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Atmospheric Carbon Capture

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Abstract

Human-generated carbon emissions are the leading cause of climate change. There is a global commitment to reduce carbon emissions, in an effort to limit climate change effects. Many climate change solutions involve the mitigation of carbon emissions, mitigation alone is not enough.

Carbon Dioxide (CO_2) can live in the atmosphere for over 100 years. If we were to switch to 100% renewable energies, we would still damage the planet with the stagnant CO_2 from the 1920's. To combat climate change, we need a solution that can remove this carbon. One such solution is carbon capture, one of our best weapons in tackling climate change. The replacement of fossil fuel energy will not happen in the next few years, maybe not even for decades. Therefore, carbon capture is a promising 'bridge' technology, while we reach a sustainable level of green energy production.

Carbon capture technology development has largely focused on singular processes (typically absorption, adsorption and membranes) capturing carbon from industrial exhaust systems. Recently, studies have delved into the idea of combining two or more of these technologies into one more efficient system and employing them in the industrial exhaust systems but also capturing carbon from the atmosphere. This project aims to develop a hybrid membrane and adsorption unit to capture carbon directly from the atmosphere. The aim is to provide the technology necessary to remove carbon from the atmosphere more effectively and cheaper than earlier technologies.

Keywords: carbon capture, climate change, environmental engineering, CO_2.

What is Carbon Capture?

We have heard of the dooms and glooms of climate change/global warming. Droughts, floods and forest fires have become all too popular. Climate change is not a new topic, it has been researched for over 100 years, and in the 21st century, its cause is well known to everybody. Global warming comes from the greenhouse effect. The greenhouse effect being the Infra-red

Radiation (IR) from the sun becoming trapped in our atmosphere. Carbon dioxide (CO_2) and other Green House Gases (GHG) absorb this IR, leading to the heating of our planet, our environmental crises. These GHG emissions come from our lifestyles. Our current economy is based on the combustion of fossil fuels which produce GHG emissions. We know of workable (pricy) solutions to limit these emissions, including driving electric vehicles, removing meat from diets, renewable energy, and the four R's (reducing, reusing, repairing, and recycling). These options could positively impact our environment, but they are not enough. These solutions will not improve our crisis but prevent it from worsening. Our issue is GHGs in the atmosphere which can last for 100 years. Implementing these solutions to their greatest ability will still leave carbon emissions from as far back as 1922 linger in our atmosphere. To combat climate change, we need solutions that can turn the world carbon negative (net uptake of carbon) not just carbon neutral.

One valuable solution to climate change that has this ability is Carbon Capture, Storage and Utilization (CCSU). CCSU, as a topic, does exactly what it says. The focus of the topic is to develop methods and technologies to catch and purify human emitted carbon emissions and store or use them in other industries. The traditional focus of carbon capture systems would be for use on the exhaust of industrial GHG emitters such as a coal power plant. These capture systems would allow for the burning of fossil fuels without the emitting CO_2. Developments in CCSU includes Direct Air Capture (DAC), the capture of carbon directly from the atmosphere. DAC is one of the most important solutions in our battle against climate change. It is the only conceived solution with the ability to reverse the damage we caused. DAC is a vital bridge technology for the short run. It removes carbon from the atmosphere and 'stalls' for us to develop other long-term solutions, such as sustainable biofuels.

Carbon Capture Technologies

Carbon capture in principle sounds simple — just trap air, filter the carbon out and release the clean air — but it is a complex topic with a variety of interesting solutions. Most carbon capture research has focused on capturing carbon from industrial combustion systems, such as gas or coal power stations. A combustion process is a chemical reaction with an energy release. Fossil fuels are a type of chemical known as hydrocarbons, compounds that contain hydrogen and carbon molecules. The basic combustion reaction for fossil fuels comprises the hydrocarbon combusting with oxygen to produce CO_2 and water. A typical industrial process would combust the fossil fuel with air. Air is nitrogen dense, so combusting fuels in air creates reactions involving the nitrogen and thus produces nitrogen-based compounds in the exhaust. With this in mind, industrial capture systems have focused on two main categories of technologies: pre-combustion and post-combustion capture.

Pre-combustion technologies focus on altering the inputs of a combustion system to leave the exhaust gases to be almost pure CO_2. Supplying pure oxygen to the combustion system instead of air is one such alteration.

Post combustion capture focuses on removing CO_2 from the exhaust of a combustion system before it enters the atmosphere, separating the CO_2 from the other compounds.

These technologies are vital, allowing us to produce energy from fossil fuels in a more sustainable manner. However, we still need to account for the excess CO_2 laying stagnant in our atmosphere, and that's where DAC proves its strength.

As a concept, DAC is superior to pre and post combustion systems. It aims to remove CO_2 from our atmosphere. DAC has similarities to post-combustion capture systems. They both remove CO_2 from other gases (unlike precombustion) and thus, post-combustion concepts are transferable to DAC. A distinction between DAC and post-combustion is the concentration levels of CO_2. Concentrations vary depending on the scenario, consider the air quality in the countryside compared to that within a city at rush hour; similarly, consider lighting a natural gas stove and burning coal in the fire, the fumes are different. Atmospheric CO_2 concentrations are at about 0.041% and exhaust fumes can be 10-15%. In statistical terms, the odds are against DAC. For every molecule of CO_2 in air, there's over 2,400 molecules of other chemicals. An ideal solution could capture carbon in all scenarios, but the complexities of chemistry make this is difficult to achieve. So, the most important question now is what can we do to pluck the CO_2 molecules out? The below section describes three popular technologies, including the two technologies used in this project.

Absorption

The most established carbon capture technology is a**b**sorption (liquid or gas 'taking in' another liquid or gas), not to be confused with a**d**sorption (gas or liquid sticking to a solid). Carbon capture absorption processes use liquids called absorbents. These absorbents work in a process comprising two columns, an absorber and a stripper. The absorbents spray down through the absorber column like raindrops and the gas passes upwards. The absorbents have a chemical attractive force that pulls the CO_2 towards it and absorbs the CO_2 into the raindrops. This leaves the absorbent liquid full of CO_2 where it then goes to the heated stripper. The heat releases the CO_2 from the absorbent. The CO_2 goes to storage and the absorbent recycles back to the absorber. A company, Carbon Engineering, has a pilot scale absorption system. They demonstrated the energy requirement of the capture system could emit approximately 500Kg of CO_2 to capture a 1,000Kg of CO_2 (this depends on the energy source, biogas would reduce the emissions).

Adsorption

Adsorption-based technologies focus on using solid adsorbents to capture CO_2. Here, the CO_2 sticks to the outside surface of the adsorbent. Figure 1 below portrays an adsorption system known as Pressure Swing Adsorption (PSA). In this system, gas fills in from the bottom of one column. The pressure in the column rises. This pressure increase makes the CO_2 stick to the adsorbents and the other gases (non-CO_2 gases) escape through the top. The bottom valve of

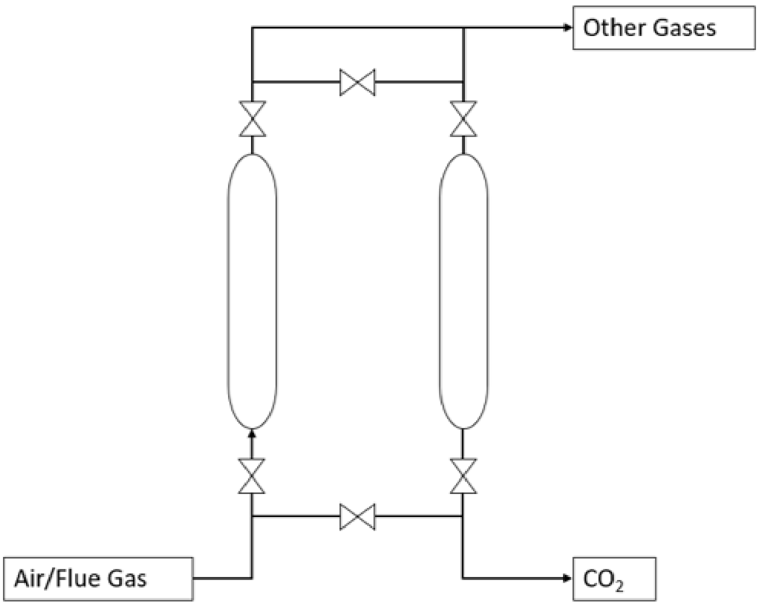

Figure 1 PSA System Diagram. Source: Author.

the column is then opened, dropping the column pressure and, as it does, the CO_2 jumps off the adsorbent and flows out the bottom valve. The columns work on opposite cycles, when one column is filling, the other is emptying. Like with absorbents, adsorbents have chemical forces which attract the CO_2 to them, but they also use thermodynamic principles to adsorb the CO_2. The pressure increasing in the system drives more CO_2 to stick to the adsorbent and the drop in pressure makes them unstuck from the solid. This thermodynamic phenomenon is known as Henry's Law. The process here describes a Pressure Swing Adsorption (PSA) system, a temperature variation of the process exists, Temperature Swing Adsorption (TSA), where the system uses temperatures to load and unload the adsorbents with CO_2. The biggest challenge of a PSA system is getting the filling and emptying times of the columns to equal, creating a constant CO_2 flow out of the system.

Membranes

Membranes are another technology used in carbon capture. Membranes come in a variety of forms and separate gas/air flow into two streams: the permeate (the part that travels through the membrane) and the retentate (the part that does not travel through the membrane). They can be porous or non-porous. Porous meaning the membranes have small passages (holes) in which molecules pass through, non-porous membranes use chemical reactions to 'pass' the CO_2 molecules through the membrane. Membranes have two basic flow patterns: cross flow and dead-end flow. Cross flow is where the feed (flow inlet) flows parallel to the membrane, the CO_2 flows through the membrane, and the other gases flow over the membrane. Dead-end flow is where the membrane is in line with the feed and the CO_2 flows through the membrane. Figure 2 below exhibits a visual representation of these flow patterns.

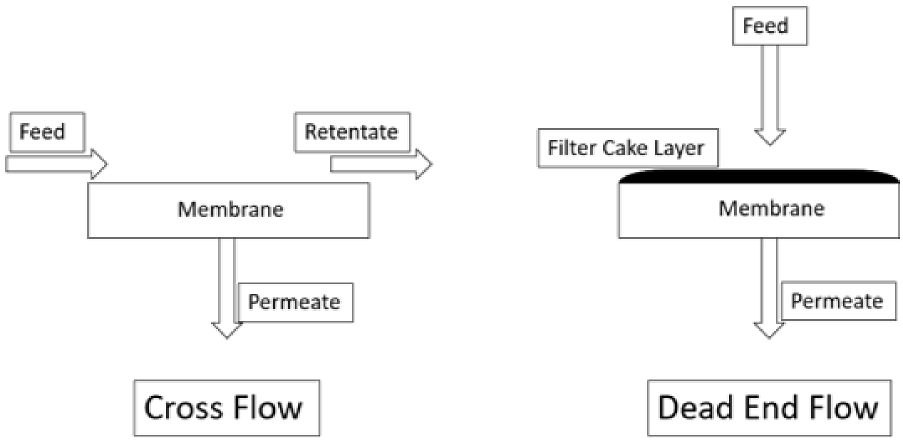

Figure 2 Membrane Orientations. Source: Author.

Hybrid Technologies

The popularity of hybrid capture technology is increasing. Hybrid systems merge two different capture technologies into a single process. They could use a membrane and absorber, or any other combination of carbon capture technologies. The key to hybrid technologies is to consider the performance they have compared to single technologies in terms of energy usage, complexity, and capture effectiveness. Hybrid technologies are more complex than singular technologies due to there being two separate systems and a control system between them. For this reason, the hybrid system needs to be superior in performance compared to singular technologies to justify the added complexity of the system. A challenge with hybrid systems is that they require researchers to develop a deep understanding of two separate processes.

Conclusions

The focus of my PhD is to develop a hybrid CO_2 capture system using membrane and adsorption technologies. The goal of the project is to develop a cost effective (under \$100 per 1000kg of CO_2 captured) and energy efficient DAC capture system.

Recent studies have focused on the enhancements of adsorbents and membranes by adding amine (group of chemical compounds) compounds to them. Results from these studies have shown that amine modified adsorbents and membranes improved the capture performance. Synthetically produced amines dominate the field so natural, abundant, and inexpensive sources of amines are desirable for capture systems. One such source of amines identified is chitosan, produced from crustaceans' shells. This project aims to make use of the amines within chitosan to improve the capture performance of silica, a common adsorbent/membrane material. Silica has shown good capture performance, and it's among the most abundant materials on Earth.

This project will involve the creation of materials in the lab comprising the silica and the chitosan. The project will then test said materials in a hybrid PSA membrane system. The material production can be seen as the chemical part of being a chemical engineer. It will involve the use of chemistry to create the materials to be used in the capture system. The aim of the final material will be a silica bulk coated in a chitosan solution to gain the benefit of the chitosan amines and the bulk properties of silica.

The process setup is the next step, the engineering part of being a chemical engineer. This involves the use of engineering principles to improve the performance of the capture system and test the produced materials. The experiment set up here will involve sticking a hose out the lab window attached to a vacuum pump to hoover air through the lab equipment and hopefully separate CO_2 from everything else. A big challenge of the project will be the equipment orientation (membrane before PSA or vice versa). Not every condition will favour the same orientation, so different scenarios may require alternative configurations. The system will undergo extensive testing (testing at different orientations, testing with different quantities of materials, testing with different operating conditions, etc.) to find the best configuration for as many scenarios as possible. The results from these tests will aid in producing process controls to optimise capture performance based on operating conditions.

The third and most difficult part of the project is the software process simulation. This stage of the project will use results from the material production and process tests to create scale-up simulations of the process. These simulations will use complex chemical relations and extremely complicated maths to predict the capture performance on a large scale. This section of the project will show the industrial costs and performance of the developed system.

This project brings innovation in both novel material knowledge and hybrid process knowledge. A chitosan silica hybrid material is not common in adsorbents/membranes, and PSA membrane systems are not popular either. So, this project will advance and hopefully improve both the chemical and the engineering aspect of carbon capture.

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