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A Technical and Economic Assessment of Direct Air Capture with Zeolite 13X and Sequestration Systems

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Summary

The atmospheric capture of CO_2 is an appropriate procedure to reduce CO_2 concentration from the past and future emissions. The purpose of this study is to consider a feasible process to capture from the atmosphere up to 84 Mtone of CO_2 per year and to integrate the proposed process into a carbon capture and storage system (CCS). Thermal swing adsorption (TSA) technology was recommended to strip CO_2 from the atmosphere using Zeolite 13X as an adsorbent. We considered a technically feasible design of the overall plant for Vostok with two sequestration scenarios. In addition, we estimated the capital and operating costs for both scenarios. The total cost of the proposed system in 2016 US dollars was 65 \$/tonCO_2 for a capturing plant with ocean storage scenario and 53.8 \$/tonCO_2 for a capturing plant with geological storage scenario. The proposed atmospheric CCS demostrates a technical and economical feasible framework for CCS systems if certain conditions are met.

1. Introduction

More than 50% of greenhouse gases (GHG) emissions are from many small dispersed sources such as residential and commercial buildings, forest, transportation, and agriculture [1]. Therefore, air capture is one of the best ways to capture past emissions. According to the research literature about separation technologies, Thermal Swing Adsorption (TSA) process requires only heat to drive off the small amount of adsorbed CO_2, and hence it is recommended for capturing low concentrations of CO_2 from a low-pressure gas stream [2]. Another large segment of literature suggests to capture CO_2 from large point sources by physical adsorption [3-6]. Based on this literature, Zeolite 13X is a good candidate for CO_2 capture from the atmosphere [7]. At very low concentrations of CO_2, Zeolite 13X has the highest working capacity compared to other adsorbents. However, Zeolite 13X has a high affinity to water vapor; therefore, to have an efficient separation of CO_2 from the atmosphere by adsorption, a dry environment is needed. Consequently, activated alumina (γAl2O3) is used as a pre-treatment desiccant material due to its good selectivity for water vapor over CO_2.

2. CO_2 Capture Plant

The atmospheric carbon capture and sequestration system (CCS) consists of three major subsystems: a power plant, a carbon capture plant, and a transportation and storage system. The CO_2 wheel that was proposed by Shimomura for mass transfer in adsorption and desorption is used as the base case for the core process in the capture facility [8]. In this study, we use Toth model to predict adsorption isotherms for temperatures and concentrations of CO_2 that have not been reported experimentally in the literature [9]. According to the literature, F-200 activated alumina can be used for removal of water content [9]. To effectively separate H_2O and CO_2 from the air, in this study we consider a three stage TSA. The first stage is to strip water content from the air. The second stage is to collect CO_2 from the atmosphere and increase its concentration to 10%. The final stage is to reach CO_2 concentration of 90%. Subsequently, cooling and compression is used to increase CO_2 concentration to more than 99% and remove other remaining impurities such as N_2 and O_2. Therefore, a CO_2 capture plant involves two plants: a contacting towers plant, which has many towers to collect CO_2 from the atmosphere, and a single hub plant for CO_2 compression and cooling. Figure 1 shows the entire process and Tables 1 and 2 list the process stream parameters for the contacting towers plant and the hub plant.

Table1. Stream lines parameters of the main components in the contacting towers plant

Description	One Block Process									
Stream No.	1	2	3	4	5	6	7	13	14	15
Flow rate (kg/s)	13,893	13,399	33.75	33.75	5.49	5.49	5.49	33.75	33.75	33.75
Conc. (v/v)	0.04%	0.00%	10%	1%	1%	1%	90%	1%	1%	10%
Pressure (MPa)	0.067	0.067	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Temperature (°C)	-40	-40	-20	-20	-20	90	90	-20	100	100

Table 2. Stream lines parameters of the main components in the hub plant and CO_2 pipeline

Description	Hub plant / Compressors				Pipeline Upstream	Pipeline Downstream
Stream No.	8	9	10	11	12	16
Mass flow rate (kg/s)	1,157	1,157	1,157	1,157	10,416	10,416.00
Conc. (v/v)	90%	Not Calc.	Not Calc.	Not Calc.	99%	99%
Pressure (MPa)	0.1	7.5	7.5	15	15	10
Temperature (°C)	5	260	5	260	40	-5

As shown in Figure 1, the red circles indicate heat exchangers that add thermal energy to the stream, while the blue circles are withdrawing thermal energy from the stream using a refrigerant fluid (Syltherm XLT). Additionally, the towers are built in four parallel rows perpendicular to the wind direction. The rows are separated by one kilometer to avoid wind shadowing and to ensure that each row has the same concentration of carbon dioxide at the inlet ducts [10].

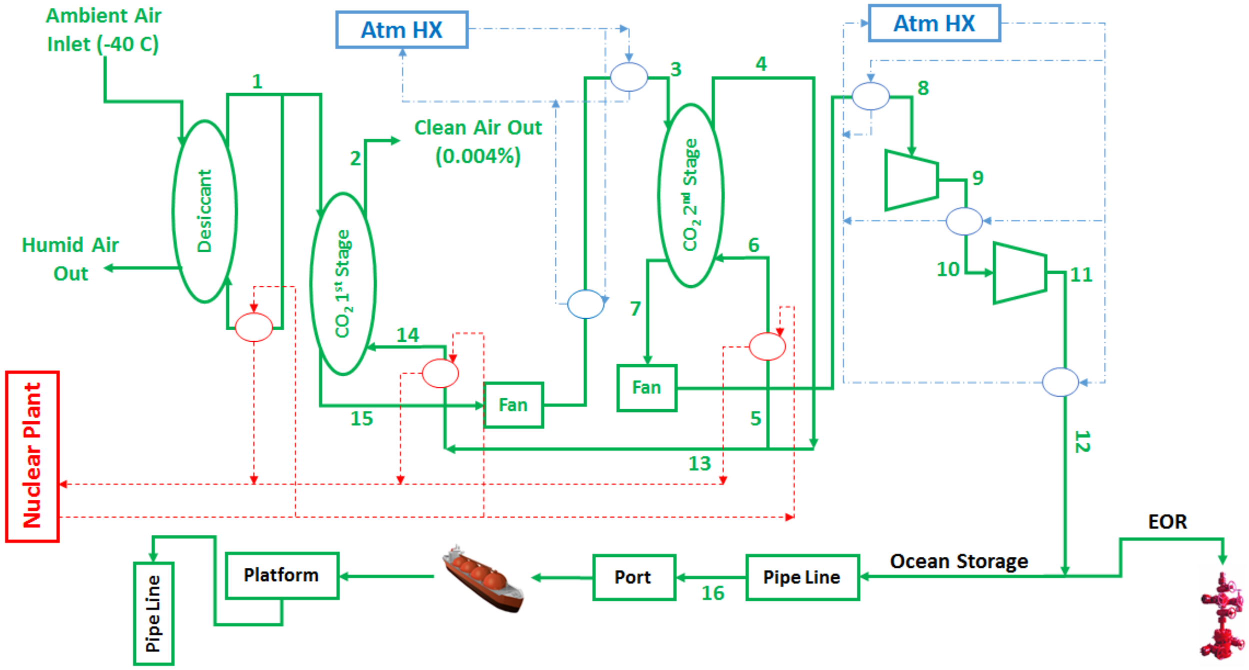

Figure 1. Nuclear CO_2 air capture process in Vostok [10].

3. Storage and Sequestration Scenarios

3-1. Ocean Storage

The onshore system utilizes one pipeline to transport CO_2 from the capture plant in Vostok to the port at McMurdo station. We developed several assumptions to calculate the pipeline diameter including 1200 km length (the distance from Vostok to McMurdo), the upstream and downstream pressures of 15 MPa and 10 MPa, and the upstream and downstream temperatures of 40°C and -5°C [10]. An iterative method, which was reported by McCoy, was used to calculate CO_2 pipeline diameter [11]. After three iterationsbased on one pipeline, we determined the internal diameter of the pipeline of 48-inch diameter and thickness of 1.055 inches. Tankers, a floating platform, and vertical pipelines are the offshore items. The size of these items is surveyed from the literature [12].

3-2. Injection into an Arbitrary Gas Condensate Reservoir

Upon depletion in gas condensate reservoirs, the reservoir pressure falling below the dew-point of hydrocarbon mixture results in liquid condensation around the wellbore. This liquid barrier causes severe reductions in gas production rates and the permanent loss of a large portion of volatile and valuable condensates. To find a solution for this problem and reduce GHG emissions, we modeled an arbitrary gas condensate reservoir is modeled with and without a CO_2 injection well using a compositional simulator (ECLIPSE 300). The grid model contained 20 × 1 × 1 grid cells with inner grid cell size in the radial direction of 0.2 ft. The external radius of the model was 6330 ft. To model PVT behavior and fluid equilibrium, we used the modified Peng-Robinson equation of state [13]. This work uses an eleven-component lumped of a retrograde gas. The investigated reservoir was produced under natural depletion mechanism until the time that maximum condensate appeared (10 years). For condensate re-evaporation and partial pressure maintenance, CO_2 injection scenarios was started. Note that the maximum well BHP constraints of 15 MPa and maximum gas injection rate constraint of 9 MMSCFD (84 Mton/yrs) for the injection well were selected after optimization on partial pressure maintenance . The result of simulation is shown in Figure 2. It is obvious that CO_2 injection into the reservoir led to a higher recovery (up to 15%) in comparison to the case without injection. This increase could be explained by the re-vaporization of the liquid dropout in the reservoir (reducing condensate saturation) and the subsequent condensation/vaporization.

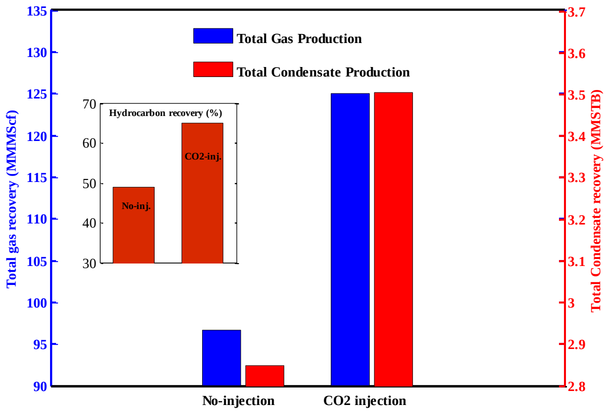

Figure 2. Comparison of CO_2 injection vs. No injection Performance.

4. Economic Feasibility of Atmospheric CCS System

We made the following assumptions in our cost analysis:

- Capital equipment costs are estimated based on information obtained from different sources in different years. Therefore, inflation rate is calculated and added to the cost of each item based on the Bank of Canada inflation rate calculator [14].
- Because the plant is supposed to be built on the eastern coast of North America, a correction regional multiplier factor of 2.5 is added for Vostok [10].
- The capture plant construction and setting costs of the piping, control valves, electrical panels, wiring, and control system are estimated as a percentage of the total main equipment costs such as adsorption wheels and heat exchangers. [15]. Based on the equipment conditions (temperature and pressure), two factors of 2.527 and 2.203 are applicable to estimate the installed equipment costs, including setting costs of these equipment as a function of the bare equipment costs.

The results of the cost analysis are presented in Table 3.

Table 3. Nuclear Air CCS Process Cost in Vostok with two sequestration systems

Description			Ocean Storage (M$)	Geological Storage (M$)
Nuclear Power Plant [10]			1,1452.1	1,1452.1
Capture Plant	Contact wheels	Desiccant [15]	140.6	140.6
		1st stage [15]	1030.4	1030.4
		2nd stage [15]	306.8	306.8
	Compressors [15, 16]		45.0	45.0
	Heat Exchangers [15, 17]		731.8	731.8
Transportation & Sequestration		CO_2 Pipe line [10]	1,412.3	0
		Road cost [10]	99.4	7.6
		Tankers [12]	1104.0	0
		Floating platform [12]	138.0	0
		Vertical Pipe line [12]	36.0	0
		Port Cost [10]	69.0	0
Multiplier Factor [10]			2.5	2.5
Total Capital Cost			41,413.6	34,286.0
Discount Rate (%) [10]			8.0	8.0
Life time of the project [10]			20.0	20.0
Annualized Capital Cost			4218.1	3492.1
O&M Costs (M$/Year) [10]			1242.4	1028.6
Total Annualized Capital + O&M Costs			5460.5	4520.7
Total Cost / Ton CO_2 ($/ton CO_2)			65.0	53.8

5. Conclusions

A process concept for carbon dioxide capture from the atmosphere using adsorption technology and nuclear power has been developed and applied in a cold dry region, Vostok, Antarctica. After assessing the technical feasibility, the annualized capital and operational costs associated with the process in a 20-year period were calculated for partial mitigation of CO_2 in the atmosphere. The following conclusions based on the assessment results have been derived:

- Nuclear plant is the main cost contributor to the entire system cost. Therefore, increasing and decreasing the thermal power load will have a significant effect on the cost of the entire project.
- The driving and controlling parameter for this process is the ambient air temperature, because it controls adsorption capacity and water content in the atmosphere. Increasing the adsorption capacity decreases the number of contacting towers and the specific heat requirement of the process while decreasing the water content in the atmosphere decreases the thermal load required for the regeneration of the desiccant wheels.
- The geological storage as the option for sequestration system might lead to the reduction of the capturing cost (around 17 percent voidance cost in this study).
- Because there is no income for Direct Air Capturing, the captured CO_2 injection into a hydrocarbon reservoir could be considered as a source of income for this technology. In this study, due to low capacity of the arbitrary reservoir, it is not practical to perform the discounted cash flow and gross margin analysis.

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