Adsorption Technology for CO₂ Separation and Capture: A Perspective

Paul A. Webley

Cooperative Research Centre for Greenhouse Gas Technologies (CO₂CRC),

Department of Chemical and Biomolecular Engineering,

The University of Melbourne, Parkville, VIC 3010, Australia

e-mail: paul.webley@unimelb.edu.au

Tel: +61 3 90357873

Fax: +61 3 83444153

Abstract

The capture of CO₂ from process and flue gas streams and subsequent sequestration was first proposed as a greenhouse gas mitigation option in the 1990's. This proposal spawned a series of laboratory and field tests in CO₂ capture which has now grown into a major world-wide research effort encompassing a myriad of capture technologies and ingenious flow sheets integrating power production and carbon capture. Simultaneously, the explosive growth in materials science in the last two decades has produced a wealth of new materials and knowledge providing us with new avenues to explore to fine tune CO₂ adsorption and selectivity. Laboratory and field studies over the last decade have explored the synergy of process and materials to produce numerous CO₂ capture technologies and materials based on cyclic adsorption processes. In this brief perspective, we look at some of these developments and comment on the application and limitations of adsorption process to CO₂ capture. We identify major engineering obstacles to overcome as well as potential breakthroughs necessary to achieve commercialization of adsorption processes for CO₂ capture. Our perspective is primarily restricted to post-combustion flue gas capture and CO₂ capture from natural gas.

Keywords:

CO₂ capture, adsorption processes, CO₂ adsorbents, pressure swing adsorption, temperature swing adsorption

1. Introduction

Over the last two decades, the management of CO₂ has become a major research “industry”. Carbon dioxide is one of the most ubiquitous molecules under investigation in global university and industrial R&D efforts. In particular, the idea of separating CO₂ from process gas streams on a large scale with the goal of either using or storing the purified form has evolved from desktop studies and small scale contributions in the 1990’s to major international efforts at pilot and demonstration scale today. Scrubbing CO₂ from process gases with liquid solvents such as methyl ethylamine (MEA) and related solvents has been the benchmark technology for over 60 years and is still the reference to which alternative technology should be compared (Wang et al. 2011). The urgency of climate change however, has spawned a concerted global effort to consider other, potential lower cost capture technologies. Amongst these alternative technologies are adsorption based CO₂ capture, membrane processes, cryogenic methods, hydrate processes, electrochemical techniques as well as other niche methods (Markewitz et al. 2012). These alternate technologies are being adapted and developed for CO₂ capture for such diverse applications as post combustion flue gas, pre-combustion process gas such as that found in the integrated gasification combined cycle (IGCC) process or other gasification processes, natural and biogas systems, cement and steel making applications, and the food and beverage industry.

The use of adsorption technology to separate CO₂ from gas streams is not new. Early applications in the 1950’s relied on molecular sieves, alumina and silica materials for removing trace CO₂ from air in enclosed environments such as submarines (Colburn, Dodge 1951). One of the first reports of cyclic adsorption processes for recovering CO₂ at high purity from process streams (natural gas) containing bulk quantities of CO₂ is that of Collins (1973). However, the use of adsorption processes for recovering CO₂ at high purity from flue gas streams containing bulk quantities of CO₂ has been explored only comparatively recently starting with the investigations of Takeguchi in the early 1990’s (Takeguchi et al. 1993). To date, there have been occasional pilot scale demonstration plants but no commercial examples of adsorption processes for CO₂ capture from low pressure flue gas streams (Ishibashi et al. 1996; Sjostrom et al. 2011; Rao et al. 2012; Qader et al. 2009; Liu et al. 2012b). Opinions offered in this perspective will address this rather pessimistic finding with a view to identifying key challenges to overcome before commercial exploitation can be envisaged.

Early process work on developing pressure and temperature swing systems relied on existing adsorbent materials from the zeolite, alumina, silica gel, and carbon families. The 1980s and 1990s saw rapid development of novel molecular sieves in the silica-aluminate, ALPO, SAPO and mesoporous zeolite families (Murakami et al. 1986). Within the last two decades, there has been an explosion of materials science research with the arrival of metal organic frameworks, nanostructured carbon and inorganic (oxide) materials and development of hybrid organic-inorganic materials with either tethered or occluded organic moieties within the inorganic substrates (Choi et al. 2009). In parallel with the development of these synthetic techniques has been the simultaneous advance in characterisation techniques which has facilitated understanding and engineering of new materials at ever smaller scales and with enhanced precision. Seldom does a week pass without the announcement in the literature (and popular scientific press) of new materials advocated for CO₂ capture. While the number of new adsorbent materials reported has proliferated, only a very select few will undergo bench-top testing and even fewer pilot testing in

part due to limited availability of materials (many exotic adsorbents are made at less than 1g level) but also due to practical constraints placed on materials (such as operation in humid environments) which are often not the goal of initial materials research.

Our goal in this perspective is not to review the literature in the field but rather to discuss the issues confronting researchers new to the field of adsorption based CO₂ capture. This perspective is arranged as follows. The application arena of CO₂ capture by adsorption is first classified since the requirements on the adsorbent and process vary widely from one field to the next. Then each application area is discussed with targets and engineering constraints identified. Finally, we summarize the current status and indicate future research and development needs for adsorption based CO₂ capture.

2. Application Space for Adsorption-based CO₂ Capture

The applications and process streams which require removal and recovery of CO₂ include: post combustion flue gases arising from fossil fuel oxidation; synthesis gas (CO₂, H₂, CO₂, H₂O) such as those arising from hydrogen production from natural gas, IGCC processes, off gas from direct reduction of iron; conventional and unconventional natural gas, biogas, vent streams in the food and beverage industry, and vent streams from cement manufacture. We confine our attention in this perspective to the areas of post combustion flue gas and CO₂ capture from natural gas sources since these application areas have dominated the literature over the last decade.

2.1 Post combustion flue gas capture with the goal of sequestration

Recovering CO₂ from large scale post combustion flue gas streams such as those arising from coal-fired power plants is extremely challenging, if the goal is to mitigate climate change. Given the large specific CO₂ emission of a coal fired power plant (generally about 800 kg CO₂/MWh), a 500MW coal fired power plant will emit on the order of 10,000 tonnes of CO₂ per day in a flue gas stream of 10-15% CO₂ saturated with water at atmospheric pressure. The only gas separation technologies on this scale with an industrial experience base are cryogenic technologies and even here the scale has not yet reached these limits. Unfortunately, cryogenic processes are not an attractive option for CO₂ capture from post combustion flue gas streams since compression of the flue gas containing only 15% CO₂ to pressures required for CO₂ liquefaction is not practical, not to mention the need to pre-dry the flue gas stream.

The current preferred option for CO₂ capture from coal-fired post combustion flue gas is scrubbing with chemical liquid solvents (Rubin et al. 2012). In this process, a solvent (often MEA) in aqueous solution is reacted with CO₂. The liquid is conveyed to a separate column for regeneration. The process has the advantage of integration with the power plant in which steam from the low pressure turbine is used for regeneration of the solvent and recovery of the CO₂. High purity CO₂ (> 99% purity) is produced at high CO₂ recoveries (>90%). The technology is mature although the recent focus on carbon capture has led to rapid and recent improvements in this technology. The energy of regeneration has been reported from 2-4MJ/kg CO₂ (strongly dependent on solvent type

and process conditions) with a corresponding power plant energy penalty of 25-35% or 7-10 percentage points, depending on the base load efficiency of the power plant in the absence of carbon capture (Bhown, Freeman 2011). The largest units in progress at the time of writing are at a 110MW scale (SaskPower 2013) and significant additional work is needed to scale the technology to 500MW and beyond. Nevertheless, this technology represents the benchmark to which adsorption processes must be compared.

A large portion (20-40%) of the regeneration energy used in the liquid scrubbing process is used to heat and evaporate water in the stripper (Oexmann et al. 2012). In principle, an adsorption process can avoid the evaporation component thereby offering potentially lower energy requirement. However, if adsorption based systems are to be competitive, they must at least match if not improve upon both the overall energy and capital costs of liquid scrubbing systems.

Adsorption based CO₂ capture from post combustion flue gas can be classified based on the mode chosen to regenerate the adsorbent: either an increase in temperature (temperature swing adsorption) or a reduction in pressure (pressure or vacuum swing adsorption). Both cases place differing demands and constraints on the adsorbent and the process and are discussed separately below.

In addition to capture from coal fired power plants, the application of adsorbents to capture CO₂ from natural gas fired combined cycle plants have also been studied. (Grande et al. 2009; Zhao et al. 2013b). In this case the concentration of CO₂ in the flue gas is 3-6% although the volume flows may be considerably smaller than in the case of coal-fired power plants.

2.1.1 Temperature Swing Adsorption Processes (TSA)

TSA adsorption processes for CO₂ capture have been investigated by numerous groups using dry regenerable sorbents in a circulating fluidised bed arrangement (Zhao et al. 2013b), amine loaded sorbents (Sjostrom et al. 2011), zeolites in fixed beds with indirect heating (Tlili et al. 2009) and even electrical heating systems (Grande, Rodrigues 2007a). Adsorbents for temperature swing processes applied to post combustion flue gas must respond strongly to changes in temperature ideally in the range 30 -150°C. This is the range of temperature at which heat is available at the power plant (eg. low pressure turbine, flue gas waste heat, CO₂ compression after cooler heat, etc) and can be used to contact the adsorbent either directly or indirectly. As a result, chemisorbents with heats of adsorption in the range 40 to 70 kJ/mol CO₂ are suitable. These are characteristic of amine and imide hybrid materials which have been extensively studied over the last 10 years (Zhao et al. 2013a). Although physisorbents may also function in this range (see application of 13X zeolite to high temperature capture (Xiao et al. 2012)), their CO₂ working capacity is diminished and fast cycling is required to offset the lower working capacity. In addition to the need for acceptable CO₂ working capacity, chemisorbents for TSA application must also be tolerant to water and impurities such as SO_x, NO_x and even occasionally HCl which may be present in the flue gas and should preferably not adsorb nitrogen. This last requirement is frequently met with most chemisorbents. If water is strongly adsorbed (and in the case of dry regenerable adsorbents is needed), the touted advantages of adsorbents over liquid absorbents disappear since energy must be expended in desorbing water. We encourage workers who are developing new chemisorbents to study the simultaneous adsorption and desorption of water in their work.

The largest drawback of the thermal swing adsorption cycles are the large cycle times needed if the gas-solid contacting devices are restricted to fixed beds. Heating and cooling times (by hot or cold gases) in conventional packed beds of pellets are of the order of hours – this effectively restricts these TSA systems to small scale applications. Alternative adsorbent structures and processes are essential if TSA is to find an application in large scale CO₂ capture. Circulating fluidised beds or moving beds are logical solutions to this problem essentially mimicking the liquid absorption systems. Unfortunately, circulating fluidised beds frequently rely on the flue gas stream to simultaneously elevate the dry adsorbent leading to a co-current contacting profile and therefore lower capacity than counter current systems. While mechanically difficult to operate, these processes do have precedence at large scale eg. fluidised bed catalytic crackers, but it is difficult to see how the capital cost of a circulating fluidised bed system can be competitive with conventional liquid scrubbing in packed towers. Attrition of the adsorbents is a significant issue as well as poisoning of the adsorbents by impurities such as SO_x and NO_x. An alternative to moving or circulating beds are rapid thermal swing processes in fixed contactors such as those under development in the Koros Group (Lively et al. 2009). This is an extremely promising approach and is arguably the leading contender for “intensifying” TSA processes. Instead of cycle times of hours, cycle times of minutes are necessary if we are to see large scale deployment of TSA systems in CO₂ capture from power plants.

2.1.2 Pressure Swing Adsorption Processes

Pressure swing processes have the advantage over TSA in that rapid cycling (minutes or even seconds) is possible in fixed beds leading to much smaller bed sizes. Compression of post combustion flue gas beyond approximately 1.5 bar is not cost effective though, given the large content of nitrogen and the low flue gas pressure. For this reason, vacuum swing adsorption (VSA) is the preferred mode of operation for post combustion flue gas. A large number of studies by many groups have examined the performance of a range of adsorbents and process cycles employing VSA as the regeneration mode (Xu et al. 2013; Wang et al. 2013; Haghpanah et al. 2013; Ebner, Ritter 2009). Adsorbents for VSA based on physisorption are more appropriate – the most common adsorbents employed are 13X zeolite ($\Delta H \sim 45 \text{ kJ/mole}$) and activated carbon ($\Delta H \sim 15\text{--}30 \text{ kJ/mole}$). Our earlier analysis (Maring, Webley 2013) has showed that an ideal heat of adsorption in the range 35 to 45 kJ/mol provides an appropriate compromise between higher CO₂ working capacity and lower regeneration energy. Adsorbent selectivity (CO₂ over N₂) and thermal effects have a more significant effect on the specific power consumption than does CO₂ adsorption capacity. Although many groups have reported promising CO₂ capacity on very high surface area metal organic frameworks, continual increase in surface area is not necessarily beneficial to overall performance, becoming more detrimental as the heat of adsorption of N₂ increases (Maring, Webley 2013). Adsorbent development for VSA applications should therefore focus on reducing the nitrogen adsorption amount and reducing the temperature swing accompanying adsorption of CO₂.

Impurities and water present in flue gas pose a significant challenge to vacuum swing adsorption processes for CO₂ capture since physisorbents are generally used. Most adsorbents which are selective for CO₂ will adsorb water and other acid gases in preference to CO₂ reducing the CO₂ capacity. We have shown that this problem can be ameliorated by layering the bed (Li et al. 2011) with little impact on CO₂ purity and recovery provide appropriate process cycles and process

conditions are imposed. However, the desorption of water in the cycle presents an added energy penalty and is less desirable than adsorbents which excludes water entirely. Upstream dehydration of the flue gas is not a practical option at the scale of power plant post combustion flue gas.

Research groups including our own have reported that CO₂ purities in excess of 90% are achievable with recoveries ranging from 70 to 90%. In all cases, however, deep vacuum levels (2-10 kPa) are needed to achieve these recoveries and purities and it is important to discuss this issue since it provides guidance for workers who are interested in developing improved adsorbents. Single stage vacuum blowers used in VSA industry are capable of providing vacuum levels down to approximately 25 kPa (absolute). Deeper vacuum (< 5kPa) requires multistage units adding to cost and power requirements. In addition, any pressure drop between the bed and the vacuum pump is detrimental to performance and minimizing the pressure drop results in very large suction and valve line sizes. This is a significant limitation and raising this vacuum level to 20-30kPa should be a focus of future R&D efforts. Both the shape of the adsorption isotherm as well as the process cycle can influence this required pressure level. Furthermore, operating valves and beds against low vacuum levels (3-10kPa) is costly especially if rapid cycling is envisaged.

The power required to desorb CO₂ from the physisorbents under vacuum has been reported by many workers and ranges from 0.6 to 6 MJ/kg CO₂ (Liu et al. 2012b). The lower end of this range is significantly lower than that for liquid scrubbing (which ranges from 2-4 MJ/kg), but it is important to note that the VSA process uses electrical energy. Using a 30% Carnot factor, a VSA energy use of 1 MJ/kg equates to a thermal load of 3.3 MJ/kg which is comparable to but not significantly better than existing liquid solvent systems. Researchers should carefully analyse their proposed adsorbents for the total energy usage by process simulation or at least simple indicative models.

Finally, it is worth noting the limitations of the VSA process with regard to scalability. The largest vacuum trains commercially available are capable of providing approximately 100,000 m³/h at 50 kPa vacuum. This equates to capturing CO₂ from a 50MW power plant assuming a vacuum level of 50 kPa can produce CO₂ at a purity of 95%. A 500MW power plant will require 10 parallel trains of these vacuum blowers. Of course, bespoke high volume vacuum machinery can be developed but the limitation will be to ensure that high purity CO₂ gas is produced at shallow vacuum levels (eg 50kPa).

In summary, research in vacuum swing adsorption systems should focus on

- Adsorbents with high CO₂/N₂ selectivity, tolerance to water (with negligible adsorption of water), and tolerance to acid gases
- Processes and adsorbents which allow the vacuum pressure to be raised to 20-30kPa while still producing gas purity of 95%

2.2 CO₂ Capture from Natural Gas Streams

Natural gas streams derive from a large variety of sources including conventional, unconventional, and biogas. Conventional sources are typically available at high pressures (50-100 bar) and may contain variable amounts of CO₂ ranging from a few percent to greater than 10%. Removal of trace CO₂ and sour gases such as H₂S from these sources is well established technology in the natural gas

industry employing liquid scrubbing technology for sweetening the gas followed by molecular sieve dehydration in preparation for the liquefaction train. Wells containing high levels of CO_2 (> 10%) are now of increasing interest and presents an opportunity for adsorptive processes. On the other hand, unconventional sources of natural gas such as coal seam gas or shale gas may be available at much lower pressures and can have highly variable levels of CO_2 . These natural gas streams are usually saturated with water and may contain significant levels of H_2S as well as higher hydrocarbons. This presents additional challenges to the researcher.

2.2.1 Conventional Natural Gas

Capture of “bulk” CO_2 (> 10%) from conventional natural gas streams by adsorption processes presents unusual and severe challenges to the adsorbent developer but also opportunities. The primary goal in this application is to produce purified natural gas so loss of the methane (and higher hydrocarbons) is to be avoided at all costs. Since the total stream pressure can be 70-100bar, pressure swing processes are attractive provided the CO_2 can be recovered without needing to extend the pressure range down to vacuum levels. Adsorbents which show good adsorption capacity up to high pressures (such as high surface area metal organic frameworks) may have a role to play in this regard. Unfortunately, unless the $\text{CO}_2:\text{CH}_4$ selectivity is very large, co-adsorption of CH_4 during the adsorption step and subsequent loss during the CO_2 recovery step will lead to unacceptable economics.

A desirable adsorbent should therefore completely exclude methane from the internal structure of the adsorbent while permitting rapid access of CO_2 and high CO_2 capacity. This rules out large pore adsorbents such as 13X zeolite. Small pore materials are more suitable. Zeolites 3A and 4A, DDR, and SAPO-34 as well as “trapdoor” chabazite zeolites we have recently developed (Shang et al. 2012) show virtually exclusive access of the adsorbent to CO_2 regardless of operating pressure. However, such a delicate sieving mechanism results in kinetic limitations for the CO_2 which should be the target of future research in these materials. These adsorbents are also sensitive to the presence of moisture in the flue gas stream and must be protected. Impurities in the gas such as H_2S present primary challenges to application of adsorption to CO_2 capture from natural gas. In addition, higher hydrocarbons are valuable constituents of the natural gas and should not be taken up by the adsorbent. This combination of unusual constraints placed on the adsorbent indicate that considerable development is required both of adsorbents and process cycles before we will see emergence of adsorption process in the natural gas industry beyond current dehydration service. However, the advent of molecular pore engineering synthesis and characterisation techniques for both metal organic frameworks as well as zeolite structures is likely to be a very useful tool for developing the required adsorbents.

2.2.2 Biogas and Landfill Gas

Biogas and landfill gas present very promising opportunities for adsorption based CO_2 capture because of the low pressures of these streams, the relatively high CO_2 content, and the low flow rates. In general, the naturally occurring sources of these gases (landfills, bio-digesters, etc) result in a biogas stream at atmospheric pressure with up to 60% CO_2 and a variety of commercial units have been demonstrated for the enrichment of these streams using adsorption processes (Grande, Rodrigues 2007b). In most cases, vacuum swing adsorption is employed but frequently upstream removal of H_2S and dehydration is needed (using a front-end TSA unit) to ensure robust

operation of the VSA system. The high selectivity of CO₂ over CH₄ for most adsorbents means that large pore adsorbents are suitable and very high purities of both CO₂ and CH₄ are attainable if appropriate process cycles are implemented (Spoorthi et al. 2010). Challenges for the researcher include the handling of high levels of H₂S and water, and the need for low energy requirements.

2.3 Emerging Application Areas for Adsorption based CO₂ Capture

The application areas discussed above in the context of CO₂ capture are the ones which have attracted the most attention in adsorbent development studies. However, there are other opportunities which in some respects are more suited to adsorption processes. Amongst these are recovery and reuse of CO₂ from the vent streams of beverage bottling plants, removal of CO₂ from H₂PSA tail gas in reformers or direct iron reduction gas streams (Voss 2005; Haraoka et al. 2013), recovery of CO₂ from cement manufacturing (Bosoaga et al. 2009), capture of CO₂ from IGCC process gas streams (Casas et al. 2013; Beaver, Sircar 2010) and high temperature capture of CO₂ from combustion processes using calcium oxide materials (Liu et al. 2012a). All of these applications benefit from higher concentrations of CO₂ and, in many cases, the goal is to remove CO₂ from the more valuable product (eg H₂ in the syngas process) rather than recover the CO₂ at high purity. The demands placed on the adsorbents for the high temperature applications are similar to those discussed earlier (tolerance to impurities, water etc) but in addition, the high temperature service can lead to sintering of many oxide adsorbents and resulting decline in performance. In many cases (eg calcium looping), morphological changes to the adsorbent leads to volume change and dusting or attrition of the adsorbents. Combining adsorptive removal of CO₂ with chemical reactions represents yet another example in which the advantages of adsorption processes are exploited in driving chemical reaction equilibrium to a desirable conversion. In this context sorption enhanced water gas shift reactors are a promising example (van Selow et al. 2009; Wright et al. 2009). These research fields are still nascent and present exciting opportunities for new researchers entering the CO₂ capture field

As an example of a niche opportunity for exploiting the advantages of adsorption processes for CO₂ capture, we have recently demonstrated a VSA system for enriching CO₂ from the vent line of a bottling line in a beverage plant. Liquid scrubbing systems using chemical solvents are not suitable for this application given the end use of the CO₂ product (consumable beverages). In this application, a gas vent stream containing ~70% CO₂ is sent to a 3 bed VSA system using 13X zeolite operating between 100 and 20 kPa to recover more than 80% of the gas producing a CO₂ stream of > 96% purity suitable for recycle to the CO₂ feed to the beverage plant. The relatively low water level in the feed stream (saturated with water at 15°C) was readily accommodated by the 13X zeolite system.

3.0 Conclusions and Suggestion for Future development

To date there are no operating large scale commercial CO₂ capture processes based on adsorption technology. In this perspective we have put forward the rationale for this position. For post combustion flue gas capture using vacuum swing adsorption, the scale of adsorption processes is limited to about a 50MW flue gas stream using today's largest vacuum pump machinery unless parallel trains are used or custom built machinery is used for larger scale operation. Developing

adsorbents and cycles which permit higher vacuum levels to be used while retaining the high purity will extend the size of these systems. Temperature swing processes for post combustion flue gas are limited due to large bed sizes for fixed bed operation – practical operation will require dramatic reduction in cycle time such as rapid swing TSA processes or moving/circulating systems. Combinations of these two options (VSA and TSA) are also promising since they may combine the merits of rapid vacuum swing processes without the need for deep vacuum. Adsorbent development for both vacuum and temperature swing processes must address the issue of water adsorption as well as handle impurities such as NO_x , SO_x . Attention should be focused on reducing nitrogen adsorption and, in the case of physisorbents, mitigating the temperature swing accompanying the pressure swing.

In the application of adsorption to capture of CO_2 from natural gas streams, there is great scope for sophisticated adsorbent development which must meet the goals of exclusive CO_2 capture at high pressure with minimal losses of methane and higher hydrocarbons. In the context of CO_2 capture from biogas, the major drawbacks are the sensitivity of the materials to H_2S and water. Development of H_2S tolerant materials will provide a major boost to the extension of adsorption technology into the natural and biogas areas.

Finally, there are additional opportunities for CO_2 capture at a scale and set of process conditions very suitable for adsorption processes. These include streams emanating from cement, iron and steel, pre-combustion, and food and beverage applications, to mention a few. These applications all differ in their demands on the adsorbent and process but the immaturity of adsorption processes suggest that rapid inroads can be made using adsorption processes.

4.0 Acknowledgments

We acknowledge funding for this work provided by the Australian Government through the Cooperative Research Centre for Greenhouse Gas Technologies program.

4.0 References

- Beaver, M.G., Sircar, S.: Adsorption technology for direct recovery of compressed, pure CO_2 from a flue gas without pre-compression or pre-drying. *Adsorption* **16**, 103-111 (2010). doi:10.1007/s10450-010-9219-0
- Bhown, A.S.A.S., Freeman, B.C.B.C.: Analysis and status of post-combustion carbon dioxide capture technologies. *Environmental science & technology* **45**, 8624-8632 (2011). doi:10.1021/es104291d
- Bosoaga, A., Masek, O., Oakey, J.E.: CO_2 Capture Technologies for Cement Industry. *Energy Procedia* **1**, 133-140 (2009). doi:10.1016/j.egypro.2009.01.020
- Casas, N., Schell, J., Joss, L., Mazzotti, M.: A parametric study of a PSA process for pre-combustion CO_2 capture. *Separation and Purification Technology* **104**, 183-192 (2013). doi:10.1016/j.seppur.2012.11.018
- Choi, S., Drese, J.H., Jones, C.W.: Adsorbent materials for carbon dioxide capture from large anthropogenic point sources. *ChemSusChem* **2**, 796-854 (2009). doi:10.1002/cssc.200900036
- Colburn, A.P., Dodge, B.F.: Adsorption process for removal of carbon dioxide from the atmosphere of a submarine. USA Patent 2545194,

Collins, J.J.: Bulk Separation of Carbon Dioxide from Natural Gas. USA Patent 3751878,

Ebner, A.D., Ritter, J.a.: State-of-the-art Adsorption and Membrane Separation Processes for Carbon Dioxide Production from Carbon Dioxide Emitting Industries. *Separation Science and Technology* **44**, 1273-1421 (2009). doi:10.1080/01496390902733314

Grande, C., Rodrigues, A.E.: Electric Swing Adsorption for CO₂ removal from flue gases. *International Journal of Greenhouse Gas Control* **2**, 194-202 (2007a). doi:10.1016/S1750-5836(07)00116-8

Grande, C.A., Ribeiro, R.P.P.L., Rodrigues, A.E.: CO₂ Capture from NGCC Power Stations using Electric Swing Adsorption (ESA). *Energy & Fuels* **23**, 2797-2803 (2009). doi:10.1021/ef8010756

Grande, C.A., Rodrigues, A.E.: Layered Vacuum Pressure-Swing Adsorption for Biogas Upgrading. *Industrial & Engineering Chemistry Research* **46**, 7844-7848 (2007b). doi:10.1021/ie070942d

Haghpanah, R., Nilam, R., Rajendran, A., Farooq, S., Karimi, I.A.: Cycle synthesis and optimization of a VSA process for postcombustion CO₂ capture. *AIChE Journal* **00**, n/a-n/a (2013). doi:10.1002/aic.14192

Haraoka, T., Mogi, Y., Saima, H.: PSA System for the Recovery of Carbon Dioxide from Blast Furnace Gas in Steel Works The Influence of Operation Conditions on CO₂ Separation. *Kagaku Kogaku Ronbunshu* **39**, 439-444 (2013). doi:10.1252/kakoronbunshu.39.439

Ishibashi, M., Ota, H., Akutsu, N., Umeda, S., Tajika, M., Izumi, J., Yasutake, A., Kabata, T., Kageyama, Y.: Technology for removing carbon dioxide from power plant flue gas by the physical adsorption method. *Energy Conversion and Management* **37**, 929-933 (1996)

Li, G., Xiao, P., Xu, D., Webley, P.a.: Dual mode roll-up effect in multicomponent non-isothermal adsorption processes with multilayered bed packing. *Chemical Engineering Science* **66**, 1825-1834 (2011). doi:10.1016/j.ces.2011.01.023

Liu, W., An, H., Qin, C., Yin, J., Wang, G., Feng, B., Xu, M.: Performance Enhancement of Calcium Oxide Sorbents for Cyclic CO₂ Capture- A Review. *Energy & Fuels* **26**, 2751-2767 (2012a)

Liu, Z., Wang, L., Kong, X., Li, P., Yu, J., Rodrigues, A.E.: Onsite CO₂ Capture from Flue Gas by an Adsorption Process in a Coal-Fired Power Plant. *Industrial & Engineering Chemistry Research* **51**, 7355-7363 (2012b). doi:10.1021/ie3005308

Lively, R.P., Chance, R.R., Kelley, B.T., Deckman, H.W., Drese, J.H., Jones, C.W., Koros, W.J.: Hollow Fiber Adsorbents for CO₂ Removal from Flue Gas. *Industrial & Engineering Chemistry Research* **48**, 7314-7324 (2009). doi:10.1021/ie9005244

Maring, B., Webley, P.A.: A new simplified pressure/vacuum swing adsorption model for rapid adsorbent screening for CO₂ capture applications. *International Journal of Greenhouse Gas Control* **15**, 16-31 (2013)

Markewitz, P., Kuckshinrichs, W., Leitner, W., Linssen, J., Zapp, P., Bongartz, R., Thomas, E.M.: Worldwide innovations in the development of carbon capture technologies and the utilization of CO₂. *Energy & Environmental Science* **5**, 7281-7305 (2012). doi:10.1039/c2ee03403d

Murakami, Y., Lijima, A., Ward, J.W.: New Developments in Zeolite Science and Technology. In: 7th International Zeolite Conference, Tokyo 1986. *Studies in Surface Science and Catalysis*. Elsevier Science Ltd

Oexmann, J., Kather, A., Linnenberg, S., Liebenthal, U.: Post-combustion CO₂ capture : chemical absorption processes in coal-fired steam power plants. *Greenhouse Gases Science and Technology* **98**, 80-98 (2012). doi:10.1002/ghg.1273

Qader, A., Hooper, B., Stevens, G., Kentish, S., Webley, P.: Demonstrating carbon capture. *The Chemical Engineer*(821), 30-31 (2009)

Rao, V.R., Krishnamurthy, S., Guntuka, S.K., Rajendran, A., Ullah, M.A., Sharratt, P., Karimi, I.A., Farooq, S.: A pilot plant study of a VSA process for CO₂ capture from power plant flue gas. Paper presented at the AIChE Annual Meeting, Pittsburgh, PA USA,

- Rubin, E.S., Mantripragada, H., Marks, A., Versteeg, P., Kitchin, J.: The outlook for improved carbon capture technology. *Progress in Energy and Combustion Science* **38**, 630-671 (2012). doi:10.1016/j.pecs.2012.03.003
- SaskPower: Boundary Dam Integrated Carbon Capture and Storage Demonstration Project. <http://www.saskpower.com/our-power-future/work-currently-underway/boundary-dam-integrated-carbon-capture-and-storage-demonstration-project/> (2013).
- Shang, J., Li, G., Singh, R., Gu, Q., Nairn, K.M., Bastow, T.J., Medhekar, N., Doherty, C.M., Hill, A.J., Liu, J.Z., Webley, P.A.: Discriminative Separation of Gases by a "Molecular Trapdoor" Mechanism in Chabazite Zeolites. *Journal of the American Chemical Society* **134**, 19246–19253 (2012). doi: <http://dx.doi.org/10.1021/ja309274y>
- Sjostrom, S., Krutka, H., Starns, T., Campbell, T.: Pilot test results of post-combustion CO₂ capture using solid sorbents. *Energy Procedia* **4**, 1584-1592 (2011). doi:10.1016/j.egypro.2011.02.028
- Spoorthi, G., Thakur, R.S., Kaistha, N., Rao, D.P.: Process intensification in PSA processes for upgrading synthetic landfill and lean natural gases. *Adsorption* **17**, 121-133 (2010). doi:10.1007/s10450-010-9302-6
- Takeguchi, T., Tanakulrungsank, W., Inui, T.: Separation and/or concentration of CO₂ from CO₂/N₂ gaseous mixture by pressure swing adsorption using metal-incorporated microporous crystals with high surface area. *Gas Separation & Purification* **7**, 3-9 (1993). doi:10.1016/0950-4214(93)85013-L
- Tlili, N., Grévillet, G., Vallières, C.: Carbon dioxide capture and recovery by means of TSA and / or VSA. *International Journal of Greenhouse Gas Control* **3**, 519-527 (2009). doi:10.1016/j.ijggc.2009.04.005
- van Selow, E.R., Cobden, P.D., van den Brink, R.W., Hufton, J.R., Wright, A.: Performance of sorption-enhanced water-gas shift as a pre-combustion CO₂ capture technology. *Energy Procedia* **1**, 689-696 (2009). doi:10.1016/j.egypro.2009.01.091
- Voss, C.: Applications of Pressure Swing Adsorption Technology. *Adsorption* **11**, 527-529 (2005). doi:10.1007/s10450-005-5979-3
- Wang, L., Yang, Y., Shen, W., Kong, X., Li, P., Yu, J., Rodrigues, A.E.: CO₂ capture from flue gas in an existing coal-fired power plant by pilot-scale two successive VPSA units. *Industrial & Engineering Chemistry Research*, 130514043648000 (2013). doi:10.1021/ie4009716
- Wang, M., Lawal, a., Stephenson, P., Sidders, J., Ramshaw, C.: Post-combustion CO₂ capture with chemical absorption: A state-of-the-art review. *Chemical Engineering Research and Design* **89**, 1609-1624 (2011). doi:10.1016/j.cherd.2010.11.005
- Wright, A., White, V., Hufton, J., Selow, E.V., Hinderink, P.: Reduction in the cost of pre-combustion CO₂ capture through advancements in sorption-enhanced water-gas-shift. *Energy Procedia* **1**, 707-714 (2009). doi:10.1016/j.egypro.2009.01.093
- Xiao, G., Xiao, P., Lee, S., Webley, P.A.: CO₂ capture at elevated temperatures by cyclic adsorption processes. *RSC Advances* **2**, 5291-5297 (2012). doi:10.1039/c2ra20174g
- Xu, D., Xiao, P., Zhang, J., Li, G., Xiao, G., Webley, P.A., Zhai, Y.: Effects of water vapor on CO₂ Capture with Vacuum Swing Adsorption using Activated Carbon. *Chemical Engineering Journal* **230**, 64-72 (2013)
- Zhao, A., Samanta, A., Sarkar, P., Gupta, R.: Carbon Dioxide Adsorption on Amine-Impregnated Mesoporous SBA-15 Sorbents: Experimental and Kinetics Study. *Industrial & Engineering Chemistry Research* **52**, 6480-6491 (2013a). doi:10.1021/ie3030533
- Zhao, C., Chen, X., Anthony, E.J., Jiang, X., Duan, L., Wu, Y., Dong, W., Zhao, C.: Capturing CO₂ in flue gas from fossil fuel-fired power plants using dry regenerable alkali metal-based sorbent. *Progress in Energy and Combustion Science* (2013b). doi:10.1016/j.pecs.2013.05.001

Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Webley, PA

Title:

Adsorption technology for CO₂ separation and capture: a perspective

Date:

2014-02-01

Citation:

Webley, P. A. (2014). Adsorption technology for CO₂ separation and capture: a perspective. ADSORPTION-JOURNAL OF THE INTERNATIONAL ADSORPTION SOCIETY, 20 (2-3), pp.225-231. <https://doi.org/10.1007/s10450-014-9603-2>.

Persistent Link:

<http://hdl.handle.net/11343/283274>