

A New Process of Capturing Carbon Dioxide Gas From The Atmosphere Using Solid & Aqueous Sorbents in Pilot Plant

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Abstract: The capturing process of CO₂ directly from air has been developed largely considering with commercial scale in pilot plants. This is done so that the capture CO₂ from air can be used as a feedstock or raw material for producing carbon free renewable fuels by applying direct air capture (DAC) process. This way of capturing is gone to be possible with using some solid & aqueous sorbents in pilot plant. The success of this capturing process is depended on the appropriate configurations of both major & minor plant operations. Heat & mass balance are required necessarily to contribute on the finding of each pilot plants data. The design of this process is modeled like this so that the captured CO₂ can be delivered at 15MPa into the pilot plant & for this, the requirements of energy inputs are about 8.81GJ or 5.25GJ of natural gas & 0 KWHr or 336KWHr of electricity respectively. Then all the results finding from the pilot contactor, reactor, calciner are optimized to reduce the processing cost of the capturing process. It is observed after the ending of the process that the amount of operating cost is ranged between 50\$ to 100\$ to capture per ton of CO₂ from surrounding air where the total levelized cost of the whole process ranges between 94\$ to 232\$/t-CO₂. If it considers the other specific choices such as financial safety, environ mental & ecological arrangements etc. then this DAC process would be the best reliable solution to capture the CO₂ from air in upcoming decades.

Keywords: Direct Air Capture; Pilot Plant Operations; Plant Configurations; Carbon Storage; Process Simulation;

1. Introduction

Carbon capturing issues have been practiced worldwide in more concerned way from past days in recent decades for its excessive growing up in the atmosphere. Recently this process has been already reached to the development on commercial basis. That means, the captured carbon dioxide gas (CO₂) is tried to use as a feedstock or raw material for producing carbon free fuels that will be used in power plants & production sectors in upcoming future. Here's a process to talk about that should be designed for capturing the (CO₂) gas from ambient air directly, referred as "Direct air capture process" briefly defined as (DAC) process [1]. This process can design a way by which approximately 1 Mt-CO₂ can be captured continuously through a sorbent KOH (aqueous) that is associated with a recovery loop made of caustic calcium. The cost required in this plant for developing the performance of some major unit operations is comparatively low with other conventional capture processes. The rationale behind this process is based on the simulation process that mainly works with the contribution of energy & material balance into the heat transfer of reactions. When the captured CO₂ is sent for delivering at 15MPa, the system designs need approximately 8.81 GJ or 5.25 GJ of natural gas & 336KWHr of electricity for estimating per ton of captured gas. After analyzing the criteria related with

financial & operating costs, appointed input & output choices, the total cost ranges from 94\$ to 232 \$/ton-CO₂ gas where approximately 50\$ to 1000\$ is needed for per ton of captured CO₂ gas in conventional non-sustainable ways. In this design, the capture of CO₂ gas is exercised at low temperature air separation. Since year 1990s, none has been able to provide a suitable design & concept of cost for direct air capture system, which can meet the up the requirements of some essential managing factors straighten from detailed commercial engineering aspects associated with third parties appraisal [2-4].

In direct air capture (DAC) process, there is essentially used of some solid sorbents or aqueous solutions, which mainly work as a plausible media are requiring less input energy & can be applicable in wide variety of scales [5-6]. Here the designs made for using of solid sorbents will be blocked after a certain time for cycling of resuscitation of temperature, pressure & humidity. It should be noted that the infrastructure cost is not considerably high in the case of determining the sorbent performance of capturing the CO₂ gas from the polluted surrounding air [7-8].

Again, aqueous sorbents also have some advantages that require some cheap hardware using for cooling the process tower. The surface of liquid sorbent gives a large contactor lifetime to allow for renewing, even there is possibility of having dust &

pollutants. When the large amount of captured CO₂ is thrown to the central recycling generation systems should have large scale of economic facilities & high air contactor. But in this case, aqueous sorbents may have some water loss in environments & perplexity of recycling system compared with solid sorbents. In this report, the main aim is to develop each unit operation of these sorbents & balancing of heat & mass generation [9].

2. Method

Here the process reactions are shown in Figure(1) with two sections where the sections discuss about CO₂ captures from ambient air through aqueous solutions that can have perceivable quantities of ions of hydroxyl ion (OH⁻), carbonate ion (CO₃²⁻) & potassium ion (K⁺). Then Ca²⁺ ion is sent to the second section for reacting with CO₃²⁻ ion aims to precipitate as a form of CaCO₃. Before forming it, the Ca(OH)₂ should be liquefied for replenishing Ca²⁺ ion. After relieving CO₂ from CaCO₃ for producing solid CaO in calciner, again the Ca²⁺ ion can be used as hydrate to form Ca(OH)₂.

These processes should be implemented in cycled way to maintain energy & material balance at industrial scale. It is observed that 1Mt-CO₂ gas is captured from surrounding air & from it, 1.52 Mt-CO₂ is delivered after drying at teeming capacity of the plan. Additional amount of delivered CO₂ is generated to fill the some electrical & thermal requisites by combusting naturally produced gas. Later, the energy & mass balance model designs an alternative configuration for balancing the carbon life cycle by using electricity & gas inputs. This data is also refereed as vendor data estimating from a simulation model on heat & material balance. This model is developing for reducing cost in some trivial items of the process.

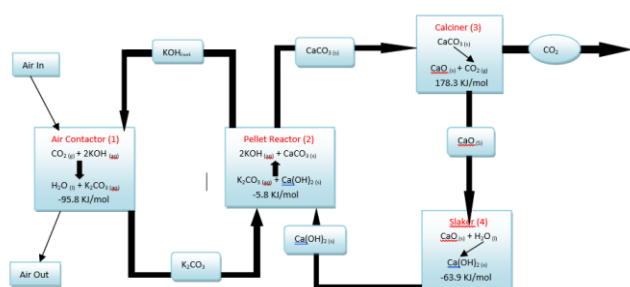


Figure 1. Process Chemistry & Thermodynamics

Here, four unit operations that are placed in the pellets required to complete the reactions of the whole process. These are contactor, pellet reactor, calciner & slaker which are needed for their four corresponding reaction based on the performance of estimating the linked data for driving the simulation of chemical processes. Each unit operation with their performance along with their reactions is briefly described below.

2.1. Air Contactor

The very first unit of the operations is the air contactor whose main aim is to make a connection between aqueous alkali solution & captured CO₂ from surrounding air shown by reaction1 in figure 1. The captured CO₂ is flowing downward through a solution of 50 μm film then it flows horizontally through a plastic packing structure. The aqueous film limits the transition of CO₂ by reaction-diffusion process. Then hydroxyl ion (OH⁻) & temperature data is used for determining the coefficient of mass transfer (K_L) of CO₂ by applying a semi-empirical relationship between temperature & ambient air. This coefficient applies an integrated relationship on past estimating values & new empirical model. A SPX cooling technology that is leading with vendor data has been used in contactor of carbon engineering system differentiated from conventional cooling system according to fluid geometry & chemistry [10-11]. The design that allows cross flow cooling system rather than counter flow cooling system are very cost effective & significant in chemical gas interchange with direct air capture technology. The cost spent for making a framework related with energy & capital operation in this unit are minimized by grading depth of packing & velocity of air to uptake the exhaled CO₂ into the sensible cooling tower.

2.2. Pellet Reactor

The second unit of the operations is called pellet reactor that is used for dispelling Carbonate ion (CO₃²⁻) from aqueous solution with caustic process shown by reaction2 in Figure 1. Here, suspended CaCO₃ pellets flow upward at velocity of 1.1 to 2.5 cm/s through a liquidized bed reactor. Then a semi liquid mixture of 35% CaCO₃ is infused into the base of the reactor vessel. The separation of Ca(OH)₂ is advancing when CO₃²⁻ ion reacts with Ca²⁺ for precipitating on the pellets within the circulating area of supersaturated CaCO₃. It is estimated that if small seed pellets are sinking through the reactor of the discharge end of the bottom, then 10% of Ca can be thrown into a downstream filter. When pellets are completed, crystal calcites can form a spherical congregation with rough porosity. In this process, the removal of CO₃²⁻ is occurred with implementing of a developed water treatment system. Actually the reformation of CaCO₃ in pellets is occurred later to strengthen the ionic solution even there is limitation of caustic agents. From pilot plant, there is application of some prototypes that designs industrially to operate waste water system plants in large scale of engineering. In direct air capture processing, there is an invention of circulating fluidized bed (CFB) that is used for lowering the expense in operational cost compare with caustic recovery loop offers some chemical

processes in Figure 1. For decreasing the risk of aqueous alkali pursued by CO₂ separation process, potassium (K) is used instead of sodium (Na) atom [12-13]. It is accepted as better choice to assess the performance of the process by having the ability to form pellets rather than to make lime mud. After forming 15-40 μm diameter of crystal calcites by precipitating, the pellets are sent for cleaned & dried up more conveniently. As vacuum filtration is omitted in these pellets, then pellets can contain more alkali solution than lime mud which results in use of CFB compare with a rotary klin.

2.3. Calciner

In calciner, there is an exercising of oxy-fired circulating fluidized bed to execute the separation of CaCO₃ by applying combustion process to produce CO₂ that is shown in reaction in Figure 1. This process has been designed with accomplishing laboratory testing through commercially in carbon engineering pilot plant. A wide steel container is lined inwardly with impervious metal to preheat the cyclones created in the calciner. Then a liquidized gas is sent to the base of calciner plate that is made from impervious arch. A bourgeois heat integrated model designs a technical way by which natural gas is straightly injected away into a liquidize bed composed from a series of lances for increasing energy efficiency at lower capital cost & technical risk. The calciner simulates at surrounding pressure. When the cyclone is preheated, then penetrating solids are also cyclones in order of counter-current flow through heat recovery cyclones. Next stage, the solids are heated again by further reducing the temperature of the emerging gas to push the gas stream towards cyclones. Before moving towards the steam slaker, the temperature of CaO is furthered reduced, which on the contrary increases the temperature of entering oxygen gas to the previous temperature in the cyclone [14]. It would be better to make a reliable comparison between calciner used in DAC process & rotary klin in Kraft process. So, a circulating fluidized bed is designed in this prototype can have the ability to supply 2Kt-CaO/day for reacting with CO₂ gas.

The minimum heat is requisite to govern the reaction is 3.20GJ/t-CaO. To make the calciner thermally effective, an equivalent amount of CO₂ (approximately 4.15 to 5.35GJ/t-CO₂) should be

uptake along with the increase of feed stream & reduction of energy loss to the ambient air. After observing the dewatering process held by pellets, the calciner is sorted to determine the fluidized properties.

2.4. Steam Slaker

The last portion of the unit operations is affixed for steam slaker which is employed for heating & drying the pellets again & providing sufficient stream for continuing the slaking reaction shown by reaction4 in figure 1. One of the most advantageous of using steam slaking is the way of occurring thermodynamic reaction for which the reaction enthalpy is forced to release at relatively low temperature over kraft rotary kline process [15]. Though the extreme point of temperature needed for slaking 100KPa steam is 500oC, still the fast kinetic reaction can be attained nearly at 280oC. An impervious turbulent fluidized bed is set up in the slaker to rotate a steam flow by a design made from partnership with Technip [16]. Then CaCO₃ pellets are received after washing & warming CaO at 670oC by preheating the oxygen in cyclone chamber at fluidized velocity up to 1m/s. This velocity conducts & quells CaO fragments to compose Ca(OH)₂. At the end, the pellets are dried up to 300oC & then sent to a pneumatic closed loop conveyor to rotate the CO₂ & steam further delivering them at the apex of calciner stack.

Actually outside of these four major unit operations, there requires also some further minor reactions in the plant to reduce the technical risks & providing enough steam of CO₂. To accomplish the remain operations of the process, a total summarize of configurations of power plant, CO₂ compressors & cleaners, oxygen plants etc. is applied this section. From these operations, some key parameters are observed that describe the performance of units based on their characteristics.

2.5. Heat & Mass Balance Configuration

Energy inputs along with heat & mass balance, power distribution etc. are provided in simplified way to describe the plant's configurations. It is estimated that the plant may need approximately 4.7 tons of water per ton of captured CO₂ from atmosphere at surrounding conditions of 25°C & 70% relative humidity. But this proportion doesn't stay always constant rather

it varies with dissolution molarity & ambient conditions which can be estimated from a relationship between water loss & humidity shown in Figure 2(b). This measurement is calculated with Aspen data & corrected by carbon engineering's pilot air contactors. In every cycle, the plant has ability to cast approximately 1% of the simulating Ca as a tailing object. This discharge acts as an evacuation to control the forming up of non-process substances that thrust into cycle by various pathways, most significantly as dirt ingested into the contactor. The overall simulation cost can be reached up to \$0.20/ton-CO₂ for making up a contribution & Ca release in CE's calculation at this discharge rate.

2.5.1. Process Simulation

The carrying out function or process in plant is calculated in Aspen Plus V8.0. The two thermodynamic property packages named RK-SOAVE & ENRTL-RK are used for gaseous phase & aqueous phase respectively. In this case, some following property databanks such as ASPENPCD, INORGANIC, PURE26, SOLIDS & AQUEOUS are followed from APV732. The sedimentation of salts & gas solubility can be identified definitely by operating manually. Chemical loops are approached in Aspen's logical order involved with modular mode where each single unit parameters are calculated in a frame of combined external spreadsheets.

2.5.2. Scalling

Actually scale is used for determining & presenting the carrying out function of any massive industrial process. Since pellet reactors as well as air contactors are available in modular amount, so the capabilities of them can be varied slightly from 1.1 Mt-CO₂/year lower down to sizes as small as 10.5Kt-CO₂/year along with close reduction of capital cost below to 100Kt-CO₂/year. In contrariwise, the calciner is considerably great in size of impervious lined chalice with perplexed materials that sharply results in cost scaling performances. The design made for calciner is applicable with internal diameter about 1m analogous to the amount of capture rate of 20Kt-CO₂ in per year where CE suggests for approximately 100Kt-CO₂ in per year applying with a cost economical scaling of small practical size in complete process. For direct air capture process, the heat exorbitance will be neared to the 1Mt-CO₂ in per year at that above mentioned scale, though the capital cost involved with unit receptivity will be about 85% higher.

2.5.3. Alternative Configurations

CE is improving several plant outlines to address appointed markets in each single unit operation. Although the configurations of unit operations are nearly constant, still these can vary according to their dealing of oxygen supply in power system & CO₂ compression.

The comparison line used for plant configuration, "A" on Table 1 which is appropriate to apply in geological storage. In this case, the location selection should be compared with low gas prices & the specifications must be suitable for pipeline to discharge CO₂ cope with the condition. The baseline arrangements should have specific sized in the energy plant for expedient analysis in order to neutralize the electrical input & output when the plants are actually connected with grid.

Again an Nth plant alternative with the constant outlines, "B" is involved together to ruminate development of construction & capital cost in some attainment & engineering firms. They are used to give a confirmation about development of tether & flexible relationship between construction & fabrication abilities of the firms.

Here two more additional process alternatives are presented on the baseline. An alternative that has no internal gas turbine & employs grid electricity along with minimum gas input, "C" meets all of power provided to further drain away the steam slaker by the steam cycle. The short description of the total energy demands & cost requirements are given in Table 1. This alternative looks for some minor changing process involved with low carbon intensity at minimum energy cost.

The last alternative is "D" that is optimized to supply CO₂ for synthesizing fuel. CE is improving the regenerations of electrolysis in air-to-fuel system where the hydrogen is used as a raw material to synthesize the fuel production steps [17]. Here ASU is dropped from DAC simulation to supply adequate oxygen into the DAC plant from electrolysis. The supply pressure should be kept approximately at 3MPa for lowering the complexity & simulation cost of CO₂ injection & clean up during synthesizing the fuel.

Table 1. Summary Performance of Plant Configurations

| Scenerio | Gas | Electricity Input (KWh/t-CO ₂) | C- Gas/C- Air | Capital \$ per t-CO ₂ /year |
|---|-------------------------------|--|---------------|--|
| | Input (GJ/t-CO ₂) | | | |
| A: Baseline: gas discharge → 15 MPa CO ₂ output | 8.81 | 0 | 0.48 | 1146 |
| B: Baseline with N th plant financials | 8.81 | 0 | 0.48 | 793 |
| C: Gas & electricity input → 15 MPa CO ₂ output | 5.25 | 366 | 0.30 | 694 |
| D: Gas & electricity input → 0.1 MPa CO ₂ output taking zero charge O ₂ | 5.25 | 77 | 0.30 | 609 |

3. Results and Discussion

Industrial counterparts of various unit operations differ adequately in case of operating conditions &

modular design that requires for testing & optimizing the overall integrated risk management. The design used for pilot plant have to meet two main aims are (1) to minimize the technical risk having possibility to occur at any unit operation using commercial scale hardware, & (2) to specify closed-loop process in building up of each unit. The CE is providing results & prototype designs for each pilot plants to improve pilot performances from some laboratory data [18-20]. Since the pilot is not used as a fully commercial plant with short-scale version, then some miniature risks presented by CO₂ compression & gas clean process is not taken for consideration. The pellet reactor as well as air contactor will operate when they both will be in combined loop with ability to capture 0.6t/day of CO₂ from air where calciner & steam slaker are also chosen for generating lime slurry in an overall chemical loop.

3.3. Pilot Contactor

Here the pilot contactor examines the representation or perfection of the fluid allocation systems & tower derived cooling CE's process. The structure used in this unit helps to cast down air through two arranged packing of banks where it is afterward removed from the central plenum through a plumb-axis fan. A bank with packing has a cross section of 3×5-m along with a depth selected about 3m packed from Brentwood XF12560 structured specification. The contactor can swallow air upto-170 t/hr at an inlet speed of 1.5 m/s that yields capture of 42Kg-CO₂ per hour. Pilot plant provides some selected data from air contactor that resembles the pressure drawdown with specified perfection has a lasting over about 0.80 year shown in Figure 2(a). Figure 2(a) has shown a relationship between air velocity & pressure drop exhibiting deficient long-duration distorting.

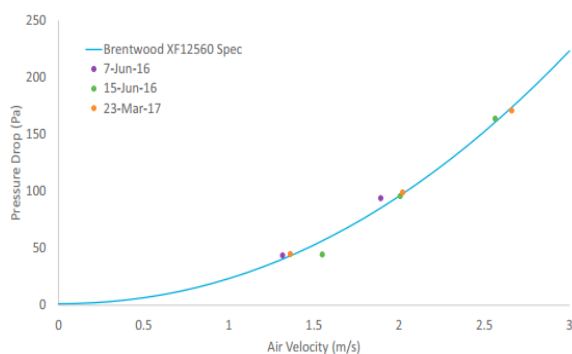


Figure 2(a). Pressure drop through dry packing & drift eliminator.

The steering performance along with some definite representations is depended on surrounding conditions. So water loss can be measured by evaluating ambient temperature, molarity of the possessed fluid & relative humidity shown in Figure 2(b). Humidity doesn't affect mass transfer co-

efficient, but will be affected by temperature [9]. Irregular changing of mass transfer co-efficient is involved with daily or seasonal temperature deflection that can be partly piece out by synthesizing the fluidized throughputs.

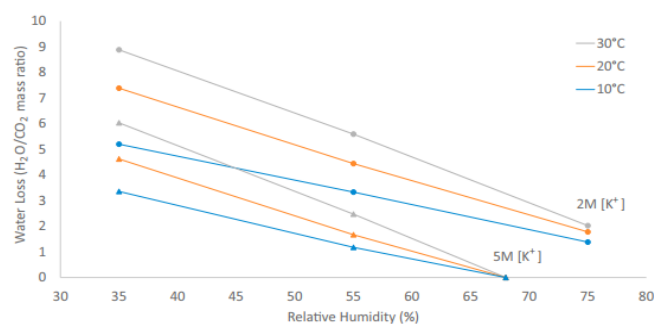


Figure 2(b). Calculated water loss from evaporation in the air contactor as a function of relative humidity & Molarity

3.4. Pilot Pellet Reactor

The pilot reactor used here is consisted with internal diameter 1.2, a 60° conical structure & height of 12m is analogous to design of commercial single cell. Automated adjunction of seeds, removal & processing of fines, & cleaning up of advanced pellets are endorsed by accessory equipment. The data from pilot plant reactor is shown by Figure 3. Figure 3(a) shows the elementary progress of process conditions being matured within several months from growth of seed bed. Again, Figure 3(b) displays the recovery of the seed bed addition to the pellet discharge cycle of 2 days. The pellet reactor can allow test the several processes under process condition, but sometimes it would be hard to maintain the pilot pellet if there are occurrence of any unexpected events of bed deterioration & seed blockage in the reactor. The performance of pilot reactor is determined based on Ca loading rate, fluid speed, bed height & the rotating concentration of calcite substances. The total accounted objective is to reduce the capital & simulated energy cost involved in reactor when the holding rate is approximately above 85%. The pumping of Ca is left from pelted bed & having an equivalent energy rate to fluidization speed & bed thickness & inverse equivalent to the Ca holding rate.

3.5. Pilot Calciner

The pilot calciner is employed here adjuvant with Technip to follow its contemplate for designing the calciner from specific data with an internal diameter of 0.15m to offer predictions of exact performance in commercial scale. The design of Technip uses a steel

container with a highly thermal jacket for reducing the heat loss through container walls. To accomplish the process of heating the jacket, there is used an external gas-fired heater along with an electric heater to heat the every small spot of the jacket & to manage the bed-heat transport system in a large impervious calciner. The pilot calciner is comprised of 8m long riser with oxy-flamed moving fluid. The configuration in this case differs from the commercial one by using additional fluoseal for solid re-circulating, but not for solid deliverance. Here the reaction enthalpy is willed by combusting the natural fluidizing gas with air for acquiring the high calcinations & high material flux. The data achieved from calciner is shown in **Figure 4**. Throughput is ascertained by fluidization velocity based on performance of the oxy-fired calciners in commercial scale.

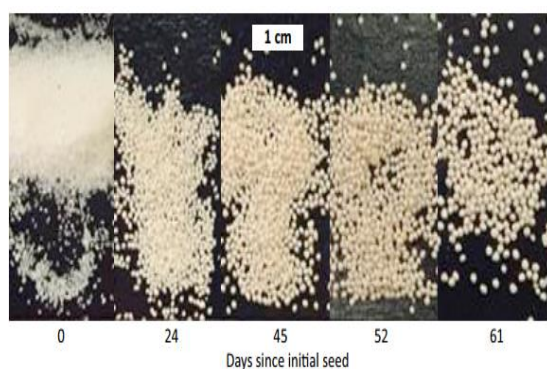


Figure 3(a). Evolution of CaCO_3 pellets sampled from bottom of pellet reactor bed.

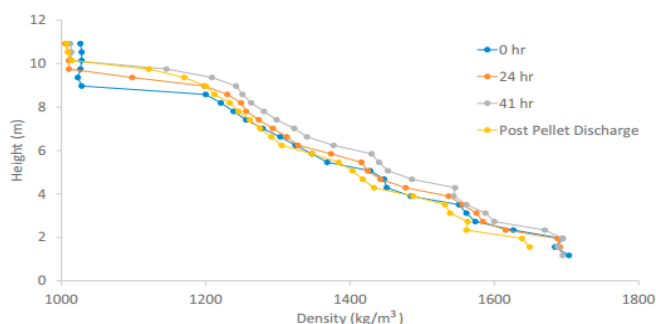


Figure 3(b). Pellet reactor density vs height profile during reactor operation.



Figure 4(a). Photo of CaCO_3 pellets fed into calciner & CaO pellets at discharge

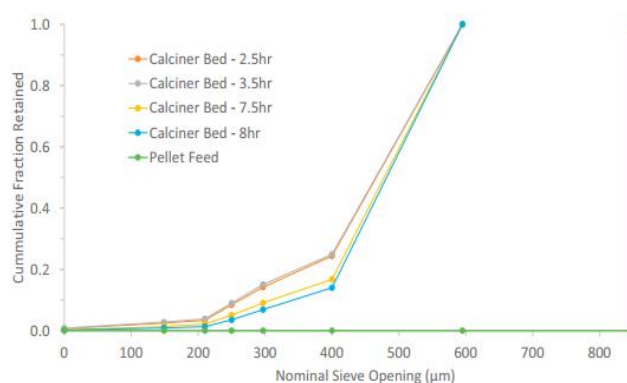


Figure 4(b). Size distribution of bed materials & feed pellets

The difficulty involved with design of circulating bed regime is not defined by Technip. Figure 4(a) shows the separation between feed & product pellets. In turn, Figure 4(b) shows the particle size distribution determined by fluidization properties.

3.6. Process Economics

Though the technology developers always have incentives to estimate the cost relevant knowledge, still the cost needed for the new technology is not inherently certain especially in DAC process [21]. Actually when DAC process is considered, then all of its commodities & equipments involved necessarily with pilot plant as well as manufacture of hardware are not yet available with moderate price in market. Because the maximum amount of money spent behind the novel processes & methods used for increasing the industrial facilities varies with manufacturing scale. Additional uncertainty of cost arises from building up of new facility in estimating the energy inputs & the capture rate.

The costs needed for DAC process can be specified in three kinds are capital cost, non-fuel operating cost & levelized cost. The front end loading (FEL) process is used in CE for project management that has started improvement of FEL-3 engineering to commercialize the CO_2 capture rate at 2Kt/year [22].

Technip works with CE through few years to estimate the processing cost involves with vendor data come out from each major & minor unit operations.

It can be observed that the causes of unanticipated on these large projects accounted for three conventional types of risks are project, storage, contextual. The rough estimation of total plant cost has been done from multiple equipment vendors & industrial cost estimating factors through using consultants & standard engineering reference sources [23]. CE & Solaris continuously run an estimation for non-fuel operations unit by unit with industrial experiences used for first & Nth plant designs includes water & make-up chemicals. In this case, the average cost of using water for manufacturing is \$0.1/m³, though the cost is not considered as fixed.

The levelized cost is estimated by doing a summation of capital cost, energy cost & non-fuel cost per ton of captured CO₂ from ambient air. The levelized cost is determined using capital recovery factor & capital intensity of fluid. The approximate amount of interest changes on annual capital cost is 5% based on equity of weighted average capital cost. This yields a CRF value of 9.4% exhaust the project over 20 years. Though the higher the project finance is used, the more financial structure would be complex include taxes, still these uncertainties can be reduced using variation of CRF value. The assumed result would be a natural gas cost of \$3.5/GJ & electricity cost of \$60/MWhr respectively.

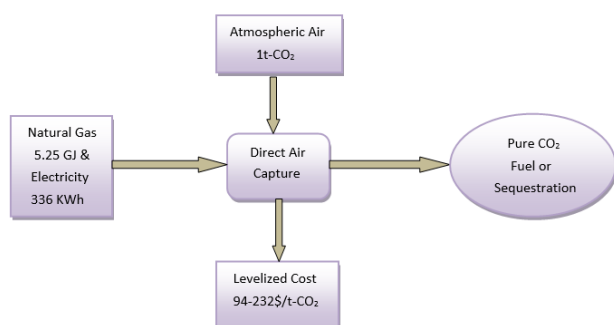


Figure 5. Process simulation cost estimates

4. Conclusion

The most significant estimation of DAC costs from emission of CO₂ & electricity supply has been closed to \$780 per ton of avoided CO₂ & to \$550 per ton of captured CO₂. The divergent design is used in these processes are re-roughly matched with American physical society (APS) design when an estimation on cost discrepancy is surveying over capital & energy cost. Here we use PVC tower packing rather than using of steel tower packing for having its higher pressure drop in per unit area of surface which costs less than \$250/m³. Sometimes the designs can't be suited for the environment, because the design needs more caustic solution to capture the large amount of CO₂ from atmosphere which release high amount of caustic

solution to the surroundings must affect the ecological hazard. Then ambient air can also be used to entrain the released caustic mist by un-enclosing the contractor simultaneously. But this concern in this case of APS design seemed to be complex & incorrect as there permitting location is not even to be possible. Vertical towers have considerably higher capital cost estimated on each unit of volume depend on using of large-scale cooling towers [24]. Also the calciner used in the DAC process has lower energy demand from using APS design which differs from about 2.75 to 3 GJ/t of processing CO₂. This low energy demand come from a heat integration in thermal efficiency using steam slaking. The little sense can be made to build up the DAC process plant by supplying electricity with emission intensity of 620Kg-CO₂/MWhr. It is also important to assess the full life cycle of DAC for addressing the direct & indirect emissions from production inputs, disposal of wastes & fugitive elements by observing the preliminary process description. Though there is prevailing of a substantial uncertainty of performance & capital cost, still millions of dollars are allocated for deploying the technology widely. The performances of each unit operations should be carefully maintained to reduce the processing cost. If everything goes well, then this process acts as a larger platform to capture largely CO₂ from ambient air.

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