RESEARCH ARTICLE

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Carbon Capture from Coal Power Plants and Algae Farming with Technical-Economic Analysis

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Abstract

CO_2 is a major cause of global warming, one of the world's most critical environmental problems and responsible for about 55% of global warming. According to research, the quantity of CO_2 in the atmosphere corresponds well with the growth in the average global temperature of the planet's surface. The main aim of this work is to investigate different emerging Technologies for the carbon capture from power plants and its atmosphere. After capturing of CO_2, it is used for the injecting in raceway ponds for micro algae cultivation. Mathematical and experimental analysis for the carbon capture and Sequestration from the coal power plant have been performed in the RKDF University and proposed the microalgae production using captured CO_2. For that total 24 experiments were performed to get the efficiency of the CCS plant. The result shows that Input of 250 kg/ hr of flue gasses has been used to capture the CO_2. Sodium Carbonate solution of 10% will be sprinkled on top of the packing in tower-A to increase the contact area. The gases are now subject to the counter-current of MEA solution of 30% contained with 1 kg of CO_2. MEA-CO_2 mixture is heated up to 155°C with the help of a Scheffler dish collector. CO2 gas released from the MEA-CO_2 mixture when heated above 130°, the maximum efficiency of the CCS plant of 87.58 % on 04 Jan 2021 at 1200 Noon.

Keywords: Carbon capture, CCS, Power plants, TEA analysis, Algae farming etc.

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Introduction

The process of capturing carbon dioxide (co_2) from various sources such as a direct air from the atmosphere, cement factory, biomass, burning of flue gases, emission from thermal power plant etc. After capturing this CO_2 transporting to a storage site and dumping it. Generally, it is an underground geological formation. The aim is to prevent the release of CO_2 into the atmosphere from various sources to mitigate global warming and ocean acidification of carbon dioxide emissions from industry and heating. [CSIRO & the Global CCS Institute 2013]

According to the IPCC, the excessive increment of greenhouse gases in the atmosphere mainly due to CO_2 causes climate change on Earth and global warming. In fifth report of IPCC, issued in 2013-2014, a scenario of climatic change by 21st century is projected. It has also estimated that earth's surface temperature will increase by 0.3-4.8^{o}c.

Approaches to Mitigate Global Climate Change

Different approaches are considered and adopted by various countries to reduce their CO_2 emissions, including

- Improve energy efficiency and promote energy conservation;
- Increase usage of low carbon fuels, including natural gas, hydrogen or nuclear power;

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- Deploy renewable energy, such as solar, wind, hydropower and bio-energy;
- Apply geo-engineering approaches, e.g. afforestation and reforestation; and
- CO_2 capture and storage (CCS).

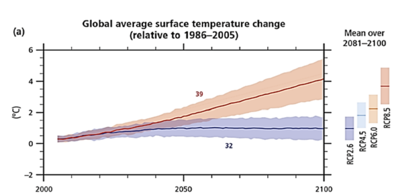
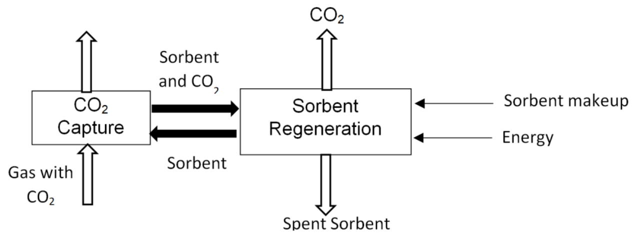
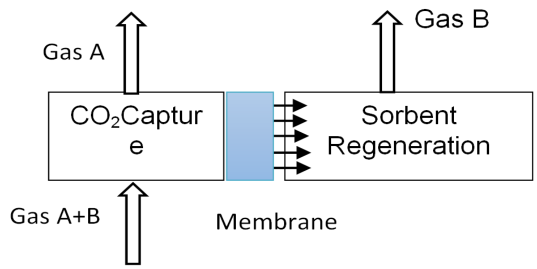
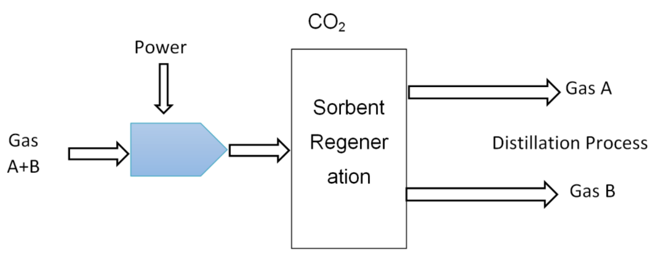


Figure1: Global surface temperature change from 2006 to 2100, determined by multi-model simulations *[A hasan et al., 2020]*

Table 1: CO2 capture systems use gas separation technique discussed below.

Technique	Description	Limitations
Separation by Solvent/ Sorbent	 **Figure 2:** Separation by Solvent/Sorbent	CO_2 contained gas is passed through liquid absorbent or solid sorbent. Solvent/sorbent can absorb CO_2. Cyclic process. Reuse of sorbent with some loss for making fresh sorbent in the next vessel.
Separation by Membrane	 **Figure 3:** Separation by membrane	Membranes are selectively permeable made up of polymer, metal or ceramics. Maintains pressure difference across the membrane for separation. High pressure is preferred.
Distillation of liquefied gas and refrigeration	 **Figure 4:** Distillation of liquefied gas and refrigeration	Gas is transformed into liquid by series of compression, cooling and expansion. Refrigerated separation is used to separate CO_2 from other gases. Oxygen can be separated from the air and can be used for CO_2 capture systems such as oxy-fuel combustion or pre-combustion capture. It can be used to separate impurities.

Different Co_2 Separation Technologies

CO_2 separation technologies can be applied to extract the CO2 from the flue gas stream before transportation *[Dennis Y.C. Leung at el. 2014]*. There are some important technologies used are as follow.

- Absorption
- Adsorption
- Chemical looping combustion
- Membrane separation
- Hydrate-based separation
- Cryogenic distillation

Most Common Carbon Capture Techniques

Capture from Industrial Process Streams

According to IPCC, Mostly carbon-capturing source are industries. in industries there is no source or need to store CO_2. But with increasing concentration of CO_2 in atmosphere it is quite needed to capture and store CO_2 emitted from industries. Many researches are done for CO_2capturing are its storage from industrial process.

Post-combustion Capture

In this technique, CO_2 is captured from gases produced due to combustion of fossil fuels or biomass. In this technique, CO_2 is not directly vented to the atmosphere, but it gets captured and passed through various equipment and get stored into the storage tank. In post-combustion capture, a chemical sorbent process is used (Ipcc.ch, 2019) for example, CO_2 capturing plant of 2261 GWe of oil, coal and natural gas power plants (IEA WEO, 2004) and 155 GWe of super-critical pulverized coal-fired plants (IEA CCC, 2005) and 339 GWe of natural gas combined cycle (NGCC) plants (IPCC).

Oxy-fuel Combustion Capture

In the oxy-fuel combustion process, combustion is done in the presence of pure oxygen instead of air, which mainly results in gases that contain CO_2 and H_2O and can be recycled to the combustor. The power plant systems are the same as post-combustion capture systems.

Pre-combustion Capture

In pre-combustion capture process, fuel is reacted with oxygen or air or steam and generates 'synthesis gas' that is

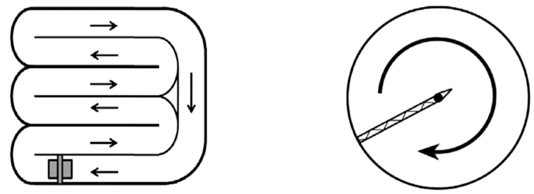


Figure 5: Open-air Algae cultivation systems

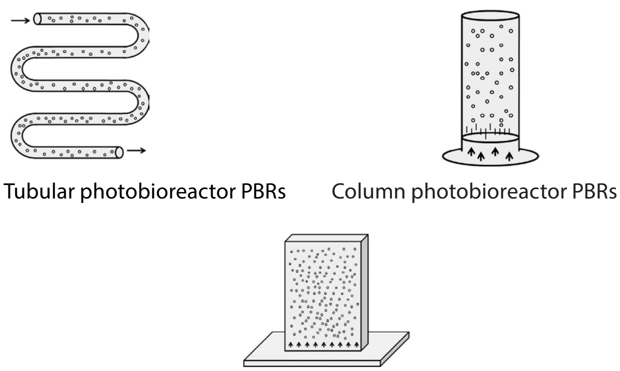


Figure 6: Closed Algae cultivation systems

composed of CO and H, then CO is reacted with steam in a catalytic reactor which is called a shift converter to give CO_2 and more hydrogen. The generated CO_2 is separated by the absorption process which results in hydrogen-rich fuel. The power plant for the pre-combustion system is integrated gasification combined cycles (IGCC) (3719 GWe; IEA WEO, 2004).

Introduction of Algae Cultivation

Algae are a group of photosynthetic autotrophs that normally thrive in various water bodies such as lakes, rivers, and sea. Microalgae can produce and accumulate many bio-chemicals with applications in human and animal nutrition, health, cosmetics, pharmaceuticals, analytics and biofuels. Microalgae exhibit higher photosynthesis efficiency (compared with agricultural and forest crops), which enables faster conversion of CO_2 and water into biomass, and thus improves CO_2 mitigation ability

Algae cultivation methods include open, closed, and hybrid cultivation systems. Open system includes raceway pond, consists of a closed loop channel with circulation pumps and underground distribution pipelines. A closed photobioreactor system consists of closed transparent reactors having tubes, flat panels, flat-plate, bags, floating-bag, vertical or horizontal tubes or columns.

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Objective

The main aim of this work is to investigate different emerging Technologies for carbon capture from power plants and its atmosphere. After capturing of CO_2, it is used for injection in raceway ponds for micro algae cultivation.

Some of the research objectives are stated further as:

- Investigate the low-cost processing Technology for treating CO_2 from different sources for microalgae cultivation.
- Enhance the production of algae farming using captured CO_2.
- To perform technical-economic analysis (TEA) for large scale industrial applications.
- To enhance the overall efficiency of the carbon-capturing process and the production of microalgae cultivation.

Figure 7: CCS Plant in RKDF University

Methodology

Flue gas generally contains 14% CO_2. It contains SOx, NOx gases, some Ammonia gases, and some dust particles such as Ash and Carbon particles. CO_2 Capture and its Sequestration through coal power plant and to produce algae than storage, the experimental setup of CCS plant is installed in RKDF University as shown in figure 7.

Working and Operation Procedure

The process is as follows,

- Flue gas is subjected to water flow which will trap all particulates with water and it will also cool down the temperature of flue gas.
- Then the gas will be sent to Tower A, where flue gas will enter scrubber from bottom.
- Soda solution (Sodium Carbonate solution of 10% will be sprinkled from top of the packing and because of packing, contact area will increase, so Ammonia, *SO*K gas, and *NO*K gases will come in to contact with soda solution and will be converted to their respective salts like Sodium Sulphate, Ammonium Sulphate and Sodium Nitrate.
- After this the gases are subjected to Tower- B (identical to Tower A) so that any traces of these impurities get observed and do not come in contact with MEA solution, as reaction with MEA solution can result in the formation of complex salts.
- Flue gases from scrubber of Tower-B are free from impurity of Ammonia, *SO*K and *NO*K. The gases are now subject with counter-current of MEA solution of 30%. Here it forms bond with CO_2 gas to form mixture of MEA - CO_2 mixture solution. MEA solution of 30% can combine with 1 kg of CO_2.
- MEA-CO_2 solution is sent to Tower C which is a 1000Ltr SS316 reactor with wall thickness of 8 mm thickness and bottom of 8 mm thickness jacketed with MS jacket and have steam jacket SS316 coil. All contact parts with MEA solution are of SS316, as MEA is very corrosive with MS.
- SS Reactor also has a vertical condenser which will act as a reflux and will stop losses of MEA and water vapour andll allow only pure CO_2 to go out so there will not be any impurity of MEA in CO_2 gas.
- This is not a chemical reaction but it is a physical property of MEA which has tendency to absorb CO2 gas and CO2 gas gets released when heated above 130°. As boiling point of MEA is 170°C, to prevent losses of MEA max temp of MEA - CO_2 mixture is to be restricted to stay below 155°C.
- The system will have an input of 250 kg/ hr of flue gasses and will be able to extract 45 kg/hr (18%) of carbon dioxide.

Thermal energy is required to heat the MEA - CO_2 solution in Tower-C to extract out the carbon dioxide. To provide this heat, the plant will rely on Solar. Thermal technology provided by Sunrise CSP India Pvt. Ltd. For the CCS plant, total 8 scheffler dish of 16 m^2 each have been used. The solar system provides 50 kg/hr of steam during sunshine for re-generation of MEA solvent.

Calculation for Microalgae Production

Algae are a group of photosynthetic autotrophs which normally thrives in various types of water bodies such as lakes, rivers, and sea. Microalgae can produce and accumulate many bio-chemicals with applications in human and animal nutrition, health, cosmetics, pharmaceuticals, analytics and bio-fuels. It exhibits higher photosynthesis efficiency (compared with agricultural and forest crops), enabling faster conversion of CO2 and water into biomass, thus improving CO_2 mitigation ability. Some literature estimated that PBR systems have higher production costs than open pond systems, more recent studies show potential for cost improvements *[Richardson et al. 2014]*.

Specific Growth Rate of Algae

$$\mu = \frac{F}{D} = D$$

Where, μ= specific growth rate (h^{-1}), F= volumetric flow (m^3/h), V= working volume of the bioreactor (m^3), D= dilution rate (h^{-1})

Estimation of CO_2-saturated Growth

$$x_{c\,sat} = \frac{(k_L a)_C . (C - C_{crit})}{SCUR}$$

Where: $x_{c\,sat}$ = CO_2–saturated growth, $(k_L a)_C$ =, Volumetric CO_2 mass transfer coefficient, C= CO_2 concentration, C_{crit} = Critical CO_2 concentration, $SCUR$ = Specific CO_2 uptake rate For approximation of CO_2 concentration, Henry law is used as stated below:

$$C = \frac{m_{co2,gas} \times P_T}{H_{co_2}}$$

Where: $m_{co2,gas}$= mole fraction of CO_2 in the gas phase, P_T= total gas pressure, H_{co_2}= Henry's constant, (29.41 L atm/mol in pure water at 25°C), $(k_L a)_C$ Can be estimate from below equation

$$(k_L a)_C = (k_L a)_O \left[\frac{D^{co_2}}{D^{o_2}}\right]^{0.5}$$

Where: D^{co_2}= the molecular diffusivities of CO_2 in water, D^{co_2}= the molecular diffusivities of O_2 in water.

Specific CO_2 uptake rate (SCUR) is calculated as below:

$$\frac{SOPR}{SCUR} = \frac{O_2\ Produce/biomass/time}{CO_2\ assimilated/biomass/time}$$

$$\frac{SOPR}{SCUR} = \frac{(Moles\ of\ O_2\ produced)\ 32\ g/mol}{(Moles\ of\ CO_2\ assimilated)\ 44\ g/mol} = \frac{8}{11} PQ$$

Where PQ moles of O_2 produced per unit mole of CO_2 can be estimated as:

$$CO_2 + wH_2O + yNO_3^- + yH^+ \rightarrow CH_pO_qN_r + zO_2$$

Where: Z = stoichiometric coefficient of O_2,
By solving H, O, and N balance equations, z or PQ can be written in terms of p, q, and r and can be determined from C, H, O, and N mass fractions of the biomass.

$$PQ = z = \frac{1}{2}\left[\frac{p}{2} + \frac{5r}{2} - q\right]$$

It has been observed that the specific O_2 production rate (SOPR) increases with the dissolved CO_2 concentration and levels off at critical CO2 concentration (C_{crit}). Furthermore, critical CO2 concentration and its corresponding specific O_2 production rate increases with the intensity of light available for photosynthesis and are highest at saturating intensity.

Overall efficiency of the CO_2 capture from the plant

$$\eta_{Co2} = \left(1 - \frac{Exit\ CO2\ \%}{Inlet\ CO2\ \%}\right) \times 100$$

Calculation of Capital Cost

$$C_{capital} = C_A + C_{pack}.D\ \$/m^2$$

Where: $C_{capital}$ = Capital cost, C_A = capital cost per frontal area, C_{pack} = packing and fluid distributor cost, D = Packing depth

Operating Cost

$$C_{operating} = E \times C_{elec} + M\&O \times C_{capital} \frac{\$}{m^2/yr}$$

Where: $C_{operating}$ = operating cost, C_{elec} = Cost of electricity, M&O = Maintenance and operation (5% of capital cost)

Total Cost Minimization $ per tonne CO_2

$$Minimum\ cost_{co2} = \frac{(C_{operating} + CCF.C_{capital})}{F}$$

Where: CCF= capital charge factor (15% per year)

Result and Discussion

Total 24 experiments performed on 24 different days from 02 Dec. 2020 to 18 Feb. 2021, and the efficiency of the CCS plant have been estimated for all these days at one hour time interval starting time is 11.00 AM to 4.00 PM. It has been observed from the experimental results the maximum efficiency of the CCS plant of 87.58% on 04 Jan 2021 at 1200 Noon, as shown in figure 8.

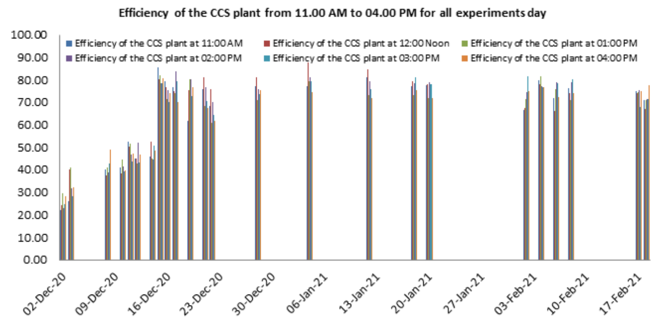

Figure 8: Efficiency of the CCS plant from 11.00 AM to 04.00 PM for all experiments day

Conclusion

Mathematical and experimental analysis for the carbon capture and Sequestration from the coal power plant have been performed in the RKDF University and proposed the microalgae production using captured CO_2. For that total 24 experiments performed to get the efficiency of the CCS plant. There are following conclusion has been obtained from the above analysis.

- Input of 250 kg/ hr of flue gasses have been used to capture the CO_2.
- Sodium Carbonate solution of 10% will be sprinkled from top of the packing in tower-A for increasing the contact area.
- The gases are now subject with counter current of MEA solution of 30% which contained with 1 kg of CO_2.
- MEA - CO2 mixture are heated upto 155°C with the help of scheffler dish collector.
- CO_2 gas released from the MEA - CO_2 mixture when heated above 130°.
- The maximum efficiency of the CCS plant of 87.58% on 04 Jan 2021 at 1200 Noon.

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