Design and Modeling of CO_2 Capture Units

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ABSTRACT

In recent years, there has been an increase in the CO_2 pollution awareness campaign across mass media. This has led the US government to impose more and more CO_2 emission regulation rules on manufacturers. Some of these manufacturers like the coal plant industry, are forced to install CO_2 emission capture units in their plants. Two mechanical engineering students from West Virginia Institute of Technology made up the team that accomplished work on understanding different processes used by the manufacturing industry to deal with government CO_2 regulations laws. Focus was put on a cycles used in a method that involved using the chemical properties of liquid amine which resulted in the building of a model in a software called "Aspen Plus."

BACKGROUND

Information about CO_2 emission and its effects on the planet are often neglected by public media and the general public. In recent years, a number of solutions have been exercised to minimize the effects of CO_2 pollution on the planet. Each year, millions of tons of CO_2 are emitted into the atmosphere through different man-made pollutants. The accumulation of this product in nature has a negative effect on the health of living things. According to the Canadian Center for Occupational Health and Safety, carbon dioxide in small quantities in a room or in the environment is not necessarily harmful. However, a large amount can cause suffocation after displacing oxygen in the air [1]. The problem with CO_2 capture units is that they are not as popular as they should be. Small capture units that are produced for home use and house air purification have not been well advertised. Therefore, the general public does not know of their importance. While a few governments and international organizations work to encourage their use in the industrial world, others are reluctant to invest in them. This is partially because the installation of such units is expensive and do not necessarily help companies in their production [2]. To illustrate, NRG Energy, a large power provider, is spending $1 billion to reduce its CO_2 released from Fort Bend County power plan, in Texas. Arun Banskota, the president and CEO said "this will basically be extremely clean emission from a coal plant – which we've never seen – at low coal prices." When it comes to CO_2, this is so far the largest project in the world [3].

In order for humans to continue thriving on the Earth for many years to come, our generation will have to understand the environment and its problems. The next step will be to change our lifestyle to meet the resources available. The goal of this project is to first study known methods of CO_2 capture and model a capture units.

Information on the subject of CO_2 capture was researched and recorded to gain a better understanding of how CO_2 capture is done and why it is applicable. This was performed to demonstrate multiple methods of capture. Finally, a unit was modeled with the students' contribution in design using Aspen Plus, a process modeling software. This article will not only touch on the feasibility, design, and installation of capture unit options available, but also provides a new model that can be implemented in the real world.

THE ROAD TO CCS

CCS, or Carbon Capture and Storage, is a concept that requires developing technologies to capture CO_2 from major manufacturing industrial plants to be carefully stored. According to the CCSA, (Carbon Capture & Storage Association), immediately adopting such a method will reduce global CO_2 emissions by approximately 19% by the year 2050 [4]. The captured CO_2 will then be stored underground. Like illustrated in Figure 1 from the IEA web page, many other technologies are available to reduce GHG (greenhouse gas) emissions, but CCS is the only technology available that will largely influence GHG emissions, according to the International Energy Agency (IEA) [5]. This shows that it is important for industries to understand the concept in order to implement it in a safe and economical manner.

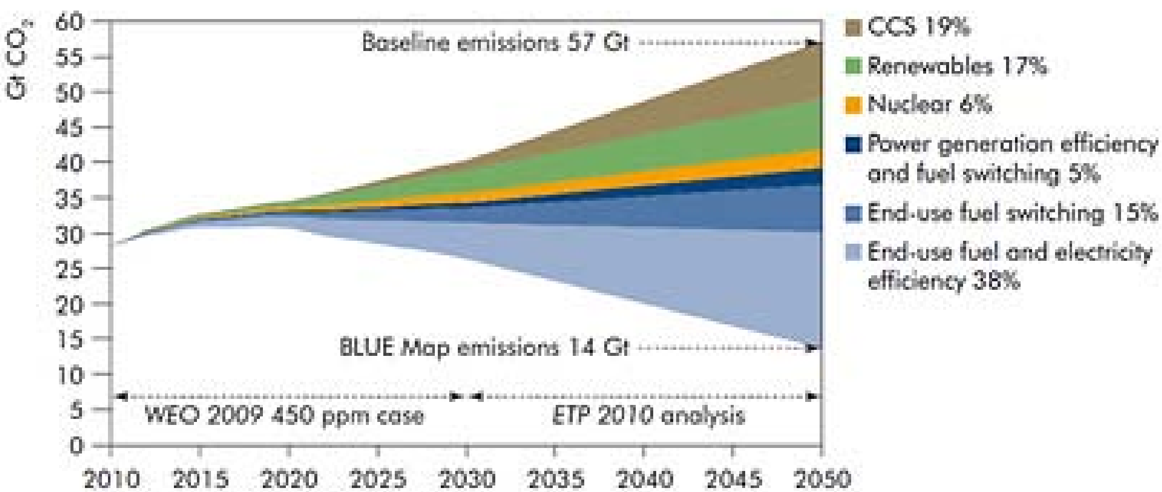

Figure 1: IEA's predictions for energy technologies to reduce GHG emissions [4].

Addressing the challenge of climate change and meeting the need for affordable energy can be addressed by CCS carbon capture and storage. CCS is not a replacement for taking actions to increase energy efficiency or maximizing the use of renewable energy. CCS's separation elements have been proven and deployed. According to the World Coal Organization, approximately one million tons of CO_2 have been stored each year since 1996 [3]. Failure to adopt CCS will seriously hamper international efforts. The Intergovernmental Panel on Climate

Change (IPCC) concluded that CCS should contribute 55% to greenhouse gas mitigation soon or consequences could be dire [6].

HOW CO_2 IS GENERALLYCAPTURED

There are three main methods for CO_2 capture that have been used in the past sixty years, but they have yet to be widely implemented in the coal power industry. The three methods include the pre-combustion method, which allows a coal power plant to transform the coal into a clean usable gas by removing the CO_2 in the gas before combustion. The second method is the post-combustion method, which involves scrubbing the plan's exhaust system with chemicals to collect the CO_2. The third method requires the burning of coal using a high concentration of pure oxygen, yielding approximately pure CO_2 to be collected. All three methods are further explained in the next paragraphs.

Pre-combustion CO_2 capture uses a process called "gasification" for solid fuels such as coal. So far, gasification is the cleanest known way to produce energy from coal, yet only a handful of plants around the world use this method to produce power [7]. In this process, the coal is crushed and made into slurry. The coal slurry is then essentially preheated to a gaseous state. After pre-heating, the yielded synthesis gas (syngas) is mostly H_2 and CO, leaving other impurities to be separated out (CO_2 and Sulfur). The syngas is passed through a scrubber unit, which will pick up the CO_2 and Sulfur, producing a purified syngas. The purified syngas can then be used for power generation, while the filtered out CO_2 and Sulfur can be transported away for sequestering. This method has many environmental benefits including: lowered emission levels, less solid waste production, and less water consumption [7].

Post-Combustion CO_2 capture functions much like any other power plant, but with an added scrubber unit to process the exhaust gasses through. This is the easiest method available to retro-fit many existing fuel burning power production facilities. This process starts after the power generation cycle of a coal plant, where the exhaust is then put through a scrubber unit containing an amine solution, which will capture the CO_2. The CO_2 rich amine solution is then put through a stripper unit which removes and contains the CO_2 so it can be transported offsite and stored. Here, the amine solution can be put back into the cycle for re-use. This process does consume more energy and decreases efficiency by 20 to 30% on average, but benefits the environment. This method seems to be the most viable method for existing power generation plants to incorporate a CO_2 capture and storage method [8]. Figure 2 shows the widely used second method. Here, the exhaust product is separated using a two-step process to obtain CO_2, the liquid solvent, and waste gas [9].

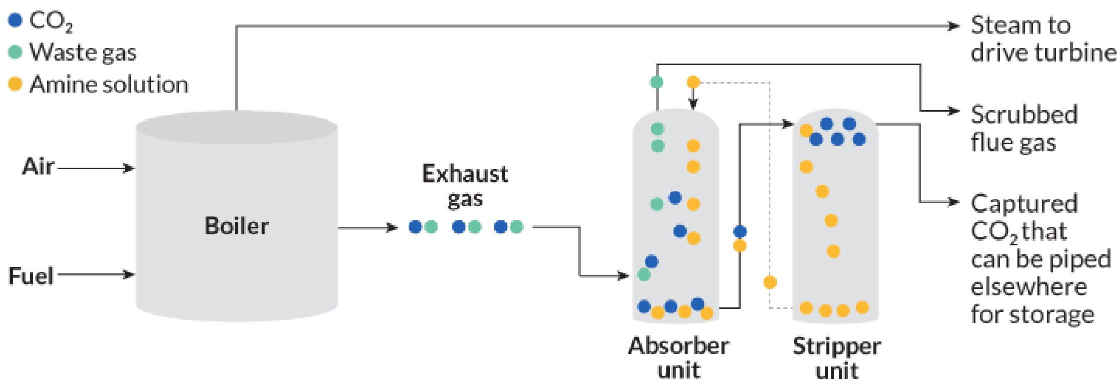

Figure 2: Amine solution absorbing $C0_2$ from the exhaust process [9].

Oxyfuel-Combustion starts with Oxygen being separated from air so that the required concentration can be met. The fuel is then combusted in the Oxygen, which is diluted with flue-gas rather than air to control concentrations. The Nitrogen-free environment then results in final flue-gas that primarily consists of H_2O and CO_2. This allows for an easy separation process of the CO_2 in a scrubber unit, then transportation, and finally storage of the CO_2. This method is essentially a highly refined version of post-combustion CO_2 capture, in being so that it also requires more equipment and more capital investment [10]. Figure 3 shows an example of an oxy-fuel combustion system, depicting a steam turbine generator, a boiler, a solid removal chamber, a desulphurization chamber, a CO_2 purification unit, a CO_2 compressor, and an air separation unit.

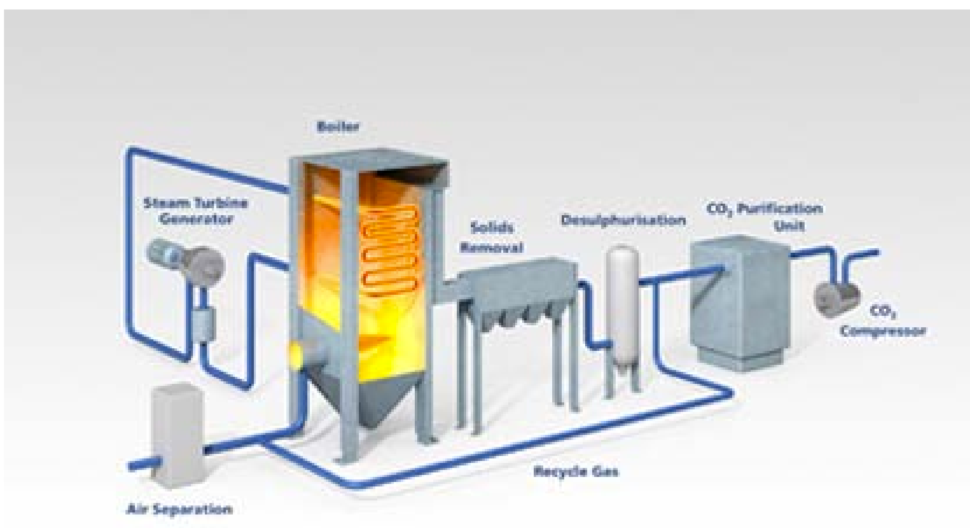

Figure 3: Costain's example of an oxy-fuel system [10].

Many current facilities could be retro-fitted to use these capture methods, but for new facilities, all of the options that capture CO_2 for power generation have higher capital and operational costs, as well as lower efficiencies than conventional power plant. Around 10-40% more energy is required with CCS in place, mostly to separate and compress the carbon dioxide.Transportation can then be done through pipeline for small distances, or super-compressed into a liquid and transported by highway or overseas as it is largely inert [3].

PROPOSED DESIGN

For this project, a post combustion process was selected. The reason for this decision is because this method is the most commonly used method in the coal industry. To continue, the state of West Virginia is well known for its coal industry; therefore it would be more relevant to use a process that is relatable to this immediate environment in order to better convey this article.

Observing and studying CO_2 capture units from different actors in the coal industry revealed certain components that are important to include in order to have a functioning system. A working design should include: a large particle collector for debris at exit of the plant's exhaust pipe (like fly ash), pumps to induce circulation in the system, modified striper columns to host the chemical reactions, a boiler for heat generation, a cooler to cool the product, a condenser to collect and compress the resulting product (CO_2), and finally a storage unit, where the captured CO_2 will be housed before transportation to a permanent storage site.

The chemical looping combustion (CLC) process presented in Figure 4 is the original flow chart explaining the functionality of the modeled process. This design was not a working design for many reasons. First, amine should be used instead of liquid ammonia, which is not very common in the industry. Also, two absorber columns were need instead of one. The second column was needed to reheat the solution of CO_2 and amine in order to separate them. To continue, the segregation column was not needed since the first column scrubs gases and releases them in the atmosphere directly. Finally, a cooler was needed to cool down the amine leaving the striper column to be reused in the scrubber. Figure 5 shows the accepted modifications for Aspen Plus system modeling.

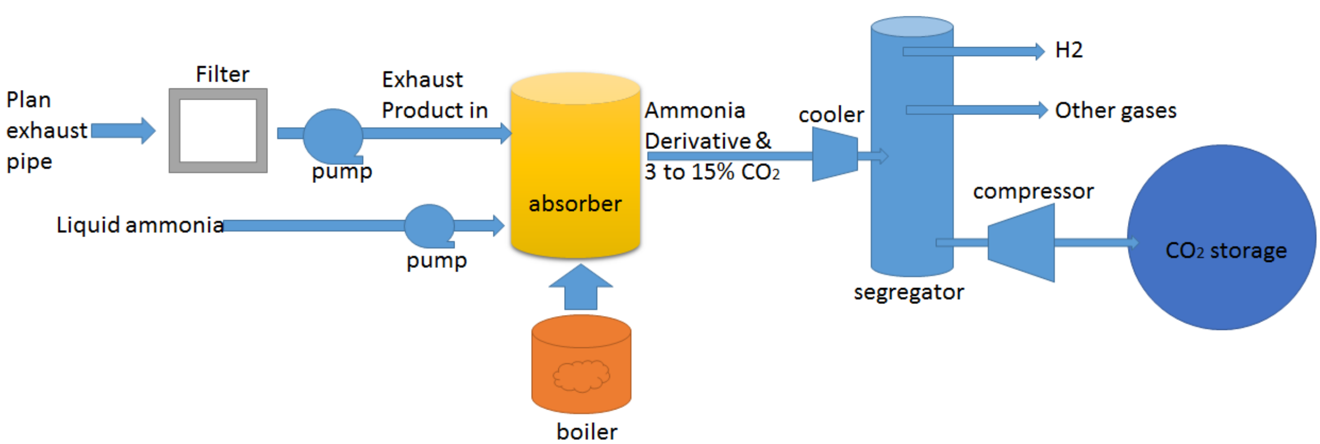

Figure 4: First proposed design for CO_2 capture unit.

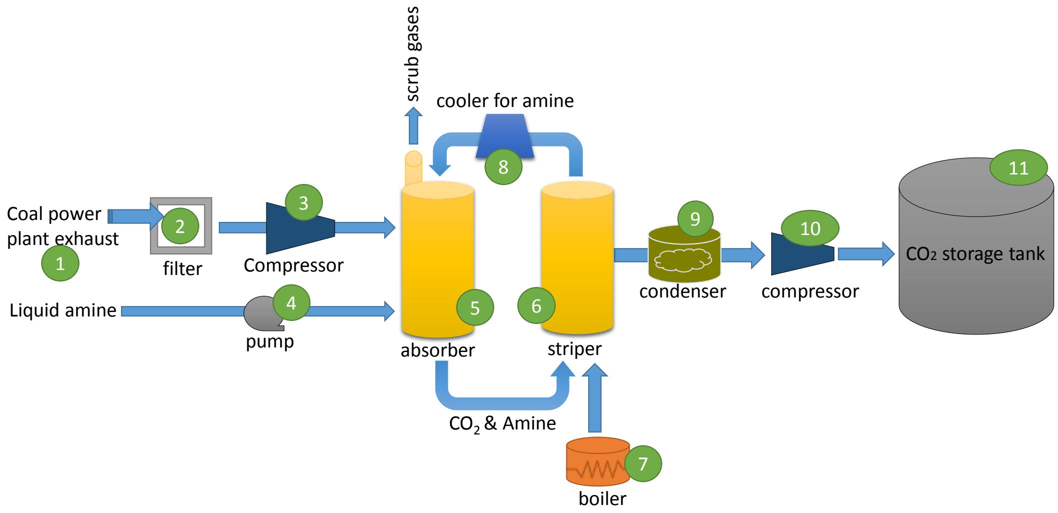

Figure 5: Complete process design of the CO_2 capture unit

As the amine absorption of carbon dioxide can be a difficult process to understand, here it will be explained plainly. Monoethanol amine (C_2H_7NO) or MEA, is an amine typically combined in a lean, aqueous solution with water (H_2O) to form an absorber material for carbon dioxide (CO_2). To start with, there is unit after the combustion process that could be in any CO_2 emitting process called an absorber unit. In this unit, the CO_2 is bubbled up through the Aqueous MEA solution where it combines with (is absorbed by) the MEA, forming a rich solution and cleaner air; this process is considered to be "exothermic". The cleaner air is then released through a port at or near the top of the absorber unit, while the rich solution is pumped to the next phase in the process. After combining the MEA and CO_2, they become MEAH+ and MEACOO-, which are then pumped into the next unit (see Figure 5). The next unit in our process is called Regenerator, or, "Stripper unit". It is in this unit that the CO_2 is separated from the MEA so it can be reused and the CO_2 can be contained, transported, and sequestered. In the stripper unit, the rich solution is heated to separate the MEA from the CO_2; this is considered "endothermic", making it the reverse of the combining reaction by separating it and releasing the bonding between the CO_2 and MEA solution. The MEA solution is then cooled and then balanced with H_2O so that it can be recycled and used in the absorber unit again. Meanwhile, the CO_2 is removed and sent to a condenser to be readied for transport [11]. Figure 6 illustrates this process.

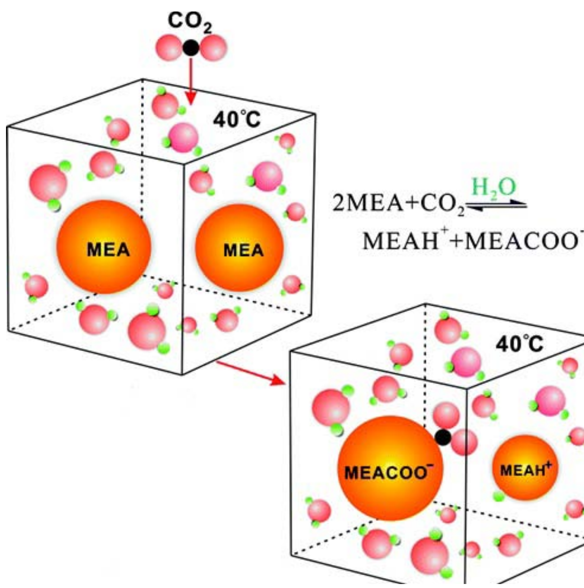

Figure 6: CO_2 capture mechanisms in aqueous mono-ethanol amine [12]

The proposed design for the CO_2 capture unit can be divided into 11 main segments, each describing a specific part in the separation process. Each part of the process is represented by a corresponding letter (1 to 11) in Figure 5:

1 – Part one has the flue gases coming out of the exhaust system of a typical coal plant. These gases include: water, methyl di-ethanol amine, oxygen, nitrogen, carbon dioxide, methane and carbon monoxide. So far, nothing has been processed yet.

2 – The filter will then sieve out the large particles that may remain, in order to avoid clogging the chemical system.

3 – The compressor will then compress what is left to 10 atm, making the process more efficient while regulating the flow to the first column. Taking the mixture from a low to high pressure is essential in the process. Note that this is an "isentropic process".

4 – While the gas mixture is making its way to the first column, a solution of 30% liquid amine and 70%water is sent to the absorber to be mixed with the gas.

5 –In the first column, the absorber will pick up the compressed gases as well as the amine solution. The reaction with amine releasing scrub gases to the atmosphere. Amine is used because it will mainly capture CO_2 while leaving all the other gases free. Therefore, water vapor, methyl di-ethanol amine, oxygen, nitrogen, methane, and carbon monoxide are released in the atmosphere. The resulting capture CO_2+ amine solution is then moved to the second column to be processed.

6 –The next column is the striper. Its job is to use heat provided by the water boiler to separate the $CO_2$from the amine solution, sending the CO_2 to a condenser and the amine to be recycled.

7 –The boiler will provide heat under the form of superheated water vapor at 250 degrees Celsius. The heat is then used in the striper since heated amine will released captured heavy gases like CO_2.

8 –The amine coming out of the striper is too hot to be reused in step 5 of the process. A cooler will therefore be used to cool the amine back to 20 degree Celsius. The amine will then reenter the absorber and be recycled back in the process.

9 – The resulting gas leaving the striper will be composed of approximately 97% CO_2, 1% lost amine and 2% water. The gas will then be condensed and sent to a compressor.

10 – The final product will require an extremely large amount of space in the form it is in at this stage. The compressor is therefore used to compress the CO_2 for storage.

11 –A large storage tank is used to store the captured CO_2.

CONCLUSION

Designing this concept in Aspen Plus was an interesting learning experience. We were able to shave the design the way we had it on the concept, like shown in figure 7. Despite the fact that the team worked on debugging the design for days and with the help of two faculty members of the chemistry department, the design did not work. All the error messages were addressed, except for the two that involved setting up the number of phases in the absorber and the striper. Both were manipulated rigorously to obtain presentable results, but did not yield a final answer.

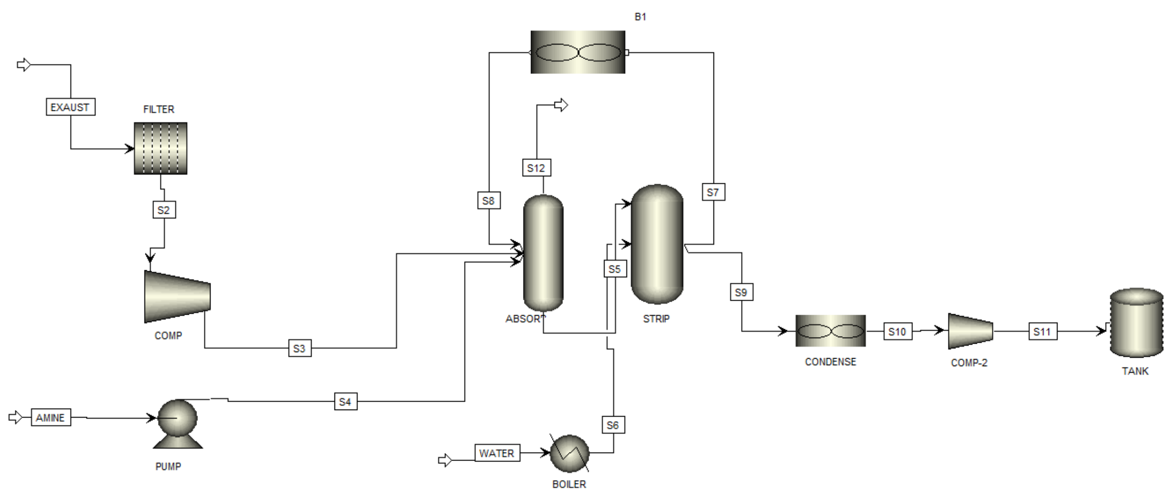

Figure 7: Aspen Plus complete process design of the co2 capture unite

The team believes the project would have been a success if the striper and the absorber did not cause so many problems that became inconclusive. More experience in the field would have been beneficial for the students. Some advanced training in the software could have helped. This was a great learning experience for the students involved.

ACKNOWLEDGEMENT

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