https://doi.org/10.1595/205651322X16631407131191 *Johnson Matthey Technol. Rev.*, 2022, **66**, (4), 497–501

JOHNSON MATTHEY
TECHNOLOGY REVIEW

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"Sustainable Carbon Capture – Technologies and Applications"

Edited by Humbul Suleman (Teesside University, UK), Philip Loldrup Fosbøl (Technical University of Denmark), Rizwan Nasir (University of Jeddah, Saudi Arabia), Mariam Ameen (Universiti Teknologi PETRONAS, Malaysia), CRC Press, Boca Raton, Florida, USA, 2022, 382 pages, ISBN 9780367755140, £110.00, €127.02, US$126.99

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NON-PEER REVIEWED FEATURE

Received 15th August 2022; Online 17th October 2022

Introduction

"Sustainable Carbon Capture – Technologies and Applications" is a muti-author book edited by Humbul Suleman, Philip Loldrup Fosbøl, Rizwan Nasir and Mariam Ameen, and published in 2022 by CRC Press, part of the Taylor & Francis Group.

The copy of the book I received to review came as an ebook available on an app called VitalSource BookShelf®. The default mode makes reading difficult and it takes a while to get used to the scrolling mode rather than discrete pages. I personally set the font size to the second option and the font to Humanist make it easier to read on an iPad. On the plus side there are several options to make accessibility easier such as the ability to turn the page colour to sepia or cyan. I would personally have preferred a PDF version to make switching between different sections easier.

Sustainable Carbon Capture

Chapter 1 introduces the concepts behind sustainable carbon capture. It includes descriptions of the types of technologies currently available and touches on the concept of sustainability in such systems. There is an extensive list of commercial or demonstration projects in operation or in the engineering phases of development. It is worthy of note that while these were most likely current at the time of writing, a number have already ceased to operate and so due diligence is needed to ensure that data are current. This is not a criticism of the authors, simply a reflection of the transient nature of technology development. While life cycle assessment (LCA) is mentioned it is not in detail but does highlight some of the issues around emissions accounting in that sustainability needs to propagate along the whole supply chain, especially in the choice of fuel feedstocks.

The 'Reactive Chemical Absorption of CO_2 by Organic Molecules' is covered in Chapter 2 and spans conventional organic bases through to alternative solvent systems. The authors point out that the reaction of water is slow but can be accelerated using bases. There are also examples where the water content of the absorbent is reduced but where there is a consequent increase in viscosity. There is also the recognition that heat is needed to affect the quite substantial temperature swing required to complete the chemical absorption followed by chemical desorption, typically between 50ºC and

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130ºC. However, the big question I wanted to see the answer to, but which I could not find, was an indication of the cycle time of the temperature swing. The heat capacity of aqueous solvents is high and so the thermal lag must be considerable. It would be a useful addition to have a table of cycle times for systems at scale, comparing between different absorbent systems. That said, the chapter is a very valuable resource for those starting off in the field of carbon capture to gain an appreciation of the opportunities and the benefits.

Technology Developments

As someone who has worked in the field of 'Ionic Liquids in Carbon Capture', I was intrigued to see these covered separately in Chapter 3. They have long been proposed as a mid-term technology development in increasing CO_2 selectivity but have taken a while to enter the mainstream. While they certainly show promise, the cost generally remains an issue. The coverage is comprehensive with over 350 references, however some key recent references to polymeric and solid ionic liquids are noticeable by their absence. There has been considerable progress in recent years, and these are not covered. With that caveat, the chapter gives an excellent appraisal of their potential and is essential reading to someone new to the field.

Chapter 4 covers 'Gas Hydrates for CO_2 Capture' which is an unusual addition to the suite of capture technologies. Indeed, this is the first time I have encountered them as a potential solution to the mitigation problem rather than as the problem themselves. There is considerable detail about their structure and mode of operation but a question remains regarding their potential use in a real life environment such as in the capture of industrial emissions. That said, the chapter is an interesting read that serves to broaden horizons.

'Sustainable Metal-Organic Framework Technologies for CO_2 Capture' are covered in Chapter 5. Metal-organic frameworks (MOFs) have been extensively studied and the structure and content of the chapter reflects this. There is in-depth coverage of the chemistry and physical properties of MOFs, including an interesting section of their fabrication into membranes. The chemistry of these coordination polymers is well understood, and they offer an opportunity to tailor their synthesis to produce very task-specific materials. While capacity, the amount of CO_2 captured per unit mass of adsorbent, is of course important, so is their selectivity to other gases in the waste stream mix. Table 5.2 in the book has some limited data, but it would have been interesting to see more given that the point of the materials is to purify CO_2 from other waste. There is a brief but interesting discussion on the commercial use of MOFs which shows that at the present time their application is limited with only six companies being identified as active in their manufacture and application.

Separation and Capture

'Novel CO_2 Separation Membranes' are discussed in Chapter 6 which opens with definitions and background theory, including a section on determining performance parameters. A section on the classification of membranes is welcome as many are described by non-experts as simply 'membranes'. The advantages of the technology are presented and a useful timeline in Figure 6.3 in the book (**Figure 1**) shows that the first commercial membranes were deployed as early as the 1980s. Despite this there are limited examples with only Korea Electric Power Corporation (KEPCO) being shown as an installed facility. In terms of being 'novel' there is only a short section on this as most of the membranes described are based on well-established methods. The area of polymers of intrinsic microporosity is of particular interest but issues of stability, fragility and long-term use still remain a barrier to widespread application.

Chapter 7 considers 'Cryogenic CO_2 Capture'. The general introduction to types of flue gas capture (pre-, post- and oxyfuel-gas capture) are again repeated. In the case of cryogenic capture of CO_2 it has been established that this becomes viable above concentrations of 70% so there is a belief that use on low concentration flue and process gases is impractical. Table 7.1 in the book appears to emphasise this but it is not clear how some of the lower limits of concentration are achieved. There are a range of techniques available for cryogenic separation but again there is an implication that these suffer at lower concentrations and require considerable energy input. The key challenges appear to be extensive for general CO_2 capture. It would have been useful to see a comparison of cryogenic processes against other established methods in order to get a feel for where the improvements could be made. Most of the discussion centres on gas sweetening which seems counterintuitive as this prolongs fossil carbon use rather than mitigating against the downstream emissions.

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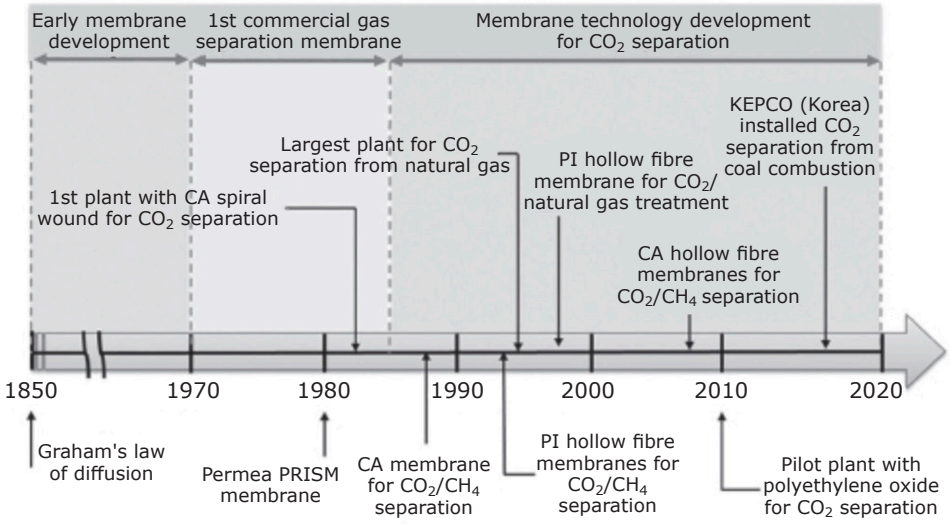

Fig. 1. A timeline of commercial membranes. Used with permission of Taylor & Francis Group LLC – Books, from "Sustainable Carbon Capture – Technologies and Applications", eds. H. Suleman, P. Loldrup Fosbøl, R. Nasir and M. Ameen, CRC Press, Boca Raton, Florida, USA, 2022, 382 pp; permission conveyed through Copyright Clearance Center, Inc

Renewable Fuels

Advanced reforming technologies for 'Bioenergy and Biofuels with Carbon Capture' is discussed in Chapter 8. This is an interesting topic, but I was quite surprised that the content does not reflect the title. Biofuels are not discussed in this chapter, which in fact discusses so-called renewable fuels of non-biological origin (RFNBO) or e-fuels. To be classified as biofuels the energy to produce the materials needs to be derived from biological energy sources and likewise so does the carbon feedstock. In this chapter there is a discussion of RFNBOs produced from the catalytic reduction of CO_2 using hydrogen. This is a very important area of carbon use and one where there is huge commercial potential. There are a number of textbooks that cover this in detail, but this is nevertheless a good yet basic introduction to the basic concepts of the technology. The field is growing at a rapid pace, so the chapter serves to highlight the field in a general way allowing the reader to look at more detailed reviews where new methods are arising. Considering the wealth of literature in this particular area of carbon capture and utilisation (CCU) the chapter is somewhat brief and does not cover the commercial success of several processes including the work of Sunfire GmbH, Germany, Oberon Fuels, USA and work from the Ozin and Steinfeld groups. It is also surprising not to see mention of the seminal work of George Olah who brought the methanol economy to the forefront of CCU (1–6).

Chapter 9 covers 'Blue/Bio-Hydrogen and Carbon Capture'. This is a very much debated area in terms of whether or not it is a sustainable approach as, unlike green hydrogen which is obtained from water splitting using renewable energy sources, blue hydrogen uses fossil methane as the hydrogen source and relies on there being sufficient carbon capture and storage (CCS) at scale and close to the production site for it to be viable. Indeed, a recent paper from Howarth and Jacobson has challenged the concept that blue hydrogen can lead to mitigation (7). Therefore, the jury is out as to whether blue hydrogen is in fact a sustainable option, as it uses primarily fossil based hydrogen sources and relies on CCS being widely available at scale and at a reasonable cost. The recognition that bio-hydrogen (for example blue hydrogen from biomethane) may be a solution is a reasonable conclusion to make. This chapter will give rise to much debate so may be useful in the teaching of graduate degree courses.

Process Design

An interesting approach is taken in Chapter 10 covering 'Improvements in Process Design, Simulation, and Control'. This considers approaches such as improved process control systems and system intensification. Both mathematical models and non-model approaches are considered, and suggestions are made of how the different approaches can be realised. While these are suggestions, they are not discussed in detail and no definitive examples are given. Process design is rightly proposed as a way to accelerate improved efficiencies; however, most seem to be based on redesign of existing systems and technologies rather than the significant step change that is perhaps required. This chapter is a good starting point for further research as it promotes a way to rethink systems.

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Four examples of capture processes are discussed in Chapter 11, 'Special Case Studies in Sustainable Carbon Capture'. The first is a post-combustion capture unit of an energy to waste facility, the second is capture onboard a liquefied natural gas transporter ship, the third biogas upgrading and finally, the fourth considers capture in the cement and metal industries. Each is presented as a template for analysis which is sensible and aligns well with the harmonised guidelines for LCA and technoeconomic assessment published by the Global CO_2 Initiative over a number of years (8) although these are not cited in the text. With the exception of biogas upgrade, which includes an analysis of the Sabatier reaction to reduce CO_2 to methane, the capture case studies stand alone in that they produce purified CO_2 but assume that this will go to a sequestration site. All the examples assume that an amine solution will be the method of choice, however the lack of sequestration sites for many countries or political opposition means that these cannot be simply assumed. That said, this is a very useful chapter for researchers as it instils a need for process in the way that analyses are carried out. The production of methane from CO_2 poses a conundrum in terms of mitigation and sustainability. Methane has a global warming potential 24 times that of CO_2 so the product is more environmentally harmful. There is therefore a need to ensure the containment of the product as fugitive methane emissions must be avoided.

Chapter 12 reports some aspects of 'Modelling the Socio-Economic Impacts of Carbon Capture and Storage Deployment – Current Practices and Pathways Forward'. This is a good general introduction that focuses on sequestration potential of carbon capture but not the added benefits of revenue generation through utilisation of the captured CO_2. The latter can add to social development through the generation of clean energy, alternative fuels and construction materials so can have a profound impact on regional economic growth, particularly where sequestration is not possible or where public opposition precludes sequestration. The chapter gives a good overview and a starting point, however the reference section is brief and omits important contributions from the Institute For Advanced Sustainability Studies (IASS) Group in Potsdam, Germany, and the work of McCord *et al*. over the last five years (9, 10). It would be useful when applying such analysis approaches to compare the results against the counterfactuals of a business-as-usual approach and alternative mitigation technologies which may create additional social impact.

Emerging Technologies

Chapter 13 concludes the book and discusses 'Emerging Technologies for Sustainable Carbon Capture'. A range of areas are covered and while some might be considered as emerging, many are already in the arsenal of available methods. For example, the Royal Society of Chemistry (RSC) Faraday Discussions on CCU and CCS in 2015 and 2016 respectively covered metal-looping, serpentine carbonation and electromicrobial methods while direct air capture (DAC) has been around for a decade or so (11, 12). It is surprising that the commercial DAC applications from Climeworks AG, Switzerland and Carbon Engineering Ltd, Canada, were not discussed nor the fuel cell work of Sunfire. Many of the techniques are now established rather than emerging so this is a difficult chapter for the authors to keep up to date as there are so many new emerging technologies that could produce a paradigm shift in the way that carbon capture can be achieved at scale and in a sustainable manner. While the book was published in 2022, it is likely that many of the newer technologies were not captured before the publication deadline.

In conclusion this is an excellent introduction to CO_2 capture technologies that will be of interest to those new to this field of research and to students studying energy related programmes.

Acknowledgements

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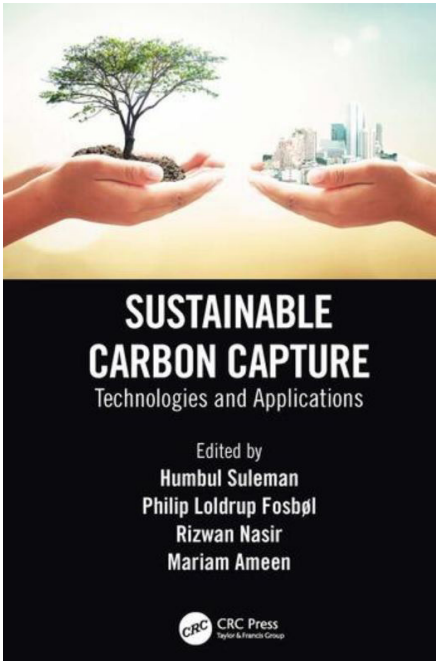

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