INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

ISSN: 2454-132X
Impact factor: 4.295
(Volume 5, Issue 2)
Available online at: www.ijariit.com

Particulate emission control and direct carbon dioxide capture

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ABSTRACT

The atmosphere is one of the valuable resources which need to be protected for future generation. It's being increasingly polluted every year. In the past 10 years the air in the many regions of our country such as Delhi, Mumbai is seriously polluted. Due to modernization and development, the usable of automobiles were increased which emit harmful exhaust toxic gases with particulate emission. The level of CO_2 content in the atmosphere was increased up to 410 ppm. In the meantime, CO_2 is also the raw products for many industries such as food processing industries, Pharmaceutical industries, fire extinguishers etc. We have conducted experiments to capture carbon dioxide from direct air. This process is carried out using a carbon absorbent solution made to react with atmospheric air in the reaction chamber in which carbon dioxide present in the air directly captured in the absorbent solution. Air is constituents of various gases. Here we discussed in capturing the carbon from the air. Direct air capture is leading technology to capture CO_2 from the air. Here various concentrations of solutions are made to effective capture of carbon dioxide. In addition, Electrostatic precipitator is implemented to control the particulate emission. It holds the small micro dust particles up to 2.5 PM. The operation performs in controlling particulate and capturing carbon dioxide from the air.

Keywords— *Atmosphere, Particulate emission, Electrostatic precipitator, Direct air capture*

1. INTRODUCTION

Carbon dioxide (CO_2) concentration in the atmosphere is the major causes of global warming. Direct air capture is one of the leading and compromising technologies for capturing CO_2 directly from atmospheric air. Air capture technology provides a vital new tool for carbon dioxide management, making it possible to capture carbon dioxide from ambient air economically. Air capture technology can compensate for any emitted carbon dioxide by capturing an equal amount of CO_2 at different regions and time. Direct Air capture is independent of the source of emission and so can be applied in any regions independent of the composition of air. Direct Air capture can be applied at a large scale can reduce the carbon dioxide content in the atmosphere, thereby reducing the greenhouse gas concentrations temporary. Finally, arresting of carbon dioxide enables the closure of the carbon cycle by recapturing CO_2, so that it can again serve as the chemical feedstock that provides carbon for fuel synthesis.

1.1 Composition of air

According to NASA, the gases in Earth's atmosphere include:

- Nitrogen: 78 percent
- Oxygen: 21 percent
- Argon: 0.93 percent
- Carbon dioxide: 0.04 percent

Trace amounts of neon, helium, methane, krypton and hydrogen, as well as water vapour.

1.1.1 Emission of CO_2: Rapid economic growth has contributed to today's ever increasing demand for energy usage. An obvious effect of this issue is an increase in the use of fuels and sometimes alternate fuels, particularly conventional fossil fuels that have become a major key energy source since the industrial revolution begins. However, the excess consumption of fossil fuels has resulted in adverse effects on the environment, particularly related to the carbon dioxide emission, a major anthropogenic greenhouse gas. According to the Emission Database for Global Atmospheric Research, global carbon dioxide emission was increased up to 33.4 billion tons in 2011, which is 48 percent more than that of two decades ago. Over the past few centuries, atmospheric carbon dioxide level has drastically increased more than nearly 40%, from 300 ppm during the pre-industrial time to the highest record level of 400 ppm in May 2013 and further increased up to 410 ppm in March 2018 with a corresponding to increasing in global surface temperature of about 0.9 °C. Without a change of climate mitigation policies it is estimated that global greenhouse emission in 2030 will increase by 25–90% over the year 2000 level, with carbon dioxide equivalent concentrations in the atmosphere growing to as much as 600–1560 ppm.

1.1.2 Direct air capture: Direct Air Capture (DAC) is a largely theoretical technique and also an economically efficient technology in which carbon dioxide and potentially other greenhouse gases are removed directly from the atmospheric air. The current method uses large fans that force atmospheric air through a carbon capture filter, using a carbon adsorbent to capture CO_2. To achieve any significant change on global CO_2 concentrations, DAC needs to be implemented on a large scale, raising serious questions about the energy it requires, the levels of water usage for particular technologies, and the toxicity impacts from the carbon absorbents used.

1.1.3 Particulate Matter Emission: “Particulate matter” (PM) is the common term used to describe solid particles and liquid droplets suspended in the atmospheric air. The composition level and particle size of these airborne substances and droplets may vary. Some of the particles are large enough to be seen through the naked eye as dust or dirt, while others are so small they can only be seen using an additional source such as a powerful microscope. Particle sizes vary largely but particularly two size ranges such as PM10 and PM2.5 are widely monitored and should be controlled. Both are considered to be the major emissions in ambient air. PM10 includes particles which have a diameter less than or equal to 10 microns and it is approximately equal to one by seventh the diameter of human hair. PM2.5 is the subset of PM10 particles have a diameter less than or equal to 2.5 microns.

Particles having sizes within those two size ranges behave differently in the atmosphere. Particulate Matter (PM) 2.5 which is also known as fine particles can remain suspended in air as airborne for long periods and migrate thousands of kilometres by the wind. Coarse particles or the subset of PM10 is larger than 2.5 microns by particle size and they do not remain airborne as long. It has a limited spatial impact because it tends to deposit on the ground. Larger size particles are not readily transported across urban areas because they are generally too large to remain suspended in air and they tend to be settled down or get deposited easily on contact with surfaces. In short, as the particle increases in size, the amount of time the particles suspended in air decreases. The PM Concentrations indicator describes the various ways PM can harm human health and the environment.

2. LITERATURE REVIEW

Yeh and Bai, 1999 [1] conducted an experiment to investigate the ammonia and MEA for capturing CO_2 in a bubble reactor. Their tests showed that the NH_3 absorbent was superior to MEA absorbent in its capacity to absorb and remove CO_2 from flue gas systems. CO_2 removal efficiency for NH_3 absorbent could be as high as 99% under proper operating conditions. And the CO_2 absorption capacity by NH_3 scrubbing could be over 1.0 kg CO_2 kg NH_3. On the other hand, the maximum CO_2 removal efficiency and absorption capacity using MEA absorbent are 94% and 0.4 kg CO_2 kg MEA, respectively and performed CO_2 absorption and regeneration with aqueous ammonia in a semi-continuous flow reactor. The result was concluded that approximately 62% of regeneration energy is saved for the aqua ammonia process than compared to MEA process.

Diao et al., 2004 [2] designed a sieve-plate tower system and performed experiments in an open continuous flow reactor. They studied the mechanism and kinetics of the reaction between CO_2 and NH_3 absorbent. Their experiment results showed that the reaction temperature played a key role in CO_2 removal. The CO_2 removal efficiency reached the highest at 33C. The overall CO_2 removal efficiency could be above 95%.

Storaloff et al., 2008 [3] studied the feasibility of a NaOH spray-based contactor for capturing carbon dioxide directly from ambient air. When considering absorbent recovery and CO_2 sequestration, the cost of CO_2 capture using NaOH solution ranges from 53 to 127 \$/ton-CO_2 under alternate operating parameters, by using a spray with 50 m mean drop diameter, the range of cost reduces to the low end. Their research suggested that a structure area of about 760 by 760 m would be required to capture 1 Mt/yr of CO_2 under the base-case contactor running at the cost-optimal flow rate.

Srivastava V. K. et al., 2007 [4] developed a mathematical model for the thin film reactor, wherein the mass transfer takes place with chemical reaction. They solved the coupled partial differential equation which describes the mass and heat transfer in the liquid by finite difference method using an implicit scheme. They observed the difference between the concentration gradient and temperature gradient due to the sensitivity of the model parameters. The temperature increases with axial distance due to the exothermicity of the reaction. Although the concentration of gas has a significant effect in the radial direction negligible change has been observed for the variation of temperature which is because of the small thickness of the liquid film resulting in not many exothermic effects occurring in the radial direction. The maxima of interfacial temperature and the mixed mean liquid temperature increases within a short distance from the inlet due to the high exothermicity of the reaction for instantaneous reaction.

3. METHODOLOGY

The process for capturing carbon dioxide makes the use of various methods with the leading technologies. This is one of the currents trends in this era in which various researcher have put their efforts to identify and simplify the process. This project deals to capture the carbon dioxide from the ambient air and to separate it with simpler methods. Air is sucked from the atmosphere by the blower through an electrostatic precipitator. The air being sent through a duct followed by charging electrodes in ESP. The dust particles in the air are ionized in the electrode and it is deposited in the collection electrodes. Then the air passes to the falling film contractor where the dust-free air is contacted with the carbon absorbent liquid. Air containing CO_2 is reacted with a solution and dissolved as a carbonate solution. Then CO_2 removed air is expelled into the atmosphere. Then the solution containing carbonate is undergoing for the further process from the separation process.

3.1 Components Used

3.1.1Pre filter: Pre-filter filters hairs and large dust particles from the air before goes into operation. Pre filters are the first layer of filtration. Fresh air is passed through the pre filter and the output air of pre filter is then passed to further process.

3.1.2 Blower: Blowers provide air ventilation and industrial process requirements. Blowers also used to pressurize the air to blow off the ducts, dampers, or other components in a system. The blower rotor receives rotational energy from a rotating shaft of an electric motor. Blowers classified into two general categories. They are centrifugal flow and axial flow. Here centrifugal blower is used. A centrifugal blower is a mechanical device used for moving air or other gases with increased pressure in a direction at an angle to the incoming fluid. Centrifugal fans are not positive displacement devices and they have certain merits and demerits when compared with positive-displacement blowers and they are selected according to the particular purposes. Centrifugal blowers are more efficient and capable to blow a large volume of air with less space occupied.

3.1.3 Electrostatic Precipitator: An Electrostatic Precipitator (ESP) is a filtration device that uses electrostatic charges to removes fine particles, like dust and smoke, from a flowing air using the force of an induced electrostatic charge.

The process of an ESP is explained below in the flowchart given:

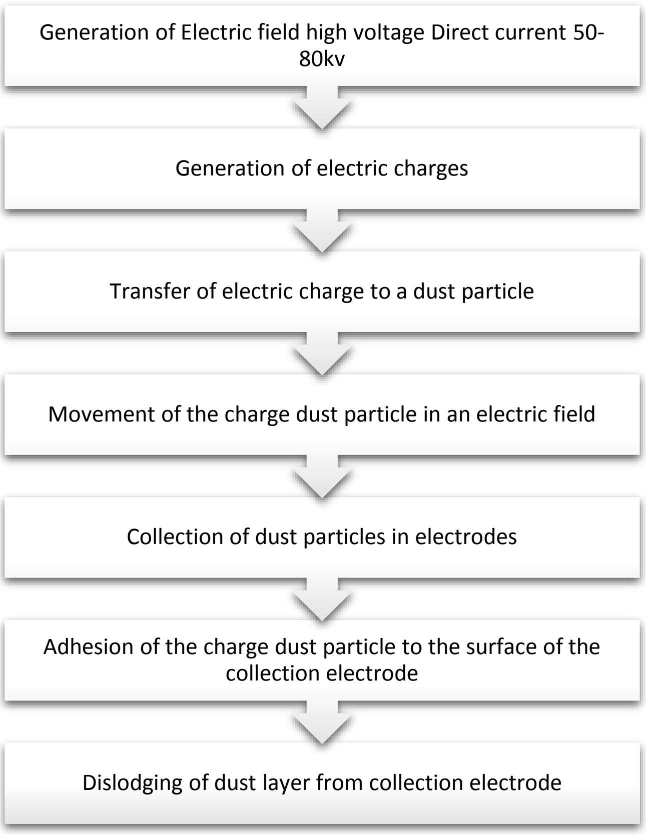

Fig. 1: Process of an ESP

Firstly the size distribution of dust particle should be determined then the migration velocity is calculated from the information of size distribution of dust. After that amount of charge on a dust particle is calculated by using the appropriate equation. On the basis of precipitation rate the surface area of collecting electrode for a given efficiency at a particular air flow rate is calculated by using Deutsch-Andersen relationship.

C.1 Field Charging

Q_f = ne = ne = $1.6*10^{-18}$ C

Where, n=Number of electronic charge, n=10; r =Radius of particle; E=Average field intensity, e=$1.602*10^{-19}$ C

C.2 Migration Velocity

The velocity of charged particles suspended in the atmosphere under the influence of an electric field is known as migration velocity of that particle. The migration velocity of a particle is the most important parameter and function of a large number of operation quantities such as- particle size, gas viscosity, Electric field strength, properties of the dust particle. Principal forces acting on the particle are an electric force, gravitational force, viscous force and inertial force.

$$V_{pm} = \frac{qEC}{3\pi\mu d}$$

C.3 Cunningham Correction Factor

$$\mathrm{C} = 1 + \left(\frac{2\lambda}{d}\right)\left(1.257 + 0.4e^{\frac{0.55d}{\lambda}}\right)$$

$$\lambda = 0.066\mu m = 0.066 * 10^{-6}m$$

$$\mathrm{C} = 1.0331$$

Therefore,

$$V_{pm} = \frac{qEC}{3\pi\mu d}$$

$$V_{pm} = \frac{1.68 * 10^{-18} * C}{3 * 3.14 * 1.81 * 10^{-5} * 0.5 * 10^{-6}}$$

$$V_{pm} = \frac{1.6 * 10^{-18} * 5 * 10^{8} * 1.0331 * 7}{3 * 22 * 1.81 * 10^{-5} * 0.5 * 10^{-6}}$$

$$V_{pm} = 9.68 \text{ m/s}$$

Where, V_{pm}= Particle migration velocity towards the collector electrode; q = ne, value of n depends upon types on charging (diffusion or field); C = Cunningham correction factor; E = Collector electric field; μ = gas viscosity; and d=particle size (μm); μ= micron, s=second.

C.4 Collection Efficiency of an ESP

The collection efficiency of an ESP as a function of precipitator size and gas flow rate is given by the Deutsch-Andersen Equation

Assumptions:

a. Particles are fully charged by field charging
b. Uniform gas velocity throughout the cross section
c. Repulsion effect is neglected.
d. No hindered settling effect.

Collection efficiency mathematically expressed as follows:
Mass of the dust=$1.81*10^{-5}$ Kg
Maximum diameter of dust=0.005 to 5μm
Molecular viscosity of gas μ=$9.3*10^{-4}$ kg/ms
Relative permittivity of medium £$_r$=10
Permittivity £=$8.854*10^{-12}$ F/M
Ion mobility rate b= $1.8*10^{-4}$ m^2/s
Charge diffusion coefficient, D=$1.0*10^{-2}$m^2/s
d = $_{\text{particle}}$ diameter

Electric charge of each particle, q = ne = $1.6*10^{-18}$ C

$$\eta = 1\text{-exp}\left(\frac{-\mathrm{Aw_e}}{\mathrm{Q}}\right)$$

$$\eta = 1\text{-exp}\left(\frac{-0.171*9.6*10^{-4}}{4}\right)$$

$$\eta = 90\ \%$$

3.1.4 Falling Film Contractor

A falling film contractor or vertical column contractor is specific chemical equipment used to get heat and mass transfer between two fluid phases. In a falling film contractor, carbon dioxide in the air gets reacted with aqueous sodium hydroxide to form sodium carbonate solution. When aqueous sodium carbonate is added to aqueous calcium hydroxide, calcium carbonate solid will be precipitated. This type of reaction is called a precipitation reaction. Synthetic fiber is used as the porous material.

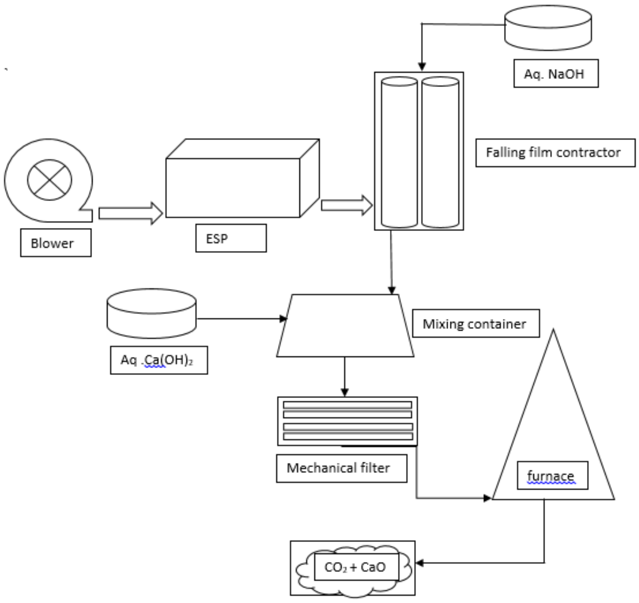

Fig. 1: carbon dioxide capture process

Aqueous sodium hydroxide absorbents are one of the most promising approaches. In this process, carbon dioxide from the atmosphere is chemically dissolved into NaOH (aq) (sodium hydroxide) solution as Na_2CO_3 (sodium carbonate); then the Na2CO3 is then reacted with solid $Ca(OH)_2$ (calcium hydroxide), which precipitates and produces $CaCO_3$ (calcium carbonate) crystals, heat is applied to the $CaCO_3$ crystals to produce pure CO_2 gas and CaO is liberated.

Air is pumped through the falling film contractor which contains CO_2 absorber as the first step of this process. CO_2 absorber for DAC is designed is a thin-falling-film contractor to maximize the contact area between the air and the solvent and hence increasing the absorption of gases. The solvent is regenerated in the causticizing process which is carried out in causticization unit by reacting the Na_2CO_3 (sodium carbonate) with $Ca(OH)_2$, which carbon dioxide to the form of $CaCO_3$ solid crystals. Then the crystals are separated in the further process using a mechanical filter. The crystals from the filter are in wet form so the steam dryer is used to dry the crystals. Then the dry crystals are allowed to heat in a furnace to produce pure CO_2 and pure CaO (calcium oxide) gas. The CaO is then hydrated to regenerate the calcium hydroxide.

4. EXPERIMENTAL SETUP

A different percentage of NaOH solution is used for testing with the prototype made and concentrations are 1%, 3%, 4% and 5% (w/w) NaOH solution in distilled water. Atmospheric air with an average temperature of 30℃ and the presence of a normal percentage of carbon dioxide in the air is used for the testing. Air flows inside the chamber is regulated with the blower. The solution is sprayed on custom-made falling film contractor made to maximize absorption at the lowest possible energy input. Air from the atmosphere is made to flow into reaction chamber continuously through an electrostatic precipitator by use of a blower in which speed of the blower can be regulated to increase or decrease the flow of air, this air first passes the first layer of dry filters called pre-filter. These dry filters do not allow large dust particles larger than 10 microns to enter into the chamber and make only clean air to enter.

Air in the chamber goes to custom-made NaOH filter. Aqueous NaOH solution is distributed from the top of the reaction chamber; distributor of aqueous NaOH solution giving a uniform spreading of absorbent solution over the porous membrane filled inside the chamber. The membrane is so designed so that, the speed of air is reduced to a certain level to give sufficient time for the reaction to takes place. The membrane is designed to make air to pass through aqueous solution layers of NaOH, hence improving higher surface area contact and reaction better efficiency.

Air passing from NaOH solution filter most of the carbon dioxide is absorbed and remaining air is exhausted out of the chamber via exhaust pipe.

The chemical equation is as follow:

$$2Na(OH)_2 + CO_2 \rightarrow Na_2CO_3 + H_2O$$

A1 mol of CO_2 will react with 2 mol NaOH to give a product of 1 mol Na_2CO_3. That is mixing of 1 mol of CO_2 (44g CO_2) into a 2 mol NaOH solution (2*40 = 80g NaOH) will produce 1 mol of Na_2CO_3 (106g Na_2CO_3). All the reactions are completed further reaction follows,

$$Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH$$

After the absorption of CO_2, the solution becomes rich in Na_2CO_3. This solution is made to react with aqueous $Ca(OH)_2$ to form $CaCO_3$ and NaOH solution, hence giving back the main working chemical sodium hydroxide (NaOH). $CaCO_3$ is precipitated as solid and it is easily removed from the aqueous solution. NaOH obtained is repeatedly recirculated into the chamber to filter out Carbon Dioxide.

5. RESULTS

These experimental results are obtained from a mixture of air and carbon dioxide gas fed to the reaction chamber just for testing the correct working of the system. The CO_2 concentrations at the inlet and outlet of spray dryer are measured by an infrared CO_2 gas monitor.

$$CaCO_3 \rightarrow CaO + CO_2$$

1 mol of $CaCO_3$ that is 100 gram of $CaCO_3$ is heated to produce 1 mol of CaO and 1 mol of calcium oxide. Finally settled calcium carbonate is collected and carbon dioxide is separation under further process. There are many processes is used to separate carbon dioxide from substrate followed by storage and transport.

According to the law of definite proportions, in a chemical substance, the elements are always present in definite proportions by mass.
Percentage of CaO present in $CaCO_3$ - 56%
Percentage of CO2 present in $CaCO_3$ - 44%

Similarly, 100g of Calcium carbonate contains 56g of calcium oxide, 44g of carbon dioxide by mass.
Let us find the masses of CaO and CO_2 present in 100g of $CaCO_3$.
Mass of Calcium Oxide present in 100g of $CaCO_3$ = 56/100 X 100 = 56g
Mass of Carbon Dioxide present in 100g of $CaCO_3$ = 44/100 X 100 = 44g

The removal efficiency of CO_2 as a function of reaction between ambient air and inlet aqueous sodium hydroxide operating at ambient temperature. In order to differentiate the influence of the carbon dioxide absorbent concentration, two different concentrated aqueous solutions of NaOH with the values of 3 and 1 wt. % is used and the results are depicted in Chart 1.

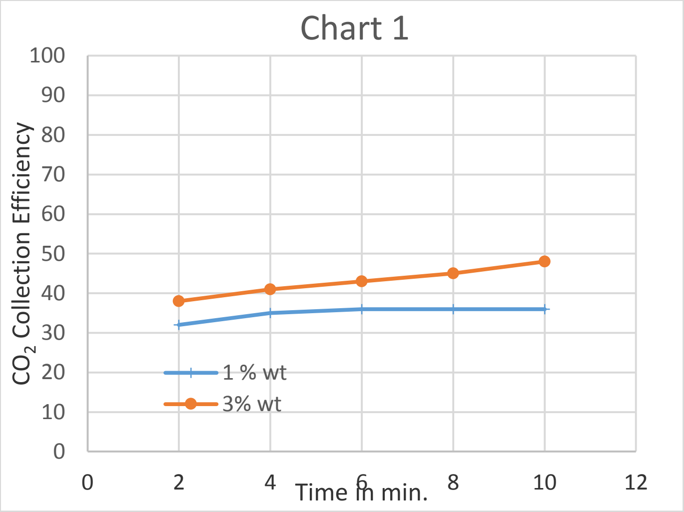

Fig. 2: Chart one

From the observations in chart 1, with increasing of the concentration of carbon absorbent, the reaction rate increases resulting in enhancement of the CO_2 removal efficiency. Chart 1 shows that the maximum removal efficiency of 32% with 3 wt. % of aqueous NaOH. As can be seen, increasing the absorbent concentration from 1 to 3 wt. % leads to an enhancement in removal efficiency due to providing a higher driving force to the reaction. As the concentration of absorbent is increased, the rate of reaction will also be favored due to providing a higher concentration of the reactant.

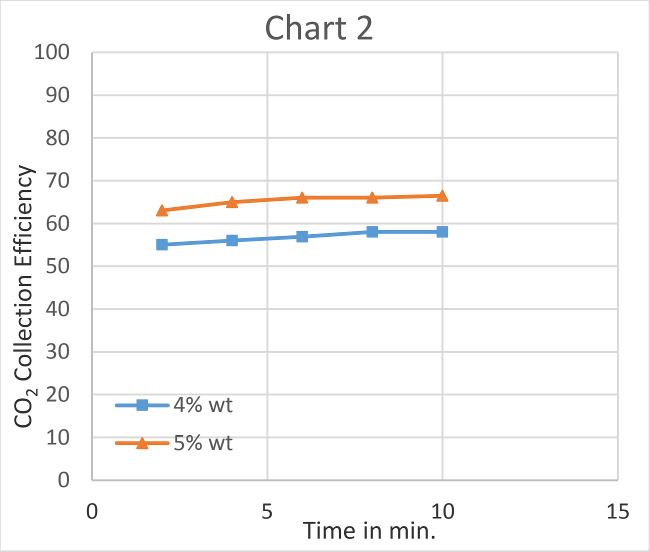

Fig. 3: Chart 2

Similarly, the chart 2 shows the increase in the concentration of aqueous carbon absorbent solution increases the collection efficiency of the carbon dioxide in the reaction chamber from the ambient air.

6. APPLICATIONS

- It can be implemented in industries to reduce particulate emission.
- It helps in removing the PM particles upto 2.5 microns hence this system helps in controlling health problems and this can be installed near public areas specially in traffic signals, parks etc.,
- It helps in removing carbon dioxide from the atmosphere hence its controlling greenhouse gases.

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APPENDIX

PM: Particulate Matter
PPM: Parts Per Million
GHG: Greenhouse Gas
CCS: Carbon Capture and Storage
CDR: Carbon dioxide Removal
ESP: Electrostatic Precipitator
NASA: National Aeronautics and Space Administration