The Promising Application of Microwaves in Carbon Capture and Storage

Claudia Fernández-Martín

Materials & Chemical Engineering Research Group, School of Engineering
King's College, University of Aberdeen, Scotland, UK
Email: cfmartin@abdn.ac.uk

Problem Background

The planet Earth is facing a real challenge due to the increased and constant emissions of greenhouse gases, GHGs. Carbon dioxide (CO_2) is the GHG most emitted gas from large point sources such as power plants (energy generation) and other industrial facilities (steel manufacturing, cement production, etc.), and is responsible of the sharp Earth's surface temperature raise since the industrial revolution started. A linear correlation between the concentration of the CO_2 in the atmosphere and the temperature anomalies observed in the Earth's surface has been observed[1] (see Fig. 1). The increasing concentration of CO_2 in the atmosphere is being carefully monitored using observatories placed in different locations. The Mauna Loa observatory monitors and publishes the CO_2 concentration in a very regular basis, and at this moment the concentration of CO_2 in the atmosphere[2] is of 396 ppm. The CO_2 emissions are causing the global and so well-known climate change problem. Governments, together with policy makers are putting effort and different type of resources to stop the increasing trend of CO_2 emissions with the aim of trying to keep its concentration in the atmosphere constant. It should be done as soon as possible before it will be too late for the consequences of climate change to become irreversible.

This situation clearly needs an imminent solution, as the renewables are not ready yet to comply with the actual demand of energy worldwide, therefore that we still need fossil fuels to produce energy. Consequently, whilst the energy panorama world-wide tries to achieve the transition towards greener energy production technologies, the imminent solution appears to be Carbon Capture and Storage (CCS).

What is Carbon Capture and Storage?

Carbon Capture and Storage (CCS) is the technology that captures the CO_2 generated from the use of fossil fuels in electricity generation and industrial processes, and therefore avoids the CO_2 release to atmosphere. It involves three steps: capture (separation), transport, and storage (Fig. 2).

After being captured, CO_2 is compressed and transported to the place where it will be forever stored. The most common places to store CO_2 are saline aquifers, depleted oil and gas fields and coal seams. CO_2 could be injected for Enhanced Oil Recovery (EOR) which is an alternative storage method that presents an economic profit and makes the cost of the technology more feasible.

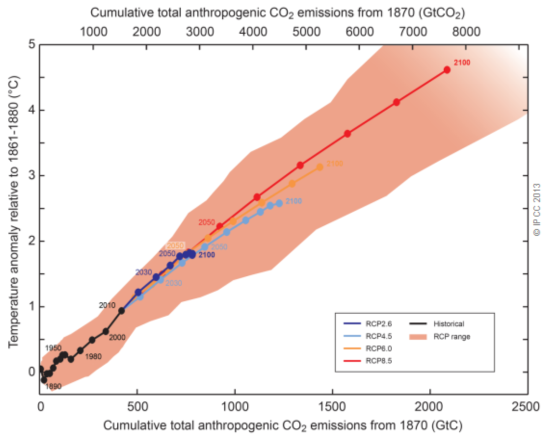

Figure 1. Global mean surface temperature increase as a function of cumulative global CO_2 emissions[1].

From the above exposed, it can be deduced that climate change evidences are urgently requiring an engineering solution to decrease the CO_2 emissions to atmosphere, consequence of the intense fossil fuel consumption needed to supply the world energy demand. Carbon capture technologies are contemplated as the hort to medium term solution to control such CO_2 increasing emissions. However, the energy penalty of CO_2 capture from the flue gas (generated at power plants after the combustion of fossil fuels) is the major challenge of post-combustion CO_2 capture technologies. The reasons are the low concentration of CO_2 in the flue gas (i.e. 15% for coal-fired and 4% for gas-fired, dry basis), and the current energy and capital costs of separating CO_2 and reaching purities of 95.5% or above needed for its transport and storage[4, 5]. A recent study[6] stated that the electricity cost would increase by 32% and 65% for post-combustion carbon capture in gas and coal-fired plants, respectively. Thus, if research were able to reduce the required energy and monetary costs of separation in a more efficient way, it would significantly reduce the barrier to the CCS implementation.

Figure 2. Schematic diagram illustrating the main stages of the Carbon Capture and Storage process[3].

Therefore, there is an unquestionable research need for more efficient technologies to capture CO_2. In this line, adsorption using solid sorbents is considered a promising solution to control CO_2 emissions from large-fixed sources such as power plants, due to the high CO_2 capture capacity and selectivity, fast adsorption and desorption kinetics, good mechanical properties and stability after repeated adsorption-desorption cycles[4-7].

For these reasons, the author has developed the laboratory-scale experimental setup called 'Microwave-regeneration Unit' to study the potential of the innovative microwave heating technology to overcome the current drawbacks of the capture process associated with its high energy penalty during the regeneration.

The practical CO_2 separation at post-combustion conditions (after burning the fossil fuel) is done by a cyclic adsorption-desorption process (Fig. 3). The first step in the process is the adsorption, which consists of the interaction of the CO_2 molecules with the surface of the solid sorbents, then CO_2 gets trapped on the surface of the solid and it is captured. The next step is called desorption or regeneration, which purpose is to recover the CO_2 previously captured to follow with the compression, transport and storage steps of the CCS process.

Figure 4 shows the schematic representation of the adsorption-desorption process and the influence of temperature and pressure on the CO_2 uptake from the adsorbent material (CO_2 capture). It can be observed that the regeneration of CO_2 from the adsorbent's surface can be done by either changing the temperature, the pressure, or both (TSA, PSA or PTSA for thermal, pressure, or pressure-and-temperature swing adsorption, respectively).

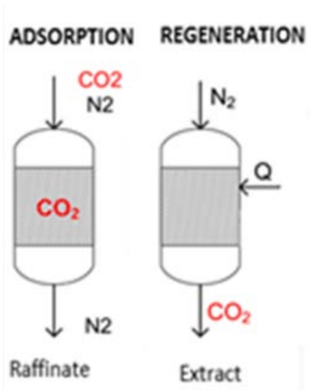

Figure 3. Schematic diagram of the adsorption-desorption cycle configuration[7].

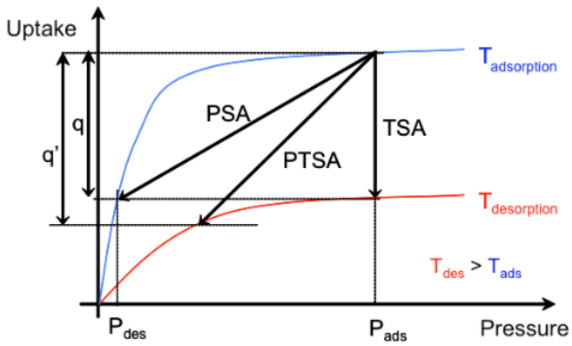

Figure 4. Separation process by changing the pressure, temperature or both (PSA, TSA or PTSA, respectively)[8].

The main drawbacks of TSA are the large amount of energy required for heating and cooling in each adsorption cycle, and the long heating/cooling times required for every cycle, and therefore the large equipment facilities needed.

What can microwave technology do for CCS?

During adsorbents regeneration with conventional heating, the heat transfer depends on the thermal conductivity of the packed bed, thus the temperature gradient along the packed bed is the result of the high thermal inertia or the limited heat transfer. To avoid these drawbacks, the design of more efficient adsorption-desorption processes is needed. For that purpose, at the University of Aberdeen we have customized a bench-scale microwave-integrated experimental rotatory-reactor to evaluate this regeneration technology on a broad range of adsorbent materials employed for CCS. Accordingly, the purpose of our research project is to study the interaction of microwave radiation with adsorbents developed for carbon capture, and to explore both the potential and the feasibility of the use of microwave as a source of heat for the desorption step of the separation process (noted as MWSA from Microwave Swing Adsorption). Figure 5 shows the typical MWSA experimental steps which are part of the first cycle when the adsorbent is pre-conditioned to start the cyclic carbon capture process. It can be observed how the partial pressure of CO_2 during the regeneration step assisted with microwaves sharply increases, and it is achieved at low to moderate temperature (120°C) after few minutes with microwave irradiation. This experimental example confirms our theory about the microwave heating potential to reduce the CCS penalties.

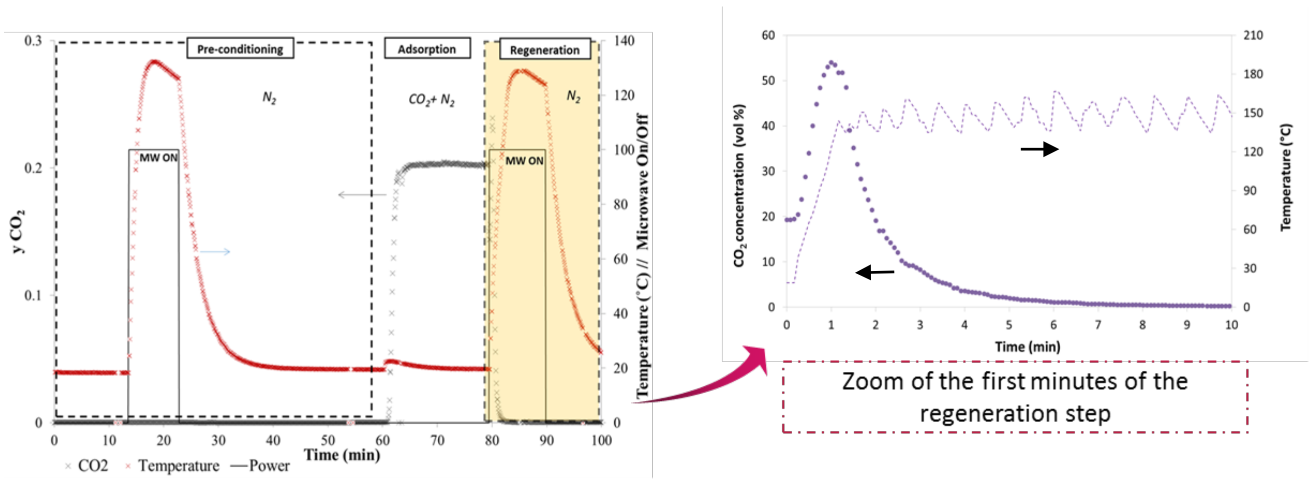

Figure 5. Typical CO_2 Microwave Swing Adosption (MWSA) experiment: steps involved in the first cycle (left); zoom of the first 10 minutes of MW-regeneration of a commercial CO_2 adsorbent.

The application of microwave heating for carbon capture processes is an emergent research technology idea that has the potential to overcome the costs of conventional heating carbon capture processes. The novelty of the process is based on the direct and selective volumetric heating of the adsorbent bed during the regeneration step, which is dependent on the adsorbent-microwaves interaction, and would avoid large thermal gradients (and consequently reduce the amount of energy applied to heat large columns of adsorbents). The main aim of using MWSA then is to minimize the overall capture process costs by reducing the energy consumption during CO_2 regeneration due to the faster cycles and the easier and lower energy-demanding regeneration of the adsorbents. Additionally, if adsorbent-adsorbate system couples with microwaves well, purity of recovered CO_2 could potentially be enhanced. Thus the aim is to elucidate whether the application of microwave energy is technically feasible, and if microwaves are converted directly into heat to increase the temperature of the adsorbents, which lead to fast desorption of the CO_2 will previously capture in the pore structure of the materials. It will have an impact in costs of carbon capture technologies, as the cycle times will potentially be reduced, as recently reported for amine-functionalized mesoporous silica[9] that was found three times faster than conventional heating.

Acknowledgements

The author acknowledges The Development Trust Fund for the financial support of the experimental equipment and Dr. Xianfeng Fan for his support during and after the feasibility of a wetting layer absorption project.

For further reading:

1. IPCC, 2013. The physical sciences basis. Summary for policy makers. Working Group I: Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
2. Daily CO_2, https://www.co2.earth/daily-co2 [last entry on the 15th of September 2016].
3. Scottish Centre for Carbon Storage, www.sccs.org.uk.
4. E. de Visser, C. Hendricks, M. Barrio, M. J. Molnvik, G. de Koeijer, S. Liljemark, et al. Dynamics CO_2 quality recommendations. Int J Greenh Gas Control, 2 (2008), pp. 478–484.
5. A. A. Olajire. CO_2 capture and separation technologies for end-of-pipe application – a review. Energy, 35 (2010), pp. 2610–2628.
6. M. Kanniche, R. Gros-Bonnivard, P. Jaud, J. Valle-Marcos, J. M. Amann, C. Bouallou. Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO_2 capture. Appl Therm Eng, 30 (2010), pp. 53–62.
7. S. García, M. V. Gil, C. F. Martín, J. J. Pis, F. Rubiera, C. Pevida. Breakthrough adsorption study of a commercial activated carbon for pre-combustion CO_2 capture. Chemical Engineering Journal, 171 (2), (2011) pp. 549-556.
8. C. F. Martín. Adsorbentes microporosos a partir de polímeros orgánicos. Aplicación en procesos de captura de CO_2 precombustión: PhD thesis. University of Oviedo, Department of Energy (2011).
9. H. Nigar at al. Amine-functionalized mesoporous silica: a material capable of CO_2 adsorption and fast regeneration by microwave heating. AIChE Journal 62 (2) (2016), pp. 547-555.

About the author

Dr. Claudia Fernández-Martín is Lecturer in Chemical Engineering, Member of the Materials and Chemical Engineering Research Group at The University of Aberdeen, and Academic Member of the UK Carbon Capture and Storage Research Centre (UKCCSRS). She has over 9 years' experience in experimental (and numerical modelling) of carbon capture processes and in the development of low-cost and advanced adsorbent materials for CO_2 capture at post-combustion conditions (capture from coal-based power plants gas emissions at atmospheric pressure) and pre-combustion conditions (capture from shifted syngas at elevated pressure).

Dr. Fernández-Martín research interests are also focused on the transformation of by-products materials and/or residues generated from industrial activities into new forms of valuable and useful materials, such as the recycling and/or transformation of wastes into new materials for air pollution control applications. She has worked developing and characterizing a wide range of materials including thermoplastic and thermostable resins; low density organic polymers; recyclable biomass residues such as olive stones and almond shells; amine-impregnated silicas; composite polymeric membranes, etc. for the separation of CO_2 from gas mixtures mainly composed by N_2/CO_2 and H_2/CO_2.

Her work on the project 'Feasibility of a wetting layer absorption carbon capture process based on chemical solvents' done at The University of Edinburgh, which aimed at investigating the microwave regeneration of a porous material used to support liquid-like regions of CO_2-absorbing solvent has inspired her to develop the current research focused on the 'enhancement of the CO_2 recovery on carbon capture processes by means of novel and energetically more efficient regeneration technologies'. It involves design, construction and experimental research on CO_2 regeneration strategies from custom-made and advanced carbon capture adsorbents in a bench-scale microwave-integrated rotatory adsorption unit.

Besides her intensive research activity, she also teaches at undergraduate and postgraduate level at the School of Engineering, The University of Aberdeen. Some of the courses she delivers are 'Air and Water Pollution Control' and 'Environmental Engineering' for Chemical Eng. and Civil and Environmental Eng. students.

For more information:
http://www.abdn.ac.uk/engineering/research/profiles/cfmartin