Chapter 2
Overview of CO_2 Capture Technology

Abstract Until cost-effective alternative energy sources are available, it is necessary to capture harmful waste gases at the source (i.e., smoke stacks). CO_2 gas can be captured prior to combustion, through an oxyfuel combustion stage, or after combustion. Currently, the most common way to separate carbon dioxide gas is through an amine-scrubbing system in post-combustion scenarios; however, this method can be costly and byproducts are harmful to the environment. For this reason, absorbents, adsorbents, membranes, gas hydrates, and chemical looping processes are considered as methods for CO_2 gas capture. Industries such as iron and steel and cement industries can also incorporate CO_2 separation and capture technologies. Once CO_2 is captured, it can be transported through pipelines and stored in geological formations and ocean reservoirs.

Keywords Adsorbent · Absorbent · Post-combustion

2.1 Rationale for CO_2 Capture Technology

It would be ideal to change the fuel source from carbon based ones to cleaner energy alternatives, such as wind and solar; however, until these can be developed at competitive prices, it is important that we have ways to capture CO_2 from existing and new power plants that use conventional and renewable fuels.

Stationary point sources, like power plants, are practical locations to implement CO_2 capture technology, because electricity generation contributes to 41 % of total CO_2 emissions (Sumida et al. 2012). Technologies that can effectively capture CO_2 from stationary point sources thus have developed recently.

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2.2 Research on Carbon Capture and Storage (CCS)

In general, CCS refers to the research and development aimed at finding viable ways to capture and transport a concentrated stream of CO_2 and then store it in underground reservoirs or oceans. CCS provides a tentative solution for continued use of fossil fuels, until the technology to transition to more sustainable energy sources is developed (Herzog 2001).

According to Herzog (2001), CCS has 4 components:

(1) Capture
(2) Compression
(3) Transport
(4) Injection

There is significant storage capacity in both land and water reservoirs. Although the ocean and deep saline formations have the greatest potential capacity (1000's GtC), depleted oil and gas reservoirs and coal seams have a worldwide capacity on the magnitude of 100s GtC. Terrestrial reservoirs have less capacity (10s GtC) (Herzog 2001).

2.3 Carbon Capture Processes in Power Plants

There are 3 gas production scenarios where CO_2 can be separated in power plants. At this time, capturing 90 % of CO_2 from power plants would add \$0.02/kWh; 75–80 % of this cost results from capture and compression processes (Herzog 2001). Figure 2.1 depicts the gas capture pathway for the three areas of energy production.

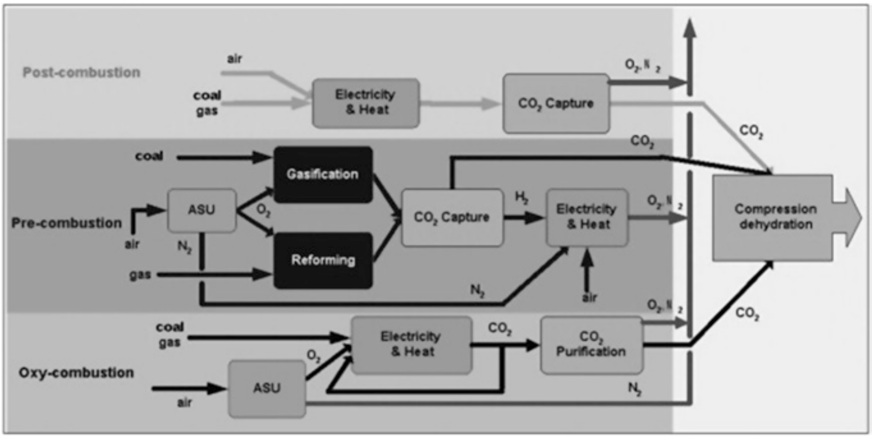

Fig. 2.1 The three CO_2 capture processes (Kanniche et al. 2010)

2.3.1 Pre-combustion

In the precombustion CO_2 capture process, coal/fossil fuel undergoes gasification and after syngas is produced, a water-gas shift (WGS) reactor prepares the syngas for extraction of fuel gas and CO_2. Therefore, CO_2 must be separated from H_2 after the gasification process. This occurs at a high pressure (1000 times higher than flue gas in post-combustion) and the remaining H_2 goes on to participate in the combustion process (Sumida et al. 2012).

2.3.2 Oxy-fuel Combustion

This is a nitrogen-free combustion technique that produces highly concentrated CO_2 flue gas streams. Oxygen Transport Membranes (OTMs) have already been developed to separate the oxygen from CO_2; another technique involving partial flue gas recycling (FGR) can be implemented to existing boilers. Nevertheless, current oxygen production techniques are costly, so in order to apply this oxy-fuel to industry, a wide range of advancements must be made.

There are a few variations of oxy-fuel combustion are currently in the conceptual phase of research.

In the Matiant Cycle, CO_2 from fuel combustion in oxygen is used to replace N_2 in air. The excess is extracted through valves. The main advantage is that a N_2 and CO_2 separation is not needed; the disadvantage is that a CO_2 turbine is required.

The Graz cycle uses water and CO_2, under a high temperature gas turbine and low temperature steam cycle, to separate CO_2.

Chemical Looping Fuel is oxidized by a metal oxide, rather than air, to improve the efficiency of the production of CO_2 and water. This can be condensed to a nearly pure CO_2 stream (Gupta 2003).

2.3.3 Post-combustion

In post combustion capture, fossil fuel is converted to energy prior to the CO_2 capture process. The major challenge is in separating the low concentration of CO_2 (16–16 %) out of the high concentration of N_2 gas (73–77 %). In this scenario, one characteristic challenge is the lower pressure of CO_2 flow. There needs to be a balance between selectivity to CO_2 verses other gases and the ability to desorb the CO_2. Chemical absorption tends to produce strong bonds, resulting in a high regeneration cost.

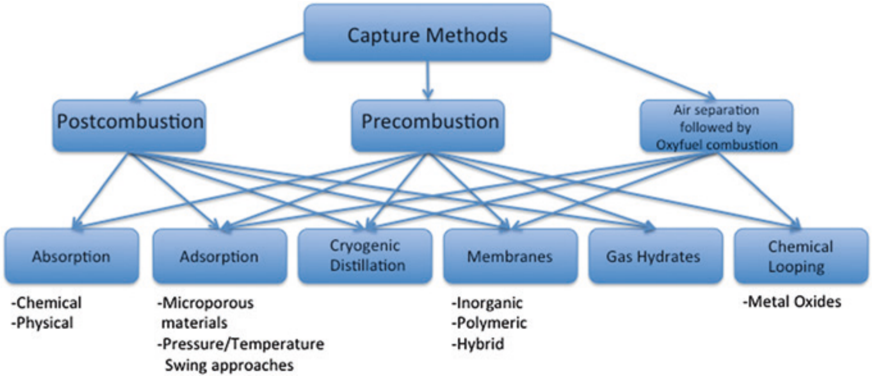

Fig. 2.2 Carbon dioxide capture methods possible for each combustion location, based on (D'alessandro et al. 2010)

2.4 CO_2 Capture Technology at Different Stages

Figure 2.2 lays out several general options for carbon dioxide capture. Post-combustion capture technology is the most developed and the processes of adsorption (surface binding of gases), absorption, distillation, membrane separation, and gas hydrates have been determined to be potential mechanisms for CO_2 capture in this area of energy production. This book will focus on the selection of CO_2 sorption materials, rather than other processes that are less researched.

2.5 Selection of Capture Technology

It is more costly to retrofit a CO_2 capture system into existing plants than for new coal fire plants because of less efficient heat integration and site-specific difficulties requiring adaptation of the capture system. The selection of CO_2 capture technology is based on the fuel composition, the heat, the influence of water, the resulting partial pressure of the gas mixture, and the configuration of the power plant (Rao and Rubin 2002).

2.5.1 Absorbents

One historically attractive method for separating gaseous compounds is to have the target gas selectively absorb into a liquid. Several commercial gas separation technologies depend on the interactions between gases and pure liquids, to remove CO_2 from natural gas. The goal of chemical scrubbing is to differentially dissolve the target gas into the liquid phase. Another method of separation is comprised of a reaction between the target gas and a liquid solute (Bates et al. 2002).

Currently, there is a large energy penalty for CO_2 capture. For example, the most commonly used and most highly developed technique uses an aqueous alkanolamine absorbent, which contributes to an energy penalty of nearly 30 % the output of the power plant. Not only does this require large capital investment, but the driving cost of CO_2 capture for amine-based systems is related to the solvent regeneration processes, as CO_2 can only be released under high temperature. Further, current materials that are used on these large gas flow applications form waste products that require careful handling and storage and the materials become unstable after heating, which limits regeneration.

2.5.2 Adsorbents

Solid adsorbents are considered promising as they can be designed to have a large capacity and selectivity for gas adsorption. The porosity and structure of the framework can be further modified to optimize the selection of CO_2 over other gases that are present within the industrial gas stream (Sumida et al. 2012). A more detailed summary on the research progress of absorbents and adsorbents will be presented in the next chapters.

2.5.3 Cryogenic Distillation

Distillation columns are used to separate CO_2 from the other gases such as N_2 and CH_4 by condensation and vaporization cycles. These gases are separated based on their different vapor pressures (yielding different boiling points) and volatilities. Flue gas is compressed into a fluid, pretreated to remove water, sent through a series of heat exchangers, and finally is distilled to separate liquefied CO_2 from gaseous N_2, CH_4, or H_2 (Wilcox 2012).

2.5.4 Membranes

Membranes are used as an alternative to liquid amine absorption, but are less developed. They are selective to certain gases, such as CO_2, due to their specific porosity, shape, and electrostatic interactions.

2.5.5 Gas Hydrates

Gases, such as CH_4, CO_2, and water form gas hydrates, or ice-like inclusion crystals at specific temperatures and partial pressures under the presence of tetrahydrofuran (THF). These crystals are separated and subsequently decomposed to create a CO_2 rich stream. At this time the system is costly and inefficient; the rate of hydrate formation needs to be improved (Linga et al. 2007)

2.5.6 *Chemical Looping*

The general principle of the chemical looping process is to cycle a metal/metal oxide through reduction and oxidation reactors, which then oxidizes the fuel to produce CO_2 and H_2O from CH_4; therefore, having inherent CO_2 capture potential. This is practical for use in oxyfuel combustion (Brandvoll and Bolland 2004).

2.6 Carbon Capture Process in Power Plant Applications

2.6.1 *Iron and Steel Production*

Iron and steel industries already employ CO_2 capture technologies to enhance the quality of flue gas. In the iron industry, when the gas is reduced, both Directly Reduced Iron (DRI) and CO_2 are produced and should be separated. The steel industry frequently will use a blast furnace during the production. The gas emissions include a mixture of N_2, H_2, CO_2, and CO. 20 % of the mixture is CO_2 and CO. The carbon dioxide capture is performed using membrane separation (where H_2 is removed), followed by an expansion turbine. The resulting CO_2 is compressed and stored. Figure 2.3 depicts this capture process (Gielen 2003).

2.6.2 *Cement Production*

The concentration of CO_2 in flue gas from cement production (14–33 %) is higher than that from power generation sources; therefore cement kilns are good places to apply CO_2 capture processes. The CO_2 could be captured by amine scrubbing, but the regeneration heat is inaccessible; oxyfuel combustion could be used, if the high CO_2 concentration doesn't negatively affect the process (Bosoaga 2009).

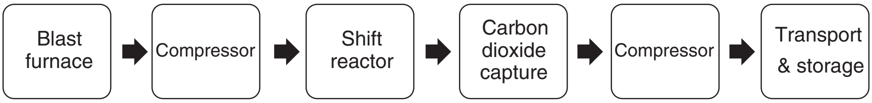

Fig. 2.3 CO_2 capture and storage system process for a conventional blast furnace. Adapted from Gielen (2003)

2.6.3 Purification of Natural Gas Streams

In natural gas purification there is a need to remove CO_2, H_2S, and from CH_4 (Gupta 2003). This would improve pipeline capacity and reduce compression horsepower. When feed and output gases are at high pressure, membrane technologies are most practical; whereas, as low pressure, adsorbing materials can be applied (Echt 2012).

2.7 Transport and Storage of CO_2

2.7.1 Transport

There are several ways that have been researched to transport CO_2 after the gas is captured from gas streams. It can be transported via pipelines under or overground, by tankers, or in ships across the ocean. This sort of transportation technology is mostly developed because of the current and historical need to transport natural gas. Finally, the captured CO_2 can be stored in underground reservoirs (Anderson and Newell 2004).

2.7.2 Storage

In its gas form, CO_2 can be sequestered in geological formations and ocean reservoirs, such as deep saline reservoirs, depleted oil and gas wells, and unmineable coal seams. Oceans and geologic formations are the most suitable sites. Residence time for CO_2 in geologic reservoirs is at least thousands of years, but ocean storage is less secure. Oceans closely cycles with the atmosphere, so 15–20 % of stored CO_2 will escape over hundreds of years. Because of this cycling, environmental impacts due to ocean storage are important to define. PH drops due to the reduction of CO_2 with seawater, but the impact can be avoided if the injection technique disperses the CO_2. On the other hand, when planning to use geologic storage, safety is a key consideration (Herzog 2001).

One practical benefit of injecting CO_2 into depleted oil and gas wells is that the pressure of the injection can actually facilitate more extraction of natural gas. Depleted coalmines and salt reservoirs have been employed as well. Nevertheless, with global emissions of 30 Gt per year, underground storage would fill; therefore, efficient conversion of CO_2 to transportation fuel is currently studied as a promising advancement (Sumida et al. 2012).

2.8 Conclusion

In order to counteract the growth of CO_2 emissions, carbon can be either converted into a more sustainable form (i.e., biochar) or captured as a gas and buried in underground (i.e., depleted gas mines) or ocean reservoirs. The implementation of carbon capture technologies is, at this time, most practical in post-combustion scenarios, where CO_2 is separated from N_2 gas at low pressure.

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