Design of a CO_2 Direct Air Capture System for Methanol Production

Analysis of the Shutdown of the Petra Nova Carbon Capture and Storage System

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By
Zexian He

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Technical Team Members: Alexandra Cresci, Nick Hoessle, Cameron Williams

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS

Benjamin Laugelli, Department of Engineering and Society

Eric Anderson, Department of Chemical Engineering

Introduction

On April 22, 2021, President Biden had set the 2030 greenhouse gas (GHG) pollution reduction target: a 50% to 52% reduction from the 2005 level. This is a part of achieving net zero (economic-wide) carbon emissions by no later than 2050 according to the Paris Agreement (The White House, 2021). Much efforts have been exerted to reduce GHG because of its potential to change the climate, and consequently damage human society (raising sea level, frequent extreme weathers). CO_2 is the major GHG associated with human activities such as electricity generation and transportation, and reducing CO_2 emission is the key to achieve the climate goals (Denchak, 2019).

CO_2 capture and conversion (CCC) as a solution to the emissions problem is receiving more and more research attention. Brown, Huynh, Lee, Park, and Smith (2020) had proposed and designed a process of CO_2 direct air capture (DAC) for methanol production. This previous project had blackboxed the power source, and the design for methanol production was left unoptimized. In order to improve the previous project, I will design the power island and optimize the methanol production process that could potentially reduce energy consumption and increase product output. However, this project is also sociotechnical in nature. Non-technical aspects such as economics, social perception, and the rise of renewable energy must be considered to comprehensively evaluate the potential of DAC for methanol production. A closely related case, the Petra Nova CO_2 capture and storage project, will be studied to illustrate how non-technical factors could compromise a technology. A few adversaries such as oil price and the COVID-19 pandemic had contributed to the shutdown of the Petra Nova project, and the Actor Network Theory would serve best to analyze this case.

In summary, reducing CO_2 emissions is a sociotechnical challenge, requiring attention on both social and technical aspects. In what follows, I elaborate a technical project that functions to capture CO_2 directly from the air and convert it into methanol, and an STS project that examines the failure of the Petra Nova project.

Technical Project Proposal

Greenhouse gases such as CO_2 are the leading causes of climate change. While diverging from fossil fuels towards renewable energy is the ultimate goal, carbon capture technologies represent an important tool in emission reduction. Direct air capture (DAC) is a new type of technology that serves to decrease ambient carbon dioxide concentrations as opposed to traditional carbon capture technologies which target point source emissions. In this project, a direct air carbon capture system and a methanol production plant are designed based on "Carbon-Neutral Production of Methanol Via Direct Air Carbon Capture," a technical report

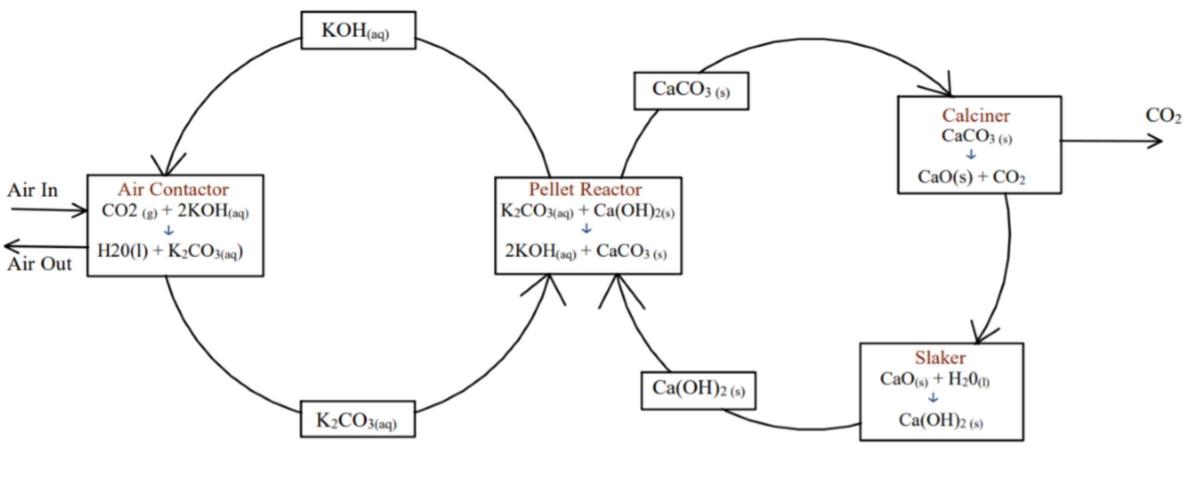

Figure 1. Process chemistry and thermodynamics for Carbon Engineering's aqueous direct air capture system.

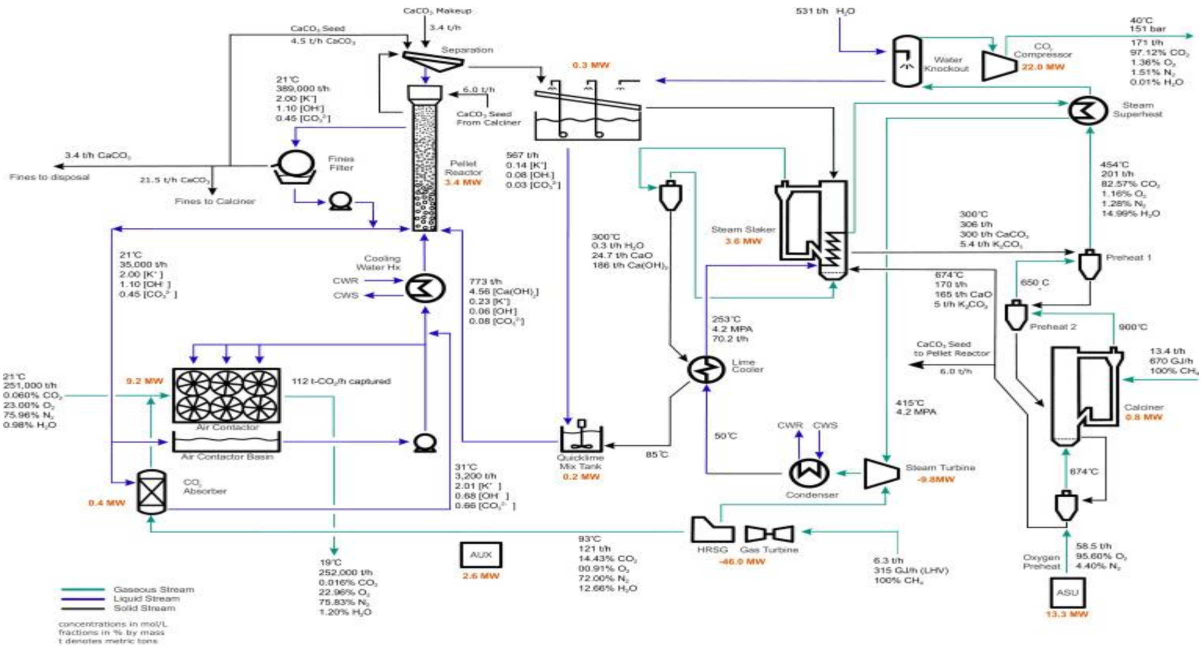

Figure 2. Overview of carbon capture and methanol synthesis system from Carbon Engineering's design. Highlighted is the power island; the methanol synthesis shows the process before the water knockout system is removed.

submitted in 2022 by Brown, Huynh, Lee, Park, and Smith. DAC is achieved by the chemical reaction cycles shown above, while methanol production is achieved by catalytic hydrogenation of CO and H_2 syngas produced from reverse water-gas shift reactions.

This project is still of interest for several reasons. First, the methanol market is expected to grow from $36,803 million in 2022 to $54.630 million in 2030 (RESEARCHDIVE, 2022). Second, most DAC systems are in early stage or experimental in nature, thus the government provides a $180 tax credit (Q45) for each ton of CO_2 captured directly from air (Cooper, Fleming, Lee, Sigler, 2022). These two factors combined creates a strong economic driving force for reconsidering this project. Moreover, some parts of the process were blackboxed and not optimized; the true potential of DAC methanol production could not be comprehensively evaluated under such conditions.

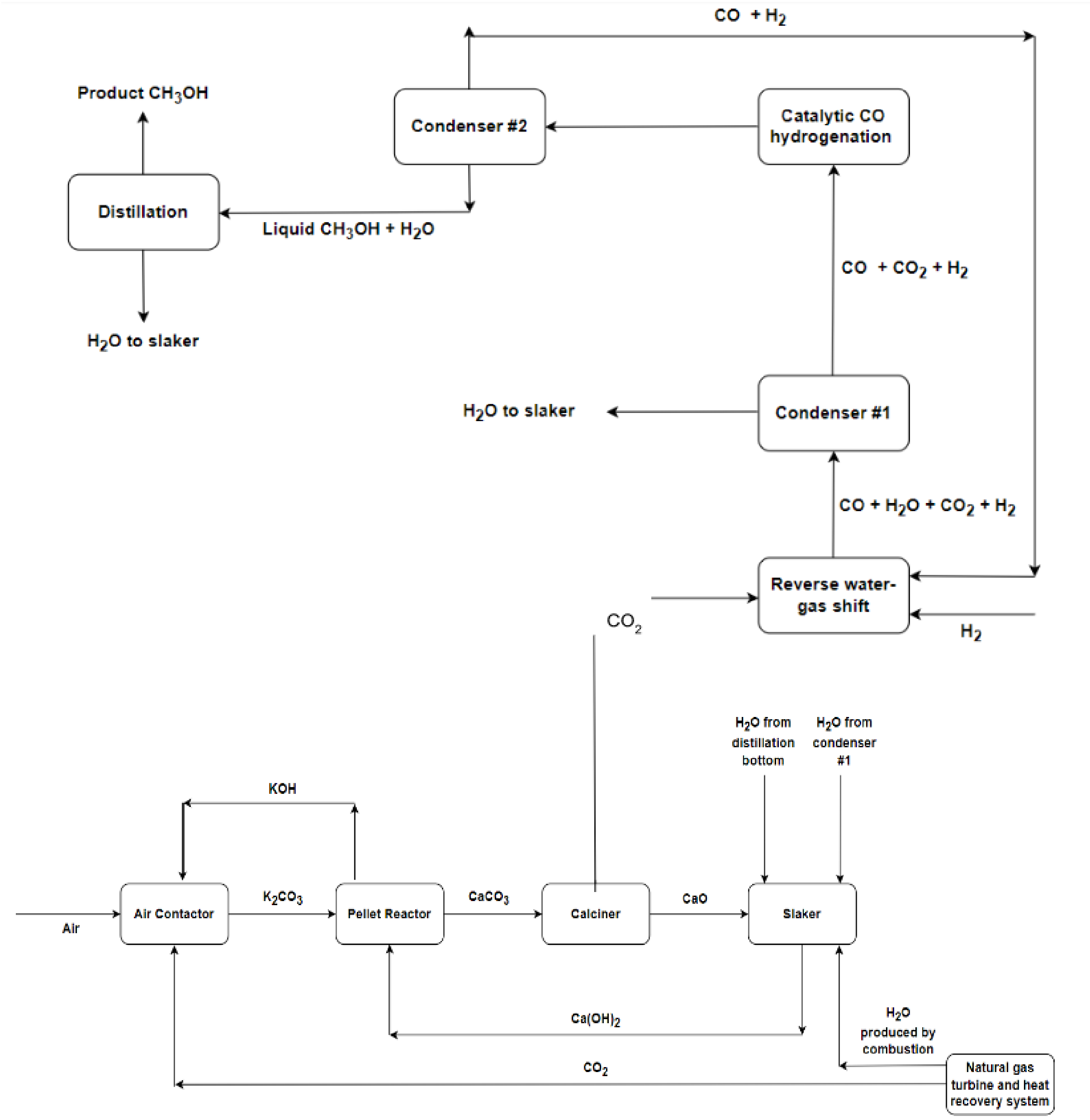

Figure 3. Overview of carbon capture and methanol synthesis system based on Carbon Engineering's design. The methanol synthesis block is redesigned without the water knockout system.

Our group aims to complete one of the blackboxed designs, the power island, and optimize the methanol production process. The power island consists of a natural gas turbine and a heat recovery steam generator (HRSG), according to Carbon Engineering's plant report. Heat recovery systems are designed to create additional steam to contribute to the turbine. To ensure no additional CO_2 is emitted from the turbine, all combusted fuel from the turbine will be sent to the CO_2 absorbers, which are also blackboxed in the 2022 design report. All amounts of fuel and products of the turbine process will be evaluated and electricity supplied to the turbine will be calculated and costed, as well. The steam resulting from the generator is combined with steam from the slacker unit, passed through the superheater to extract heat from the calciner off-gases, and then used to drive a steam turbine that generates the remainder of the power required for the plant. As done in Carbon Engineering's Aspen simulation, we will also reduce the complexity by using independent steam cycles for the gas turbine and the slaker/superheater. Material and energy balances for this process will be found and cost evaluated in this report.

The previous design had a water knockout system for the CO_2 product stream out of the calciner and precedes the methanol synthesis process. However, this system is costly in terms of both capital and utilities. The excess water comes from the combustion of natural gas in the calciner. To address this issue, the calciner will be redesigned as a heat exchanger-reactor, in which combustion takes place at the outer shell of the calciner, providing heat for the reaction at the inner shell. Water from the distillation bottom and condenser #1 will be recycled back to the slaker to increase $Ca(OH)_2$ production. New material and energy balances and economic analysis will be derived based on the improved model.

Similar to the 2022 design report, the scale up of this project will be designed with a capacity to produce 0.98 Mt of CO_2 per year based off of an internal pilot plant designed by Carbon Engineering with a capacity of approximately one tonne of CO_2 per year. The goal of the methanol synthesis is to yield 412 million kilograms of methanol per year at a production schedule of 6000 hours per year.

This project will be done as part of a two-semester team project fulfilling the requirements of CHE4474 Process Synthesis, Modeling, and Control. Modeling of process flow diagrams will be performed using ASPEN software. Two members of the team will likely focus on the power island and two members will focus on the methanol synthesis process. However, in order to create a seamless design and report, all team members will aid in work for the process as a whole and likely will shift focus as the semester progresses to work more on areas which require more complex modeling and design effort.

STS Project Proposal

On June 18, 2010, the Department of Energy (DOE) started a cooperation with NRG Energy Inc. (NRG) to design a post-combustion carbon capture and storage (CCS) system for the W.A. Parish coal-fired power plant in Thompsons, Texas; project ownership was later transferred to the Petra Nova Parish Holdings, LLC (Petra Nova). A total of $190 million was provided by the DOE to support the Petra Nova project, and the CCS system went operational in December 2016 (US Department of Energy Office of Fossil Energy and Carbon Management, n.d.). The goal of this project was to capture approximately 90% of carbon dioxide (CO_2) in a flue gas stream from a 240MW generator, using a high-performance solvent that could absorb and release CO_2 as needed. The captured CO_2 was then dried, compressed, and transported through an 80-mile pipeline to the Hilcorp's West Ranch oil field for enhance oil recovery (EOR): pressurized CO_2 would be injected into the underground oil reservoir, then more oil could be extracted under a higher pressure (NRG Energy, n.d.). However, the Petra Nova project was placed in reserve shutdown during the COVID-19 pandemic in 2020, and this status had not been changed since then.

Plenty of writings have been dedicated to analyze the cause of Petra Nova shutdown. An analysis from IDTechEx (2021) attributed the shutdown to a drop in demand for oil, and consequently a drop in oil price during the COVID-19 pandemic. This project was once expected to make profit: predictions in 2014 claimed that oil price would not possibly drop below $75 per barrel. Moreover, the federal government was providing up to $50 tax credit for each ton of CO_2 stored underground (the 45Q tax credit). $75 per barrel drew the line where the cost of operating carbon capture was balanced by the profit of additional oil output, but oil price had never reached $75, and went as low as $12 in 2020. All economic incentives combined would not cover the money loss of operating the plant with carbon capture, and a shutdown was inevitable.

Nevertheless, this economic approach failed to account for other factors such as technical failures and design flaws in the carbon capture system, and the rise of clean energy. For example, in a demonstration and monitoring period from 2017 to 2019, 367 days of unplanned outage were observed (one outage every three day); the main carbon capture facility accounted for 104 days of outage. These days of outage caused a 16 % loss in the expected total amount of CO_2 captured (Smyth, 2020). Environmentalists had been advocating for the retirement of the W.A. Parish coal-fired power plant, as solar power and wind power were becoming less expensive. Moreover, the carbon capture system only eliminated a small portion of emission; the plant was still emitting other pollutants (from coal combustion) such as particulate matter (PM) and sulfur dioxide (SO_2) (Shelley, 2020).

Continuing with the economic approach would lead to a failure in capturing the effects of non-economic actors, such as the carbon capture system itself, clean energy, and environmentalists on the shut down of Petra Nova project. The experiences would not be effectively utilized to plan future CCS system. I argue that the shutdown of Petra Nova is a result of dropping oil price during the pandemic, rise of clean energy, opposition from environmentalists, and technical immaturity.

The Actor Network Theory (ANT) identifies a network builder who tries to solve a problem. In order to solve this problem, the network builder recruits human and non-human actors to form a network; the process of forming and maintaining a network is called translation. However, actors can be allies that help to solve the problem, or adversaries that destroy the network (Cressman, 2009). ANT will be used to describe the formation and destruction of a network associated with the Petra Nova project to better understand the effects of each actor on the shutdown of the project. Evidence from governmental reports, economic analysis, and press releases will be utilized to perform this analysis.

Conclusion

The technical part of this project will include the full design of a DAC for methanol production system based on the project proposed by Brown, Huynh, Lee, Park, and Smith in 2020, where the blackboxed power source will be designed and the methanol production process will be optimized. The STS part of this project will utilize the Actor Network Theory to understand how the technical and non-technical actors contributed to the shutdown of the Petra Nova project. Combining the technical and the STS part of this project brings insights on the feasibility of implementing this promising technology that could add to the solutions of the GHG problem.

Word Count: 1,836

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