

Carbon Dioxide Capture and Separation Techniques for Gasification-Based Power Generation Point Sources

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ABSTRACT

The capture/separation step for carbon dioxide (CO₂) from large-point sources is a critical one with respect to the technical feasibility and cost of the overall carbon sequestration scenario. For large-point sources, such as those found in power generation, the carbon dioxide capture techniques being investigated by the in-house research area of the National Energy Technology Laboratory possess the potential for improved efficiency and reduced costs as compared to more conventional technologies. The investigated techniques can have wide applications, but the research has focused on capture/separation of carbon dioxide from flue gas (postcombustion from fossil fuel-fired combustors) and from fuel gas (precombustion, such as integrated gasification combined cycle or IGCC). With respect to fuel gas applications, novel concepts are being developed in wet scrubbing with physical absorption; chemical absorption with solid sorbents; and separation by membranes. In one concept, a wet scrubbing technique is being investigated that uses a physical solvent process to remove CO₂ from fuel gas of an IGCC system at elevated temperature and pressure. The need to define an ideal solvent has led to the study of the solubility and mass transfer properties of various solvents. Pertaining to another separation technology, fabrication techniques and mechanistic studies for membranes separating CO₂ from the fuel gas produced by coal gasification are also being performed. Membranes that consist of CO₂-philic ionic liquids encapsulated into a polymeric substrate have been investigated for permeability and selectivity. Finally, dry, regenerable processes based on sorbents are additional techniques for CO₂ capture from fuel gas. An overview of these novel techniques is presented along with a research progress status of technologies related to membranes and physical solvents.

INTRODUCTION

Carbon sequestration is a viable alternative to reduce the emissions of the greenhouse gas carbon dioxide from large point sources. It holds the potential to provide deep reductions in greenhouse gas emissions. As mentioned in the Carbon Sequestration Program, managed by the U.S. Department of Energy, of particular interest are power generation

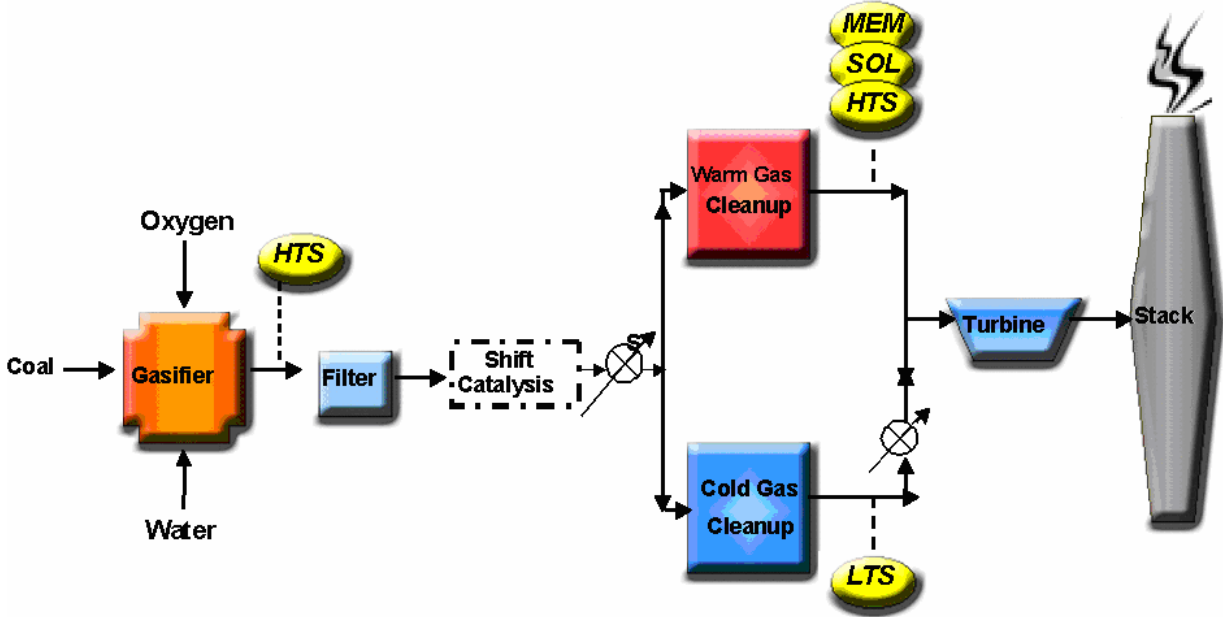
point sources that use fossil fuels.¹ Since nearly one-third of the anthropogenic CO₂ emissions are produced by these facilities, conventional coal-burning power plants and advanced power generation plants, such as integrated gasification combined cycle (IGCC), present opportunities where carbon can be removed and then permanently stored. Although pulverized coal-fired-base steam cycles have been the predominant electric power generation technology for many years, it is projected that advanced power generation technologies (for example, gasification-based IGCC) will make in-roads in the power generation sector in the near future. FutureGen, a power and chemical generation system with negligible atmospheric emissions, is just one example of future gasification-based systems.²

In IGCC power plants, a fossil fuel is reacted with oxygen and steam in a gasifier to produce a fuel gas (also frequently referred to as synthesis gas or syngas) consisting mainly of carbon monoxide and hydrogen. This mixture is then cleaned and burned to generate power in a gas turbine combined cycle. The high efficiency of this process can be exploited by fuels, such as residual oil and coal.³ Plants consist basically of three main building blocks: coal gasification, gas cleaning, and power generation.⁴ A process diagram can be seen in Figure 1. Assuming oxygen-blown gasification with coal (near pure oxygen is used to eliminate the pressurization of the diluent nitrogen), the main products of the gasification process are CO, H₂, CO₂, H₂O, H₂S, some gaseous hydrocarbons, and trace amounts of certain pollutants, including mercury. The gas cleanup system of the plant involves particulate removal and acid gas scrubbing. In a typical IGCC plant, the crude fuel gas is first fed to a facility to remove the particulates from the gas stream. The gas leaving the particulates scrubber is then cooled and dewatered and, at this point, consists mainly of CO, H₂, and CO₂. It also contains the acid gas H₂S, which will be removed in the desulfurization system. The acid gas scrubbing process (cold gas cleanup in Figure 1) is generally designed for the removal of sulfur-bearing compounds with very little CO₂ removed in the process. Selexol is one process that can be used. Additionally, removal of CO₂ at this location can be performed and Selexol could be used for this purpose. Some designs employ sulfur-tolerant shift catalysts followed by acid gas removal at low temperatures. This approach is preferable when CO₂ recovery is desired due to the increase in CO₂ partial pressure after the shift reaction.⁵ The power generation consists of a gas turbine system followed by a steam turbine bottoming cycle. The desulfurized gas is first injected with steam and partially expanded in gas expanders to recover some work. The partially expanded gas, which is rich in CO and H₂, is then burned with air and expanded in a gas turbine to recover more work. The residual thermal energy in the gas turbine exhaust is used to produce steam for the steam turbine bottoming cycle.

The upper flow path in Figure 1 indicates the option where acid gas cleaning occurs within a warm gas cleanup system rather than at the previously described cold (lower) temperatures. The main advantage in cleaning the gas in an IGCC application at higher temperature is that the thermal plant efficiency will be as much as 2-3% greater as compared to the lower temperature acid gas cleaning scenario. The moisture content in this humid gas stream remains as compared to the cold gas cleanup case.⁵ The areas of efficiency improvements are that the transfer of heat and latent heat to the more efficient

gas turbine cycle are maximized; the capital and operating costs are lowered by reducing the duty on any heat exchangers; and the need for waste water treatment facilities are eliminated.⁶

Figure 1. General Case: Advanced Gasification/IGCC – Fuel Gas



With respect to CO₂ capture in an IGCC system, post-combustion and pre-combustion technologies can be used. After the gas turbine combustor, about 9% carbon dioxide exits in the flue gas and partial pressure of the carbon dioxide is low. However, precombustion techniques within the IGCC system offer the opportunity to remove CO₂ from the fuel gas before it is combusted in the turbine. The high pressure of the system and shifting of the CO to CO₂ produce a high partial pressure of CO₂ that could be advantageous with certain removal technologies.

In a carbon sequestration scenario, the cost of the capture/separation step is much higher than that of the storage step.¹ For IGCC systems, commercial processes for CO₂ removal, such as Selexol, are used as a baseline from which other capture technologies can be compared. The U.S. Department of Energy’s National Energy Technology Laboratory (NETL) is conducting in-house research investigating novel techniques to capture/separate CO₂ from gases from advanced power generation systems. These technologies fall within the process categories of wet scrubbing with physical absorption; chemical absorption or adsorption with solid sorbents; and separation by membranes. Except for membranes, all capture techniques must be regenerable due to the excessive amount of carbon dioxide produced in a power generation plant.

With respect to the first category, physical solvents for CO₂ removal at high temperatures in IGCC applications are being studied. The higher temperature of operation for these solvents enhances the thermal efficacy of the IGCC power generation system.

Depressurization or flashing of the CO₂ from the rich solvent is the means for regeneration. A temperature swing is another means for regenerating the solvent although vapor pressure and thermal degradation of the solvent must be considered. (See “SOL” location in Figure 1.)

The use of solid sorbents is another method to remove CO₂ from gas streams. Past work has included alkali and alkaline earth metals as the basic component of sorbent structures.⁷ These sorbents could be used in higher temperature absorption processes.⁸ More recent work has included lower temperature sorbents for potential use as a substitute for the Selexol process. The regeneration step is crucial for these types of sorbents and either pressure swing and/or temperature swing can be effectively utilized. Regenerable low temperature sorbents that operate below 300°F are identified as “LTS” in Figure 1 whereas regenerable high temperature sorbents “HTS” operate above an arbitrary 300°F level. The 300°F cutoff temperature was chosen since, in an IGCC application, this temperature typifies the lower end of the warm gas range for obtaining the 2-3% thermal efficiency advantage discussed previously.

Another method is separation of carbon dioxide from fuel gas by the use of a membrane system. Simplicity, flexibility, ability to maintain high CO₂ pressure, and the potential to perform separations at low energy penalties make membranes interesting for CO₂ removal for IGCC applications. In addition to the standard requirement of obtaining high permeability, challenges exist in the development of membranes capable of selectively separating CO₂ from the process gas stream. In addition, the reducing conditions and the presence of water and various minor contaminants necessitate the design of membranes with exceptional chemical and physical stability. (See “MEM” in Figure 1 as a potential location for these membranes.) Development of membranes for the separation of CO₂ must satisfy the requirements for a durable membrane, especially at elevated temperatures.⁹⁻¹¹

The research status of two of the above novel capture technologies that fall within the in-house research area at NETL follow along with implications of the experimental research on technical direction and costs. An overview of these novel techniques is presented.

RESULTS AND DISCUSSION

Membranes for CO₂ Separation

For the membrane technology, the membrane is envisioned to separate CO₂ within the precombustion zone of an IGCC plant. The high pressure of the gasification-based power generation cycle provides an excellent driving force for the membrane, and other inherent advantages of membranes exist, i.e. non-moving parts, etc.¹⁰ If the water-gas-shift reaction within the IGCC scheme is performed to increase the hydrogen production for the gas turbine combustor, the CO₂ concentration, and thus partial pressure, increases substantially and further enhances the driving force across the membrane. Additionally, if the membrane is fabricated to withstand higher temperatures (300-700°F), an additional benefit with respect to maintaining the higher thermal efficiency of the plant (as compared to cold scrubbing of CO₂) is obtained.⁵

The initial venture in developing such membranes involved the modification of an inorganic substrate, a stable and permeable alumina, with organic groups to increase selectivity towards CO₂. A surface diffusion mechanism was desired. The grafting of organosilanes onto the inorganic surface is a well-studied method. Attachment is accomplished when halogen atoms on the silane molecule interact with hydroxyl groups on the inorganic surface, eliminating HCl and forming a covalent attachment. As many as three such interactions can occur per silane molecule, anchoring it to the surface. Since the silane molecule can also contain nearly any organic group, this method provides an extremely flexible tool for surface modification.¹² An attempt was made to develop membranes useful in CO₂ abatement for IGCC using this method. Specifically, the membranes consisted of a rigid frame with an organic being the active membrane layer. CO₂-philic groups on the ends of the organosilanes act to enhance the preferential surface diffusion of the CO₂ across the membrane.

Testing of the siled membranes was conducted in a concentric tube, continuous flow screening unit describe elsewhere.¹³ A pretreatment had been developed and this, combined with a certain silation procedure, allowed pore penetration and development of a silane monolayer capable of significantly affecting membrane performance. However, results indicated that although the permeance of CO₂ was adequate, the selectivity of CO₂ over He (used in place of hydrogen) was low.¹³ Thus, direction of this work shifted to a new membrane design.

One approach to enhancing flux through solution diffusion membranes is the fabrication of those membranes in a liquid rather than solid state. Higher liquid phase diffusivities allow significant improvements in permeability over most solid state counterparts. Supported liquid membranes are prepared by impregnating porous substrates with a liquid transport media. Though performance results have often been encouraging^{14, 15} a major problem has been encountered with respect to long term stability. Evaporation of the liquid transport medium eventually leads to incomplete filling of the substrate pores and membrane failure.¹⁶

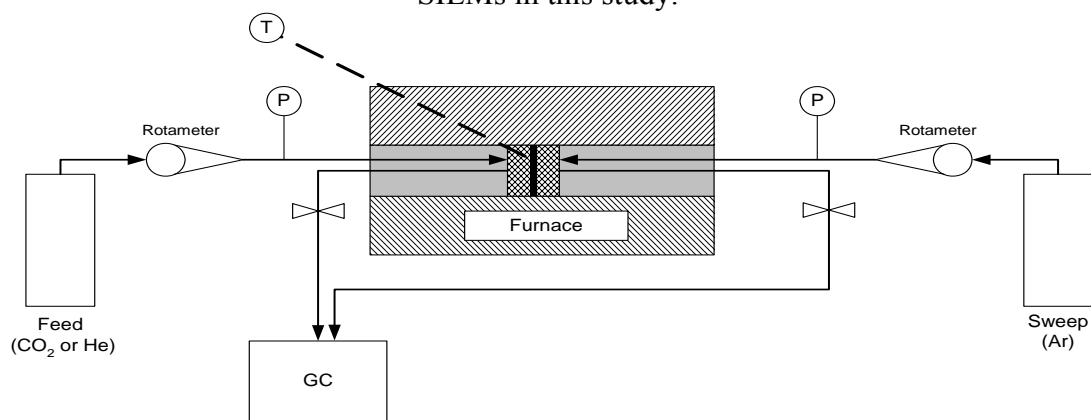
Ionic liquids are a class of salts which are liquid at or slightly above room temperature. The unique nature of the materials leads to a number of interesting properties including negligible vapor pressure. Because the variety of available anions and cations make the number of potential ionic liquids nearly limitless, it is possible to tailor them with high solubility selectivities, particularly for CO₂, over most other gases. Together with these properties, stability of many ionic liquids to temperatures above 200°C has led to examine them as transport media in membranes designed to selectively remove CO₂ from fuel gas.

In a collaborative effort with the University of Notre Dame, supported liquid membranes have been prepared by impregnation of commercial porous polymer films (polysulfone or polyethersulfone-based) with a specific ionic liquid. Because the ionic liquid impacts the glass transition temperature of the resulting membrane, the polysulfone was used in the testing. The ionic liquid, 1-n-hexyl-3-methylimidazolium

bis(trifluoromethanesulfonyl)imide ([hmim][Tf₂N]), was synthesized and characterized at the University of Notre Dame. This ionic liquid was chosen as the ionic liquid for use because it has high CO₂ solubility, excellent thermal stability, and is one of the most well-characterized ionic liquids (serving as the IUPAC standard for physical property measurement validation). It is expected that He will have a very low solubility in this ionic liquid, based on previous work in which H₂ had a solubility in a similar ionic liquid that was below the detection limit of the apparatus¹⁷. The supported ionic liquid membranes or SILMs were made by placing the unmodified substrate into a container and then depositing ionic liquid on top of the membrane with a pipette. Enough ionic liquid was added to completely cover the surface of the substrate, and the membrane was allowed to absorb the ionic liquid for at least eight hours. The SILMs were then removed from the container and excess ionic liquid was removed by blotting with unmodified supports.

Testing was performed in a flow system where the permeate and retentate gas compositions were measured using a HP 5890 gas chromatograph with twin TCD detectors and Alltech Hayesep D 100/120 packed columns. Flows were measured with a digital, bubble flow meter. Temperature was measured by a Type K thermocouple in contact with the surface of the testing cell. Pressure transducers were used to monitor the transmembrane pressure. A schematic of the permeation system is shown in Figure 2.

Figure 2. Schematic of the experimental flow system used to measure the permeability of SILMs in this study.



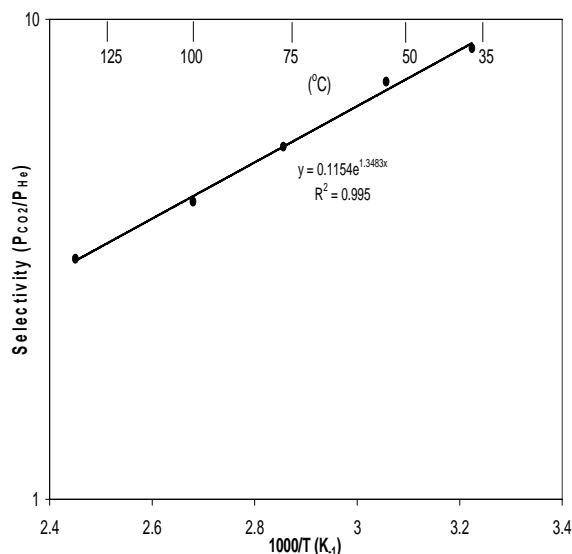
The membrane was placed on the permeate side of a Millipore® filter holder and an unmodified substrate identical to the one used to prepare the membrane was placed against the membrane on the feed side to reduce the stress on the membrane. The feed consisted of approximately 30 ml/min of carbon dioxide (99.99%) or helium (99.999%) while a sweep of 1.0 – 2.0 ml/min of argon (99.999%) was used. The pressure was approximately 108 kPa for the feed and the permeate pressure was less than 102 kPa. After introduction of a feed, the system was allowed at least 4 hours to reach steady state, and data were then recorded for at least 2 hours.

Performance results for [hmim][Tf₂N] supported in a polysulfone substrate are presented in terms of permeability rather than permeance for the purpose of comparison with

information already available in the literature. The permeability is that of the SILM not the ionic liquid. In the temperature range from 37 to 125°C, CO₂ permeability increases from 744 to 1200 barrer. He permeability increases from 86 to 270 barrer over the temperature range of 37 to 100°C. Arrhenius dependencies are observed for both gases. When the membranes are heated to 135°C, a gradual reduction in permeability is observed over the course of 5 hours resulting in values of 155 and 50 barrer for CO₂ and He, respectively. Operation of the membrane at greater temperatures leads to failure.

Selectivity exhibits an Arrhenius dependence with a coefficient of determination of 0.996 over the entire temperature range as it decreases from 8.70 to 3.12 (Figure 3). Perhaps most striking among the performance results is the Arrhenius dependence of selectivity over the entire temperature range despite a substantial reduction in permeability at 135°C. The result would seem to indicate that the change occurring within the membrane limits diffusional pathways, but does not alter the dominant transport mechanism. A phenomenon that is consistent with the observations is the densification of porous polymer films above the glass transition temperature. As the polymer film becomes less rigid, it can more easily move toward its equilibrium dense film state.¹⁸ Ionic liquid is forced from the collapsing pores, and the number of available diffusional pathways for CO₂ within the membrane decreases. This hypothesis is also supported by measurements showing the glass transition temperature of an identical polysulfone film containing [hmim][Tf₂N] to be in a similar temperature range, 133.4 to 141.6°C.

Figure 3. The temperature dependence of [hmim][Tf₂N] SILM selectivity for carbon dioxide over helium is shown between the temperature range of 37 – 125°C.



To date, the SILMs have shown permeabilities and selectivities comparable to or exceeding most membranes known from literature in the selective separation of CO₂ from light gases. For example, at 37°C, the carbon dioxide permeability was 744 barrer with a carbon dioxide/helium selectivity of 8.6. Higher liquid phase permeabilities give the SILMs an advantage over polymer membranes, while the lack of volatility of the ionic liquid allows them to overcome the traditional problem of supported liquid membranes.

The ionic liquid [hmim][Tf₂N] on which this study was based, has a high solubility for CO₂ relative to light gases, but greater solubilities and selectivities should be possible with more tailored ionic liquids.

Stability of the membranes to 125°C approaches the range of interest in the capture of CO₂ within coal gasification plants. It is probable that polymer supports stable to much higher temperatures in the presence of ionic liquids will be identified in the future. The higher temperature of operation combined with excellent characteristics of permeability, solubility, diffusivity, and selectivity of CO₂ will make these SILMs key components in the precombustion separation of CO₂ within IGCC power generation schemes.

Physical Solvents for CO₂ Capture

Conventional processes for acid gas (H₂S and CO₂) removal from coal-based gasification streams include a chemical/physical process using methyl-diethanolamine (MDEA), a physical solvent process using chilled methanol (Rectisol), and a physical process using mixtures of dimethylethers of polyethelenglycol (Selexol). The MDEA process requires high thermal energy for solvent regeneration. The Rectisol process is complex, and refrigeration makes it a very expensive acid gas removal process. The Selexol process can be more expensive than the MDEA process, and the chilling option could increase the process costs. However, as mentioned earlier, in an IGCC application, these physical and chemical processes for acid gas removal require cooling and subsequent reheating of the stream before the gas turbine, which decrease the plant thermal efficiency and thus increase the overall costs. Consequently, there is a need for the development of an alternative process which should be economical and absorb carbon dioxide without significant cooling of the humid gas streams.¹⁹

The objective of the physical solvent research is to investigate the potential use of chemically and physically stable compounds as physical solvents for selective CO₂ capture from post water-gas-shift reaction streams under elevated pressures and temperatures that are representative of gasification conditions. For IGCC context applications, it is envisioned that the high-temperature solvent process for CO₂ capture would ultimately follow the steps of a physical wet-scrubbing solvent process, not chemical absorption. In a physical solvent process (Selexol is an example), the regeneration of the solvent is usually done by a pressure swing step, not thermal swing. Certainly, a thermal swing could be used, but the thermal stability of a solvent that absorbs at an already high temperature (300-700 °F) could become an issue. If a solvent could be developed that could operate with a thermal swing, the CO₂ could, in principle, be released at the pressure of the fuel gas itself, reducing the energy penalty connected with CO₂ compression. This potential benefit would need to be weighed against the energy needed for thermal regeneration, and the temperature stability of the solvent itself.

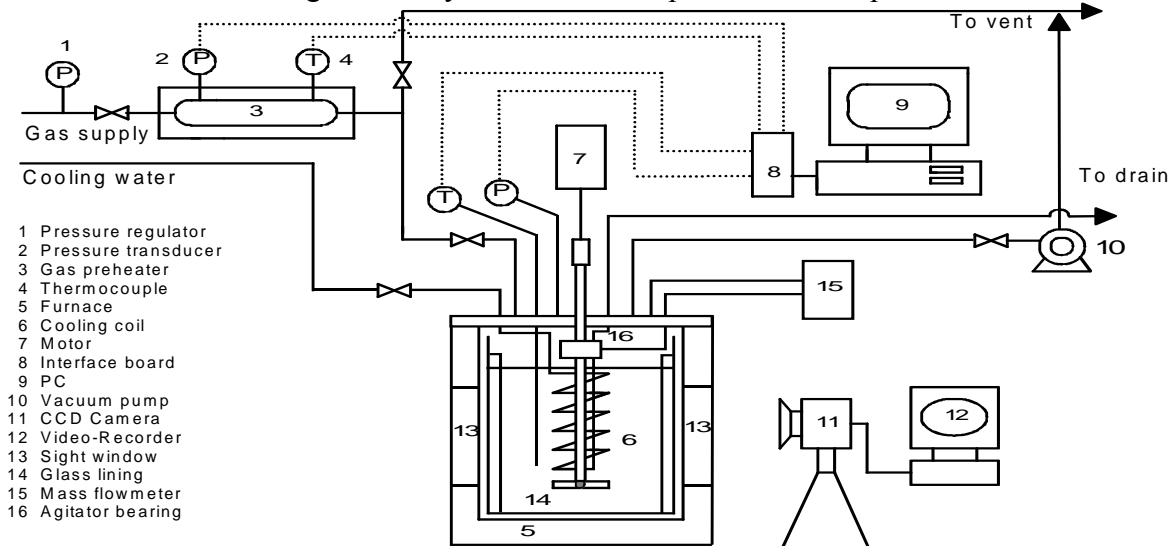
Prior to solvent selection, criteria were defined for an “ideal” physical solvent for CO₂ capture. This definition was based on maximizing CO₂ solubility in accordance with Pearson’s “hard and soft acid-base” principles where the solvent should possess a Pearson “hard base,” permitting a strong affinity to CO₂, a Pearson “hard acid.” From regular solution theory, the solvent should have solubility parameters which are as close

as possible to CO₂. Other solvent characteristics were based on sound engineering principles aimed at maintaining thermal stability to prevent degradation under CO₂ capture process conditions; environmentally benign so as to prevent formation of unwanted byproducts; negligible vapor pressure to prevent or severely minimize gas-stream solvent losses; a low enough viscosity at operating conditions to insure optimum/economical plant performance under CO₂ capture process conditions (e.g., to insure that pumps operate at optimal performance levels); and possession of a high regeneration efficiency. The definition of an “ideal” CO₂ capture solvent was used to facilitate the choice of the first fluorinated candidates but also more rigorously applied to the baseline ionic liquids currently being investigated.

A study was performed with the first family of candidates, perfluorinated compounds (PFCs). A comprehensive literature review¹⁹ revealed that the PFCs have high chemical stability due to the high energy of their C-F bonds. They have high boiling points and low vapor pressures and high molecular weight. They also have negligible dipole moments and very low molecular interactions due to the repulsive tendency of fluorine atoms. These unique properties lead to high gas solubility, low vapor losses, and low forces required for expelling the gas molecules upon decreasing pressure or increasing temperature. Thus, PFCs showed a high potential for selective CO₂ capture from post-shift fuel gas streams at elevated pressures and temperatures. After the literature review for PFCs, an experimental program was devised to obtain the equilibrium gas solubility and the hydrodynamic and mass transfer parameters (gas holdup, Sauter mean bubble diameter, and volumetric mass transfer coefficient) for CO₂ and N₂ in three different PFCs, namely perfluoro-perhydrofluorene (C₁₃F₂₂), perfluoro-perhydrophenanthrene (C₁₄F₂₄), and perfluoro-cyclohexylmethyldecalin (C₁₇F₃₀), known as PP10, PP11, and PP25, respectively. These solvents (Flutec Fluids) were manufactured by F2 Chemicals Ltd., UK.

Testing of these physical solvents occurred in an experimental setup shown in Figure 4 that consisted of a reactor, preheater, vacuum system, and data acquisition system. The reactor is a gas-inducing 4-liter ZipperClave reactor with two sight-windows. The reactor is equipped with four symmetrically located baffles, a cooling coil, a specially designed heating jacket, a thermowell, and a six flat-blades impeller with hollow shaft. Holes located at the upper and lower end of the shaft allow the reactor to operate in a gas-inducing mode. The transient physical gas absorption technique was employed to measure the volumetric mass transfer coefficient, and the gas solubility was determined when the thermodynamic equilibrium was reached in the reactor. The expanded liquid height method and a photographic method were used to obtain the gas holdup and the Sauter mean bubble diameter, respectively. The experiments were statistically designed for the reactor operating in a gas-inducing mode. A wide range of operating conditions for the central composite statistical design matrix was investigated: pressures (6 - 30 bar), temperatures (27 – 227°C), mixing speeds (10 - 20 Hz), and liquid heights (0.14 - 0.22 m).

Figure 4. Physical Solvent Experimental Setup

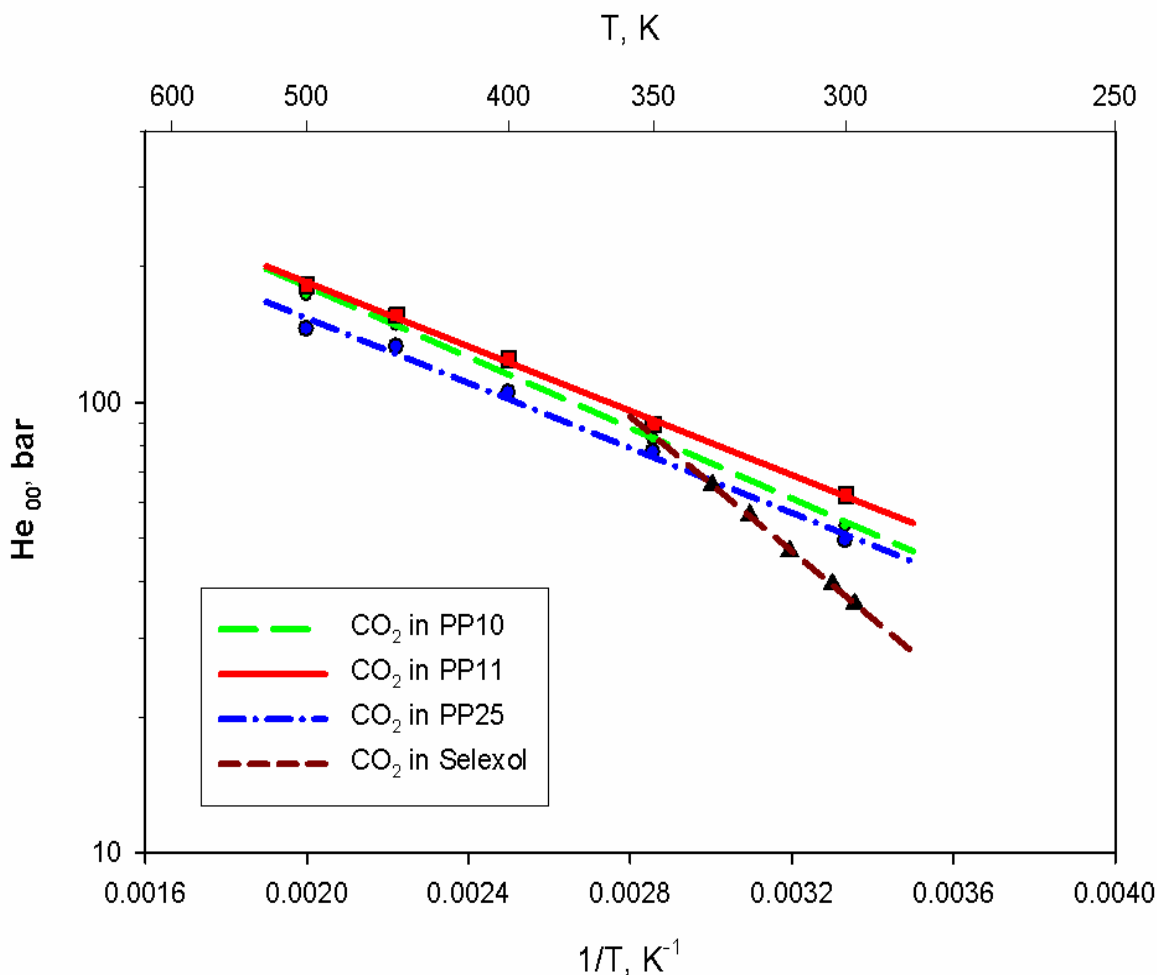


The equilibrium solubilities of CO₂ and N₂ in PP10, PP11, and PP25, expressed in mole fraction, appeared to increase with pressure at constant temperatures, where the values at infinite dilution were found to follow Henry's law. Figure 5 relates the scrubbing temperature with the Henry's constants for the three PFCs and compares such results to Selexol data obtained from the literature.²⁰ The solubilities for both gases were greater in PP25 than in the other two PFCs. Under similar operating conditions, the solubility of CO₂ in the three PFCs appeared to be about 7 times that of N₂, which was attributed to the closeness of the solubility parameter of CO₂ to those of the PFCs when compared with that of N₂. The results also showed that CO₂ is more soluble in the Selexol solvent than in the PFCs only at low temperatures ($\leq 60^\circ\text{C}$). The Selexol process, however, is customarily operated at temperatures of about 39°C , indicating that the Selexol solvent would not be effective at higher temperatures typifying those at the exit of the gasifier system in a warm gas cleanup application. This study revealed the thermal and chemical stability and the ability of the PFCs to selectively absorb CO₂ at temperatures up to 227°C and pressures as high as 30 bar.²¹

The volumetric mass transfer coefficients ($k_L a$) of CO₂ and N₂ in PP10, PP11, and PP25, increased with increasing mixing speed, pressure, and temperature due to the increase of the gas-liquid interfacial area (a) and the liquid-side mass transfer coefficient (k_L). The increase of the gas-liquid interfacial area with these operating variables was attributed to the increase of the gas holdup and the decrease of the Sauter mean bubble diameters. The volumetric mass transfer coefficients of CO₂ and N₂ in the three PFCs, however, decreased with increasing liquid height above the impeller due to the decrease of the gas holdup and increase of the Sauter mean bubble diameter, which led to the decrease of the gas-liquid interfacial area. The volumetric mass transfer coefficients of CO₂ in the three PFCs were found to be always smaller than those of N₂ due to the smaller gas-liquid interfacial areas (smaller gas holdup and larger Sauter mean bubble diameter) of CO₂ when compared with those of N₂ under similar operating conditions. The volumetric

mass transfer coefficients for CO₂ and N₂ in PP25 were smaller than those in PP11, and both were smaller than those in PP10, indicating that the volumetric mass transfer coefficients decrease with increasing viscosity of the PFC. Also, under the operating conditions investigated, the gas-liquid interfacial areas of CO₂ and N₂ in the three PFCs appeared to control the behavior of the volumetric mass transfer coefficients in the gas-inducing reactor.

Figure 5. Solubilities of CO₂ in Fluorinated Solvents and Selexol



Testing with mixtures of gases to simulate representative fuel gas mixtures has been completed and the data summarized. One aspect of this work with PFCs where improvement could be made was in the vapor pressure of these solvents. With this in mind, future work will include an in-depth investigation of ionic liquids, which have negligible vapor pressure, used at elevated temperatures as a physical solvent for CO₂ removal. Provided the ionic liquid(s) meet the established definition of an “ideal” physical solvent, a parametric study of ionic liquid performance on humid multi-component fuel gas mixtures (those containing CO₂, CO, H₂S, H₂O, and H₂) will be conducted. Specific experiments will involve utilization of the experimental setup at the University of Pittsburgh to measure CO₂ solubility and hydrodynamic/mass transfer

parameters for CO₂ and other fuel gas constituents in ionic liquids.

SUMMARY

Various techniques for the capture/separation of CO₂ from power generation point sources are being investigated within the in-house research effort at NETL. The novel technologies include a wet scrubbing physical solvent process to remove CO₂ from fuel gas of an IGCC system at elevated temperature and pressure and membranes separating CO₂ from fuel gas produced by coal gasification. All these techniques have the potential for significant cost savings and plant thermal efficiency improvements as compared to more conventional CO₂ capture techniques. Future system analyses will attempt to integrate these methods into various power generation schemes with the intent of further optimizing the process with respect to plant efficiency.

DISCLAIMER

Reference in this report to any specific commercial process, product, or service is to facilitate understanding and does not necessarily imply its endorsement or favoring by the United States Department of Energy.

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Keywords

Carbon dioxide, Carbon capture and separation