Carbon Dioxide Separation and Capture for Global Warming Mitigation

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Since the beginning of industrial revolution, the ratio of fossil fuel used has been increased yearly. Fossil fuels, which include the oil used to fuel gasoline-powered vehicles and machines and the coal mined to power plants that supply electricity, are integral to modern life. Burning fossil fuels releases carbon dioxide into the atmosphere and accounts for rising carbon dioxide concentrations. Actually, fossil fuel burning results in more than 30 billion metric tons of carbon dioxide being added to the atmosphere each year. Carbon dioxide is also the major cause of the global greenhouse effect and global warming. Nearly 60% of the contribution to rise in worldwide temperature has come from carbon dioxide emission [1]. According to International Panel on Climate Change (IPCC) working group I fifth assessment report (final draft), it predicts that, by the year 2100, the atmosphere may contain up to 421–936 ppm CO2, causing a rise of mean global temperature of around 1.0~3.7°C. Although energy consumption and requirement increase quickly at present, there is still no reliable and sustainable type of energy available for use as a power source. Therefore, it is most important to separate and capture carbon dioxide from the industries or power plants emission gases for global warming mitigation.

To capture carbon dioxide it is first separated from other mixed gases resulting from combustion or processing. It is then compressed and purified to make it easier to transport and store. Carbon dioxide resulting from combustion, particularly in the electricity sector, can be captured using one of three systems: post-combustion, pre-combustion and oxyfuel combustion capture systems.

In post-combustion capture system, the CO2 is removed from flue gas after combustion of the fossil fuel such as coal, oil or natural gas in a traditional power plant, or a vehicle engine. It can also be applied to cases of integrated gasification combined integrated gasification combined cycle (IGCC) and natural gas combined cycle (NGCC) flue gas capture. The flue gas will contain some CO2, typically in the range from a few percent to ten percent. The rest will be mainly nitrogen and water vapor. The advantages of post-combustion capture system include that all the existing power plants can be retrofitted without any or with only minor modifications and it can be applied to capture CO2 from industrial manufacturing such as cement industry and steel industry [2].

In pre-combustion capture system, the CO2 is separated or removal from fuel before the combustion process. Instead of burning coal or natural gas in a combustion plant, the fuel can be converted to hydrogen and CO2 prior to combustion. The CO2 can then be captured and stored and the hydrogen is combusted to produce power. Pre-combustion capture system is applicable to new fossil fuel power plants like IGCC power plant, because the capture process requires strong integration with the combustion process. As compared to the post-combustion capture, pre-combustion capture system is much easier and cheaper, but fuel conversion steps are costly [2].

Oxyfuel combustion capture system is very similar to post-combustion capture system. The main difference is that the combustion is carried out with pure oxygen instead of air. As a result the flue gas contains mainly CO2 and water vapor, which can be easily separated by condensation of the water. The challenge is that it is expensive to produce pure oxygen because the air separation to generate pure oxygen required for combustion can be costly for a large scale power plant. Almost three times more oxygen is required for an oxyfuel-combustion power plant as compared to an IGCC power plant of equal size [2].

During the past few decades, much effort has been devoted to developing new technologies for CO2 capture and separation, including chemical absorption, physical absorption, membrane separation, adsorption, and some of the novel separation technique. Chemical absorption uses an alkaline solvent to react and capture CO2. The chemical absorption processes use gas-liquid contacting and separating equipment where gas and liquid streams flow in a counter-current fashion in a vertical bed, sufficient contacting and mixing being ensured by the inclusion of trays or packing material inside the
bed. It is generally adopted for CO2 capture because a scrubbing solvent for CO2 capture is close to commercial development. The most chemical absorption scrubbing amine solvent is monoethanolamine (MEA), a primary alkanolamine, in carbon dioxide capture which has 98% CO2 recovery [3]. Besides, such as 2-amino-2-methyl-1-propanol (AMP), secondary amines such as diethanolamine (DEA), and tertiary amines such as methyl-diethanolamine (MDEA) are also used for CO2 capture and separation [4]. However, amines apply to chemical absorption which has some disadvantages such as, a large amount of energy and cost are required to remove the dissolved CO2 and recover the solvent. Oxygen present in the gas stream causes degradation of the solvent and produces corrosive products. In addition, the degradation products will be harmful to both human health and the environment. Therefore, some aqueous solution of ammonia and potassium carbonate can be used in carbon dioxide capture. The former one has been shown to have significant advantages over the conventional amines including lower solvent costs, high absorption loadings, and less energy requirements for the solvent regeneration [5]. Using aqueous ammonia have been shown significant improvements in the cost of electricity and CO2 avoidance cost in a coal fired power plant, when compared to the MEA solution of 30% by weight [6]. The latter one has been shown lower energy for regeneration and a low environmental impact when compared with the traditional amine-based solvents [7]. Aqueous solution of potassium carbonate can be used for both pre-combustion [7] and post-combustion [8] carbon dioxide capture.

Physical absorption (non-reactive absorption) is made between two phases by the intermolecular force. A liquid solvent absorbing CO2 is according to Henry’s Law which depends on the solubility of gases, the pressure and the temperature. So, at high CO2 partial pressure and low temperature, the CO2 loading capacity of the solvent is higher and no stoichiometric limit for a physical solvent than for a chemical solvent. As said, the solvent can be regenerated by any of pressure reduction, inert gas stripping, and thermal regeneration. For the CO2 absorption and capture, many solvents are formulations of tributyl phosphate, polycarbonate, methylecycloacetate, n-formyl morpholine, Selexol and Rectisol [9]. Where the Selexol solvent by Union Carbide is a physical solvent based on dimethylether polyethylene glycol for bulk CO2 removal and H2S removal in synthesis gas produced by gasification of coal, coke, or heavy hydrocarbon oils. Rectisol based on cold methanol solvent has mainly been used to separate CO2 from a mixture of H2, CO and CO2 in the coal gasification plant. In general, CO2 removal using physical absorption allows consuming energy on a reasonable level for its application in large industrial scale.

Membranes are porous/semi-permeable materials that are like as filters, and therefore can be used to separate CO2 from other gas components. Membrane surface allows the desired gas molecule to adsorb onto the surface of the high pressure side, and then this molecule permeates through the interior of the membrane into the low pressure side. Compared to absorption separation for CO2, the advantages of the membrane process are no required separating agent, regeneration and maintenance. Recently, membrane is wildly using in CO2 separation from raw natural gas components or flue gas [10-11]. A number of membranes apply in CO2 separation, including polymeric membranes and inorganic membranes, have been investigated. Polymeric membranes are made in glassy polymers and rubbery polymers. The former one has exhibited high selectivity but low permeability; it may decline over time due to aging. The latter one has exhibited high permeability but low selectivity and plasticization suppression properties. Generally, advantages of polymeric membranes include low cost, ease of synthesis, and mechanical stability which have been successfully applied for the separation of carbon dioxide from natural gas streams [12-14]. Inorganic membranes can be classified into two categories based on structure: porous and non-porous. In porous inorganic membranes, a porous thin top layer is cast on a porous metal or ceramic support, which provides mechanical strength but offers minimum mass-transfer resistance. Alumina, carbon, glass, silica, zeolite, and zirconia membranes are mainly used as porous inorganic membrane materials supported on different substrates. Porous inorganic membranes are cheaper and have low selectivity. In non-porous inorganic membranes, a thin layer of metal is consisted, such as palladium and its alloys (metallic membrane), or solid electrolytes, such as zirconia [15]. Non-porous inorganic membranes have high selectivity for hydrogen or oxygen separation but low permeability and are limited as compared to porous inorganic membranes [16]. Both porous and non-porous inorganic membranes have been effectively applied for concentrating CO2 from flue or fuel gas mixtures [15, 17].

CO2 capture and separation by adsorption include physical adsorption and chemical adsorption. The former one, physical adsorption, uses the affinity of CO2 to adsorb CO2 on material surfaces and relies on the weak van der Waals forces which adsorption capacity increases with higher partial pressure of CO2 and lower temperature with. The latter one, chemical adsorption, involves gas molecules forming chemical bonds with the surface of the adsorbent to form surface compounds, in a reversible reaction which can be reversed by changing the temperature. Due to that the adsorption is a surface phenomenon, in which atoms or molecules stick to the adsorbent surface, various adsorbent have been proposed for removal of CO2 from fuel/flue gas including carbonaceous materials/activated carbon, zeolite molecular sieves, and metal organic frameworks (MOFs) materials [18]. An adsorption process is basically composed of two steps, adsorption and regeneration, which operate on a repeated cycle. In the adsorption step, the gas stream is fed to a bed of solid adsorbent, which adsorbs CO2 selectively until equilibrium is reached. An adsorption process possesses a number of advantages over the conventional absorption process including: low regeneration energy equipment, no liquid waste, and a much wider range of possible operating temperature [19]. Adsorption processes for CO2 capture and separation can be mainly divided into pressure swing adsorption (PSA), vacuum swing adsorption (VSA) and temperature swing adsorption (TSA). PSA and VSA processes are preferentially adsorbing the target gas species at high pressure, then swing to low pressure to desorb the adsorbed gas by the cyclic operation to achieve gas mixture separation. TSA processes are using.
increasing the temperature of the adsorbent bed to regenerate adsorbents, which may be applied on both physical and chemical adsorption. The three main methods for adsorption are currently working on CO2 capture from flue gases or post-combustion CO2 by researchers around the world [20-23]. Besides, PSA, VSA and TSA have been used in H2 production, O2 separation, and CO2 removal from natural gas [24].

Two novel techniques, cryogenic distillation and electrical swing adsorption (ESA), for carbon dioxide separation have been developed. Cryogenic separation relies on the assumption that all components of the flue gas are removed except for the N2 and CO2 prior to cooling. Once all of the other gases and particulates are completely removed, the remaining gas is sent into a cryogenic chamber where the temperature and pressure are manipulated to cause the CO2 to liquify [24]. Cryogenic distillation has one advantage over most other separation processes: its product is liquid CO2, which is ready for transport via pipeline or tanker for sequestration. However, cryogenic distillation is extremely energy intensive. In order to keep the system cool, the energy required makes the process cost ineffective. Similar to PSA or TSA, ESA is that in the desorption stage desorption is achieved by passing a current through the saturated electrically-conductive adsorbent [26]. In the ESA process, carbon fiber composite molecular sieve (CFCMS) and activated honeycomb monolith are used for CO2 separation [27-28].

CO2 emissions have an impact on global climate change. Many various technologies such as absorption, membrane separation, adsorption, etc., can be used for CO2 capture and separation. Although some of the technologies being developed are still at the early stages, but wide investigation and deployment of these technologies are necessary to mitigate CO2 emissions and ultimately achieve climate stabilization. In addition, the energy or co-feed derived from renewable resources (solar, nuclear, wind, biomass, geothermal energy, etc.) for CO2 activation is also important to cut the carbon emission for sustainable development.

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