured within the bed. In other words, its mass transfer zone (MTZ) is in totality in the adsorber. Due to a good kinetics, the length of the MTZ is short, and therefore most of the adsorbent is fully used (loaded) where **6a** represents only a small area.

Similarly as shown in Fig 3b but with a lower value of the kinetics, the MTZ length is prolonged and the area of **6b** corresponding to the non-saturated adsorbent becomes important. The productivity in term of quantity of feed being treated is noticeably less than in the first case shown in Fig 3a. The adsorption kinetics shown in Fig 3c is the same as in Fig 3b but complete removal of the adsorbed species is not required. With a 95%+ recovery (instead of 100%), one

can see it is possible (see area **6c**) to obtain as good productivity as in the case shown in Fig 3a.

For a TSA (ESA) application of the structured adsorbent bed, it is preferred to increase adsorbent casting thickness δ **i**n order to maximize the adsorbent loading without too much compromise the mass and energy (heat) transfer rates. For example, with the same wire mesh **100** of wire diameter 100 microns and increasing the adsorbent coating thickness δ to 600 microns, the adsorbent loading increases to 69% by maintaining the same channel opening **204** at 0.5 mm. However, the molecular diffusion distance only reduces 5 times compared to conventional beaded material at particle diameter of 3.0 mm. As a result, the characteristic heat and mass transfer time of molecules traveling inside the adsorbent layer **105** decreases 25 times. This number is still enough for TSA operation. For example, with such improvement, it may reduce an 8-hours of conventional TSA half cycle time to less than 30 minutes half cycle time.

The structured adsorbent module **200** comprising a number of parallel straight flow channels **204** is made from individual adsorbent sheets **104**. The adsorbent sheets **104** consist of nano-adsorbent fine powder (crystal) applied to a metallic wire mesh sheet substrate **100**, or a macro-porous, thin, metallic membrane or metallic monolith, more generally of a power conducting and electrical heating material, selected from the materials which have better electric conductivity and carrier properties, such as Nichol, copper, aluminum, stainless steel, carbon or combination of these materials. The process of fabrication of the adsorbent sheets **104** includes casting (coating) the nano-adsorbent fine powder (or a nano zeolite crystal particle) onto the substrate wire mesh sheet **100** with the help of selected binding material. This binding material glues nano particle together and is then converted to macro-porous frameworks inside adsorbent layer **105** after thermal treatment. The macro-porous structured of the frameworks create macropore diffusion passage to increase mass and energy transport rates inside the adsorbent layer **105**. In addition, this nano-adsorbent fine powder or zeolite crystal is modified

(ion exchanged) or impregnated with certain promoters to enhance CO2 adsorption, such as amine impregnation, if CO2 adsorption is a targeted application.

The preferred thickness δ of the nano-adsorbent fine powder layers **105** on the wire sheet **100** is dependent on the application and is in the range of 0.1 to 1 mm. For a PSA application, higher molecular mass transfer rate inside the adsorbent layer is desired, therefore, a short molecular diffusion length, in other words, thinner adsorbent layer, is preferred. On the other hand, for a TSA (ESA) application, the amount of adsorbent loading per bed is a primary concern within the acceptable mass and heat (energy) transfer rate compared with conventional beaded adsorbent. Increase the adsorbent layer thickness δ; enhance the loading of the adsorbent in the bed. In the design of the structured adsorbent sheet, the wire thickness (diameter) **101** of the substrate wire mesh **100** itself is less than 1.0 mm, preferentially less than 0.5 mm. The actual wire diameter **101** is determined based on the electric heating material used as the substrate and amount of power requirement for heating the structured adsorbent module, as well as mesh size of wire grid opening. The amount of mesh size **102,103** of grid support can also be determined based on mechanical strength requirement for the structured adsorbent sheet **104**, amount of binder material used in the process, potential thermal contraction and expansion of the wire material during TSA cycle, etc.

Different shapes and forms of channels **204** can be created for fluid to flow between adsorbent sheets **201, 202**. To enhance the adsorbent loading per volume of structured module, the channels **204** are made from the same adsorbent sheet material **104**. The adsorbent sheet **104** can be made in different shapes and forms. For example, it can be made by folding the adsorbent sheet **104** in a curvature, triangular or rectangular shape. The individual straight and curved adsorbent sheets **104** stacking together form straight flow channels **204**. In addition, as indicated in Fig 5a, 5b, and 5c, the channels **204** can be made from by inserting coated discs 5a, wires 5b, foams 5c, membranes or random wires as mattress types. These inserting materials are preferably coated with nano-adsorbent fine powder to enhance adsorbent loading in the structured bed. The channel opening

204 is controlled by curved shape of the individual adsorbent sheet, which is in a range of 0.1 to 2 mm distance. The actual channel opening **204** can be designed based on the TSA process requirement; such as gas superficial space velocity, cycle time, mass and energy transfer rates, etc.

The channels **204** are created in the same direction as fluid flows through the bed. The structured adsorbent module is formed by stacking two straight adsorbent sheets adjacent to the curved adsorbent sheet or inserted adsorbent coated materials as a sandwich-type structured adsorbent. The channels **204** separated by curvature shaped adsorbent sheet allow process gas and regeneration fluid or regeneration purge fluid to pass through, where CO_2 is readily adsorbed onto the nano-adsorbent crystal layers during adsorption step and released from the adsorbent during high temperature regeneration process.

Regeneration of adsorbent is achieved by raising the bed temperature with electrical energy. By selecting a good electrical conducting substrate material, such as copper, aluminum, stainless steel, carbon, or combination of them, the metal substrate wire mesh can be quickly heat up with electricity to a desired temperature. Due to direct contact of build-in electric thermal elements with coated adsorbent, and thinner adsorbent coating layer (less than 1mm thickness) compared to conventional beaded adsorbent material on the wire mesh substrate, the heat energy of thermal flow can be rapidly transferred into the adsorbent by thermal conduction and convection with a small amount of gas purge; therefore, it releases the adsorbed CO_2 from the surface of the adsorbent and the released rich CO2 is further carried out with small regeneration purge flow. More importantly, during the heating of the adsorbent bed, the adsorbent inside the bed are heated homogenously throughout the whole volume of the bed with supplied electric energy. In other words, the adsorbent temperature at the top and bottom of the bed is raised simultaneously. The released CO2 remains in the gas phase, and then is readily moved out off the bed with a small amount purge fluid. This is different than the conventional regeneration process where the introduced hot regeneration fluid has to flow from one end to another. The temperature wave front gradually moves

through the bed due to thermal exchange caused by heat transfer. These heating and cooling steps in conventional TSA process are normally the controlling step and are energy intensive. More specifically, the amount regeneration fluid is normally limited and flow rate tends to be low to minimize energy requirement. The released CO2 from hot adsorbent zone is partial adsorbed onto cool adsorbent in the fluid flow direction because of increase of CO2 partial pressure in gas phase in cool adsorption reign. Therefore, it takes longer time to regenerate the adsorbent bed with conventional regeneration process compared to the electric heating process of the present invention. In addition, small amount of purge fluid during regeneration process enhances thermal transfer of convection effect to help homogenizing the bed temperature in the structure and avoiding hot surfaces or spots, for example, near the electrical wires. The purge fluid can also effectively remove the desorbed CO2 from the bed in present invention. In order to not dilute the CO2 desorbed, it is preferable of use a CO2 rich stream as the purge. In addition to the benefit of promoting homogenous heating of entitle adsorbent with small amount CO2 rich purge stream, it can also avoid components such as water or other impurities migrating to the downstream by purging the bed in counter-current direction (from top of the bed to bottom).

The bed cooling, or partial cooling, can be achieved by purging the bed with CO_2 lean feed effluent stream or feed gas, preferentially by nitrogen through the structured bed channel **204** after disconnection of the electric power supply sources. The adsorbent should be cooled down rapidly due to much shorter heat transfer distance in the structured adsorbent layer compared to conventional beaded material.

To compare with conventional beaded adsorbent bed, Figure 4 lists the estimated characteristic parameters of structured adsorbent.

In Figures 2a and 2b, the folded or curved structured adsorbent sheets are used to create flow channel **204**, for example in the form of triangle.

The actual shape of the structured bed can be varied depending on the applications. It can be designed as a planar shape of structured adsorption TSA bed type or circuit shape of structured adsorbent column. One possible configuration for adsorption vessels of the present invention is to insert a roll of the structured beds. The structured bed consists of modules stacked together. Each module consists of thin porous adsorbent sheets with straight and curved sheets adjacent each other as sandwich type to form channels **204** between repeating layers; this type of bed is suitable for producing large rolls that can fill cylindrical adsorption bed. This configuration brings the advantage of low construction cost.

The structure adsorbent sheet is made from nano-particle or crystal zeolite adsorbent with binder material gluing together onto a substrate support framework made from electric conducting materials. Thick adsorbent layer is used with build-in electric wire mesh substrate for TSA application to improve heat transfer property, at meantime maintaining reasonable fast mass transfer characteristic of the structured material. The flow channels **204** in the structured bed are formulated from adsorbent sheet with straight and curved adsorbent sheets sandwiched together. The adsorbent regeneration is carried out by electric energy with build-in electric filaments as wire mesh substrate to uniformly heat adsorbent quickly by thermal conduction and convection. The entire adsorbent bed is heated homogenously with potential less energy requirement with small amount of purge fluid to avoid hot surface and meantime to carry out desorbed CO2. Less regeneration gas (CO2 rich stream) is needed compared with conventional beaded adsorbent bed.

A method of forming a structured adsorbent sheet is provided. The method includes, combining a nano-adsorbent powder and a binder material to form an adsorbent material, and sandwiching a porous electrical heating substrate **100** between two layers of adsorbent material **105**. The nano-adsorbent powder may be a nano-particle adsorbent. The nano-adsorbent powder may be selected from the group consisting of crystal zeolite, activated carbon, activated alumina, silica gel, and metal organic framework (MOF).

The size of nano-adsorbent powder may be less than 1 micron, preferably less than 0.1 microns, preferably less than 0.01 microns. The size of nano-adsorbent powder may be between 0.1 and 1 micron, preferably between 0.02 and 0.5 micron.

The porous electrical heating substrate **100** may be a wire mesh. The wire mesh may have a wire diameter of less than or equal to 1000 microns, preferably less than or equal to 500 microns. The wire mesh may have a center to center spacing of greater than 500 microns, preferably less than 5000 microns, preferably less than 1000 microns. The porous electrical heating substrate **100** may be nichrome, copper, aluminum, stainless steel, or carbon, alone or in combination.

The adsorbent material may have a thickness δ of between 50 and 1000 microns, preferably between 100 and 1000 microns, preferably 400 microns.

The nano-adsorbent powder may be modified by ion exchange or impregnated with promoters to enhance CO2 adsorption. The promoter may be amine.

What is claimed is:

Claim 1. A method of forming a structured adsorbent sheet, comprising:

combining a nano-adsorbent powder and a binder material to form an adsorbent material, and

sandwiching a porous electrical heating substrate between two layers of adsorbent material.

Claim 2. The method of claim 1, wherein the nano-adsorbent powder is a nano-particle adsorbent.

Claim 3. The method of claim 2, wherein the nano-adsorbent powder is selected from the group consisting of crystal zeolite, activated carbon, activated alumina, silica gel, and metal organic framework (MOF).

Claim 4. The method of claim 1, wherein the size of nano-adsorbent powder is less than 1 micron,

Claim 5. The method of claim 4, wherein the size of nano-adsorbent powder is less than 0.1 microns,

Claim 6. The method of claim 4, wherein the size of nano-adsorbent powder is less than 0.01 microns

Claim 7. The method of claim 4, wherein the size of nano-adsorbent powder is between 0.1 and 1 micron.

Claim 8. The method of claim 7, wherein the size of nano-adsorbent powder is between 0.02 and 0.5 micron.

Claim 9. The method of claim 1, wherein the porous electrical heating substrate is a wire mesh.

Claim 10. The method of claim 9, wherein the wire mesh has a wire diameter of less than or equal to 1000 microns

Claim 11. The method of claim 9, wherein the wire mesh has a wire diameter of less than or equal to 500 microns.

Claim 12. The method of claim 9, wherein the wire mesh has a center to center spacing of greater than 500 microns.

Claim 13. The method of claim 9, wherein the wire mesh has a center to center spacing of less than 5000 microns.

Claim 14. The method of claim 13, wherein the wire mesh has a center to center spacing of less than 1000 microns.

Claim 15. The method of claim 1, wherein the porous electrical heating substrate comprises nichrome.

Claim 16. The method of claim 1, wherein the porous electrical heating substrate comprises nichrome, copper, aluminum, stainless steel, or carbon, alone or in combination.

Claim 17. The method of claim 1, wherein the adsorbent material has a thickness of between 50 and 1000 microns.

Claim 18. The method of claim 17, wherein the thickness is between 100 and 1000 microns.

Claim 19. The method of claim 17, wherein the thickness is 400 microns.

Claim 20. The method of claim 1, wherein the nano-adsorbent powder is modified by ion exchange or impregnated with promoters to enhance CO2 adsorption.

Claim 21. The method of claim 20, wherein the promoter is amine.

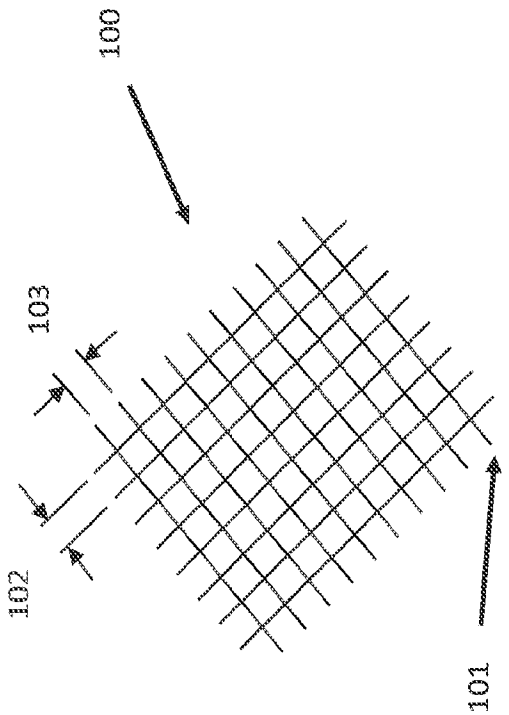

Figure 1a

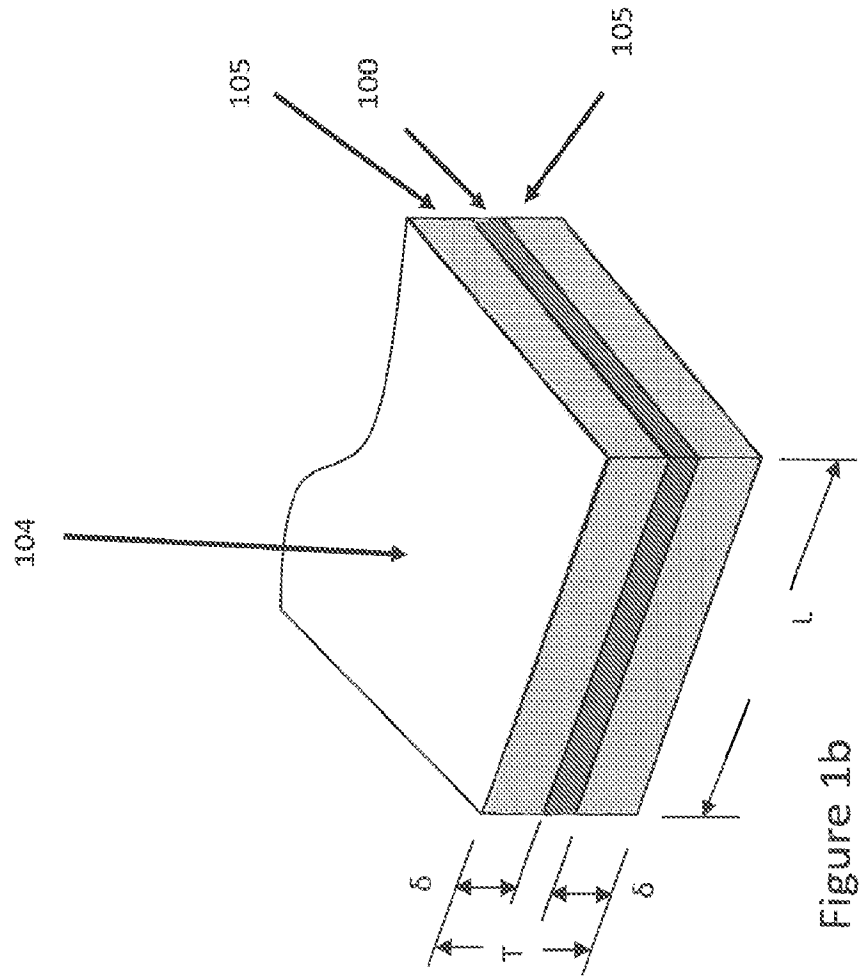

Figure 1b

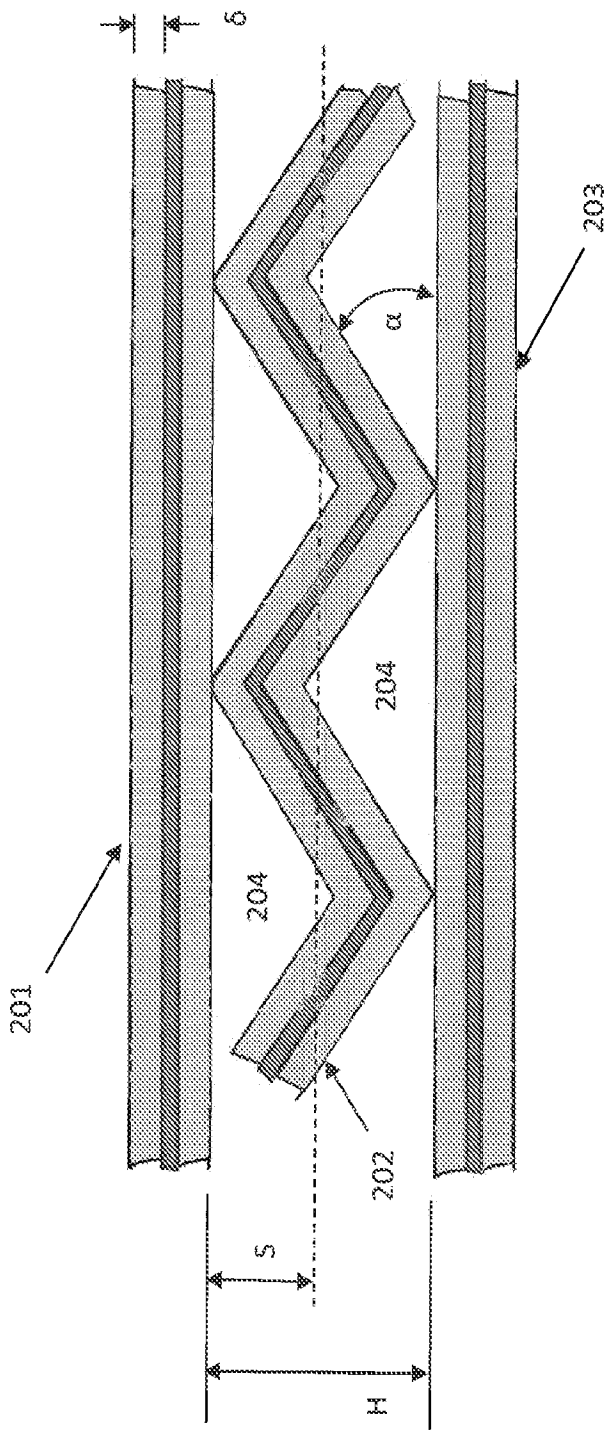

Figure 2a

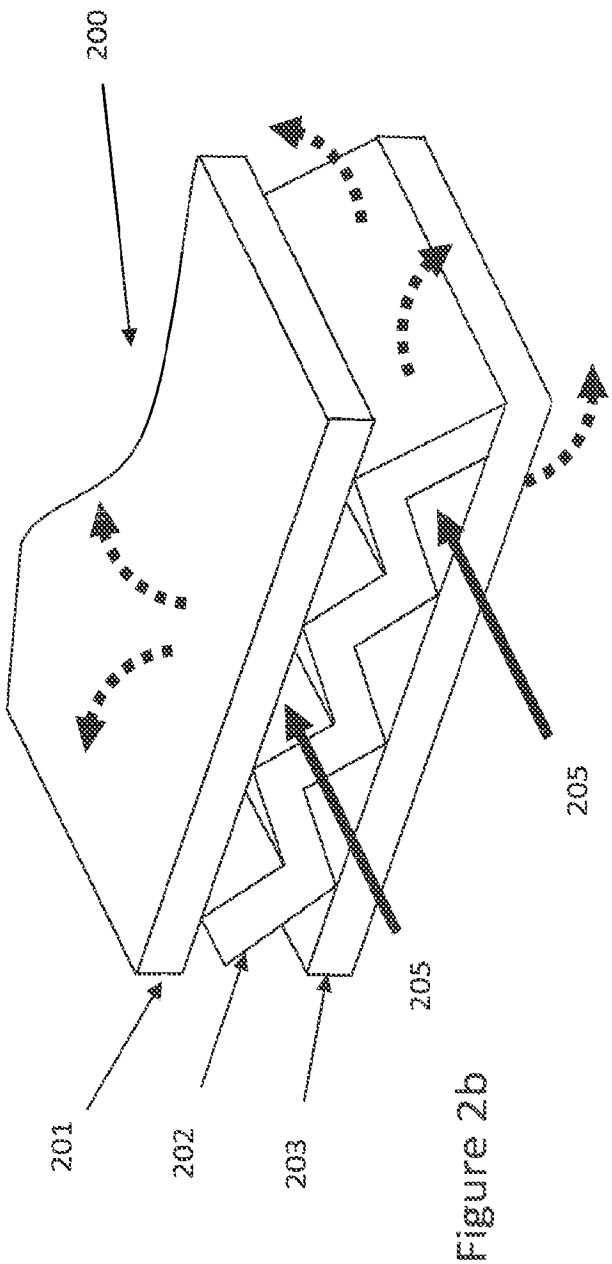

Figure 2b

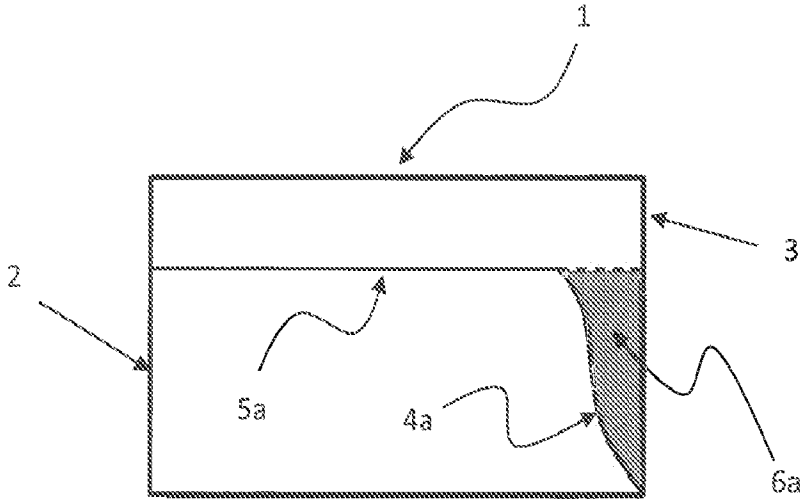

Figure 3a

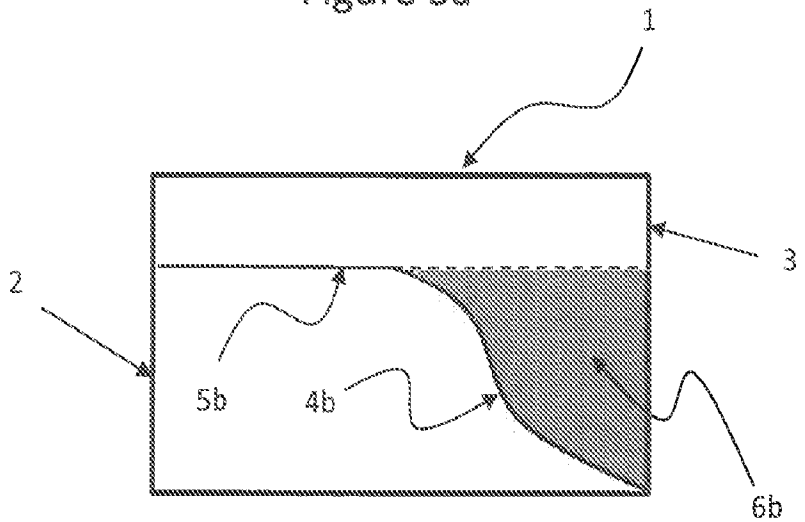

Figure 3b

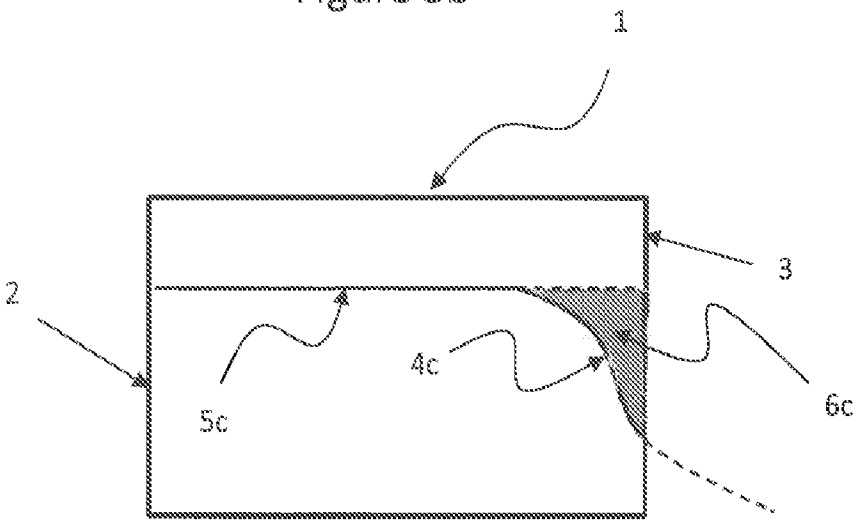

Figure 3c

Table 1, estimated characteristic parameters for structured adsorbent

	Adsorbent thickness (mm)	Channel opening (mm)	Substrate thickness (mm)	Adsorbent fraction(%)	
Case 1	0.2	0.15	0.1	57.1	
Case 2	0.2	0.5	0.1	42.9	
Case 3	0.5	0.5	0.1	65.2	
Case 4	0.75	0.8	0.1	67.2	
Conventional beaded bed	1.5 (particle radius)			~60.0	

Figure 4

Estimated Characteristic Parameters for Structured Adsorbent

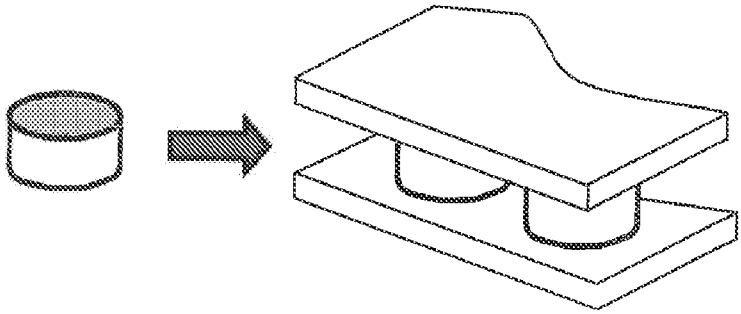

Figure 5a

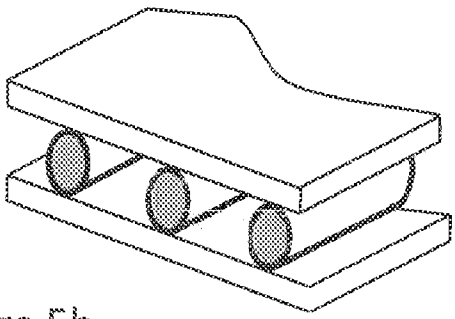

Figure 5b

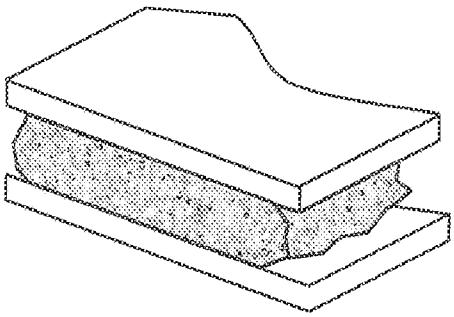

Figure 5c

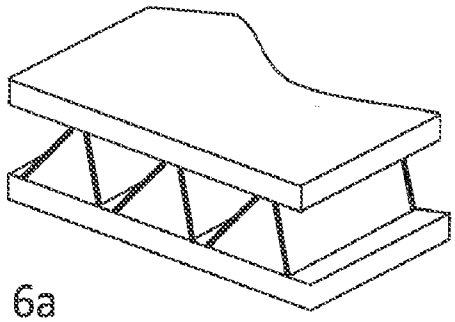

Figure 6a

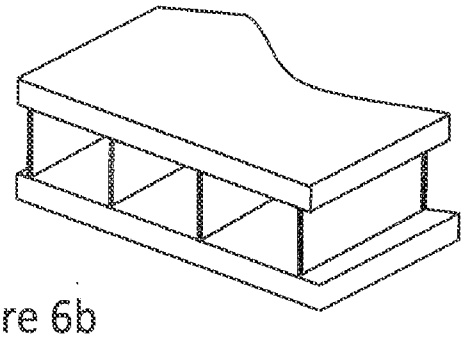

Figure 6b

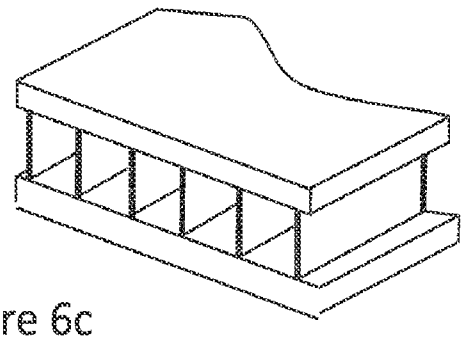

Figure 6c

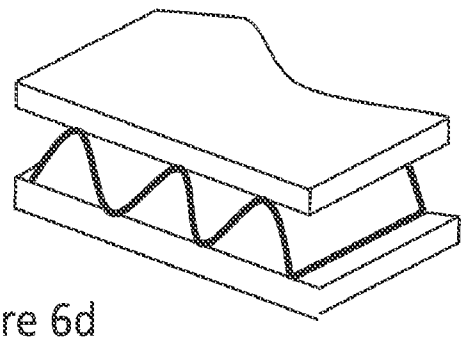

Figure 6d

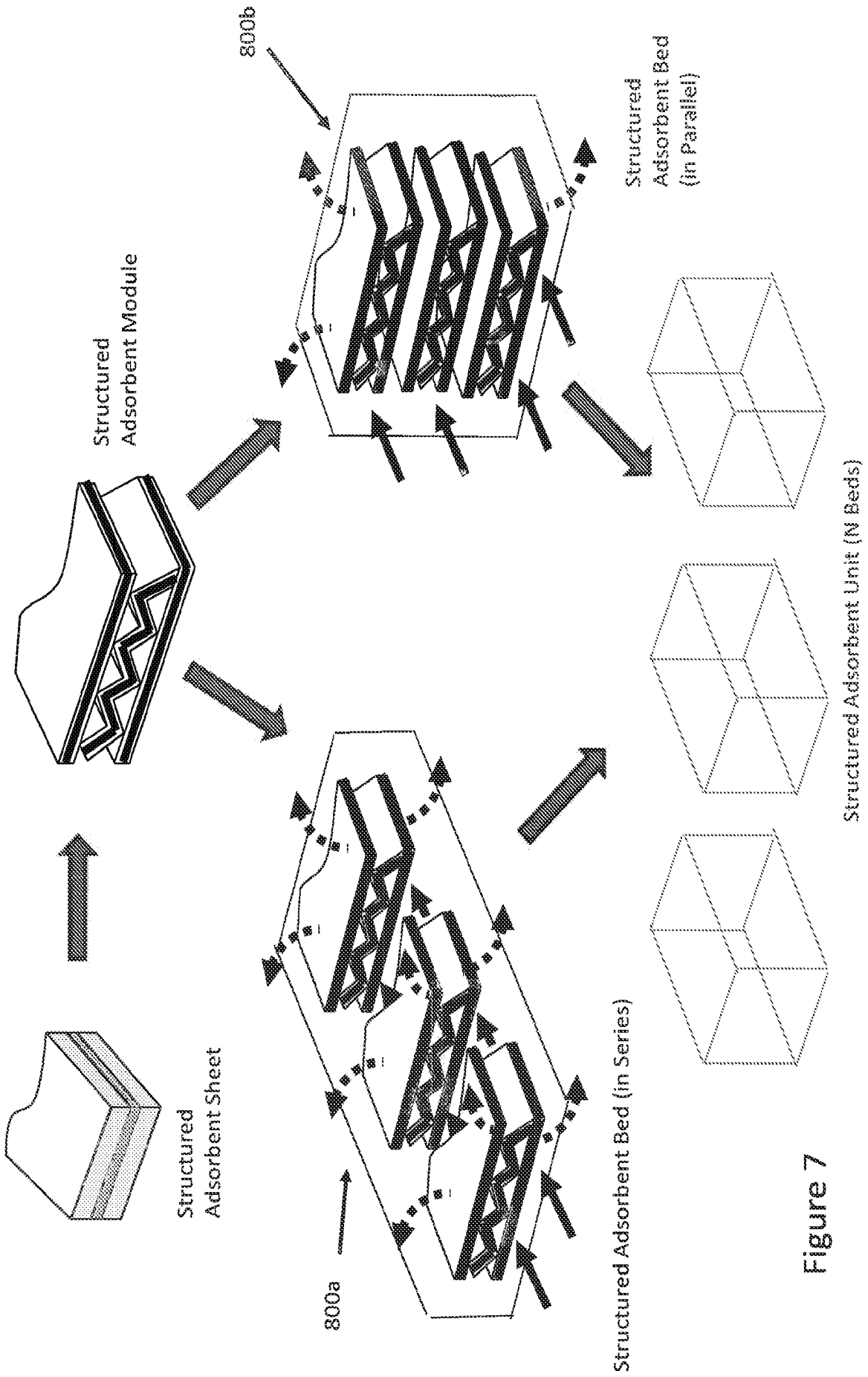
Structured Adsorbent Sheet
Structured Adsorbent Module
800a
800b
Structured Adsorbent Bed (in Series)
Structured Adsorbent Bed (in Parallel)
Structured Adsorbent Unit (N Beds)

Figure 7

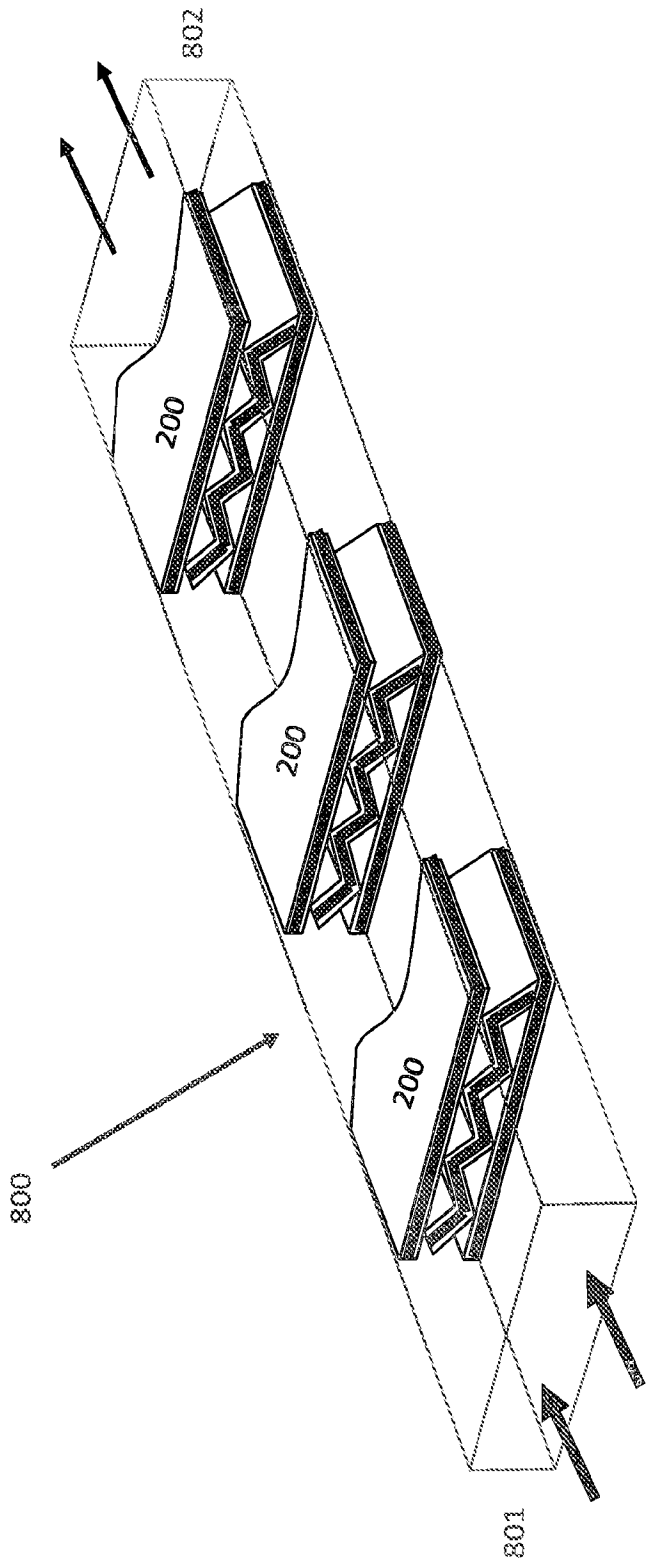

Figure 8