Electrostatic Precipitator (ESP) for Reducing CO2 and Particulate Matter (PM) Emission from Automobile Exhaust

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Abstract— Electrostatic precipitators are majorly used in the power plants and industries to eliminate the harmful flue gases that are emitted into the atmosphere. The constantly increasing growth in the number of automobiles is one of the main causes of toxic atmosphere which require ESPs to be installed into the system to overcome air pollution by eliminating harmful gases like CO, CO2 (a greenhouse gas), NOx, SOx and PM from the large vehicular exhaust. The industrial ESPs are very huge in size and operate on very high voltages but ESPs for automobiles need to be scalled down into a retrofit device. In this paper we brief about the reduction of CO2 and PM emission from the engine exhaust.
Keywords: ESPs, CO, CO2, NOx, SOx, PM, retrofit, automobiles, vehicular exhaust

I. Introduction

Electrostatic filter or electrostatic precipitator (ESP) is a device, which produces an electric field that can decompose particles in air or gas. Compared to other conventional filters, ESPs have the low air pressure drop, high efficiency, and less maintenance. ESPs disintegrate particles less than ten micron while other filters work with a poorer performance. It can collect particles with diameters of 0.1 pm to 10 pm (pico-meter)

An electrostatic precipitator works on the principle of electrostatic precipitation with the application of high voltage which leads to corona discharge, ionization, transmission and finally collection of the suspended particles in the exhaust gas based on attraction and repulsion of charges. ESP consists of vertical parallel discharge plates and the ground collector plate that act as electrodes. The electrodes are powered with high voltage source to generate the static electric field between the two. The voltage can go up to a million volts based on the requirement of application. The electrodes are kept at a calculated safe distance to avoid shorting. When the gas enters the ESP, it gets into the zone of strong negative electric field produced by the discharge electrodes which after a certain voltage produces corona discharge that is nothing but the electrical breakdown of the gas leading to ionization. The electric current will flow through the particles by ionizing them and reaching the grounded electrode. In this process, the dust particles will get ionized and they will be negatively charged, in turn giving rise to free electrons that bombard with other gas molecules to give more free electrons and this process leads to a chain reaction responsible for emitting a greater number of free electrons that eventually get adhered to the solid particulates present in the flue gas and make them negatively charged. The strong negative electrical field around the discharge electrode repels the negatively charged solid particulates while the strong positive electrical field around the ground plate attracts the solid particulates towards it and forms a layer on the plate. To eliminate the solid particulates accumulated on the electrode, rapping mechanism and hoppers are used but for a pilot-scale ESP, a small waste collecting unit can be made. For this application the electrostatic precipitators should be scaled down to be be fitted onto the exhaust manifold of the automobiles. The already existing catalytic converters in the automobiles will convert the highly harmful gas carbon monoxide into a lesser harmful gas carbon-dioxide and alongside when the ESP is used the lesser harmful gas, which is a major contributor to greenhouse effect can be eliminated including solid aerosols. The difference between an ESP that is used for an automobile and an ESP that is used for industrial purpose is the operating voltage, operating temperature and working gas. Working gas here is the emissions from petrol or diesel engines. The figure 1 shows the principle of electrostatic precipitation.

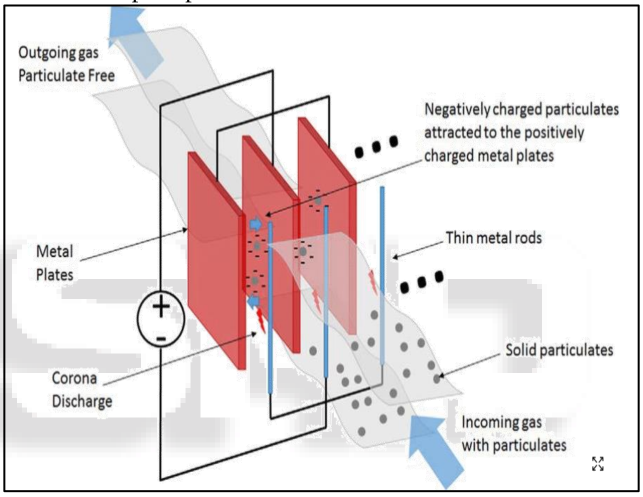

Fig. 1: Principle of Electrostatic Precipitator

II. Mathematical modelling

The equations for governing the flow problem are the continuity and Navier-Stokes equation while the effect of electric field on the flow field plays an important role. In addition to this, because of the small effect of particles on the electric and velocity fields, an appropriate simplification is made by assuming a one-way coupling, i.e., the particle motion is affected by the electric field, but not the other way around. The unsteady equations governing the incompressible electro-hydrodynamic flows in 3D, including a force as the source term i.e. electrostatic force, are given as

A. Electrostatics module:

The dependent variable is the electric potential, V

By Gauss's law,

$\nabla . D = \rho\ v$

Electric potential V and the electric field E are related using the formula:

$E = -\nabla V$

Where, D: electric displacement (C/m2), ρv: volume charge density (C/m3), E: electric field intensity (V/m), V: electrostatic potential (V).

B. Motion module of charged particles:

Newton's second law is used to describe the motion of any dust particle, which is given by:

$$d(m_p v)/dt = F_t$$

Where, m_p is the mass of the particle; v is the velocity with which the particle is moving, and F_t is the inertia force experienced by the particle

The electrostatic force experienced by the particles is given by:

$$F_e = Q_a E$$

Where Q_a is the region where the electric field strength E is acting, F_e is the electrostatic force experienced by the charge.

After the initial modelling, an efficient mathematical equation is required to find out the collection efficiency of the collecting electrode which is given by,

$$\eta = 1 - \exp(- w_e p)$$

$= 1 - \exp(- w_e A/R)$

Where, w_e is the migration velocity (w/s),

p is A/R is the specific collection area (s/m)

A is the area of collecting electrode (m^2) and

R is the flow rate of gas (m^3/s)

Collection efficiency is also affected by the following factors:

1) Electrode geometry
2) Characteristics of the dust particles

III. PARTICULATE MATTER IN WORKING GAS

Although particulate matter is found in both petrol and diesel engines, diesel exhaust is a major contributor to the particulate matter pollution. The black smoke emitted by the old diesel engines is nothing but the particulate matter emission. It is proved that the solid particulate matter given out by the automobile engine exhaust is harmful to the environment and it also puts human health at risk, majorly causing lung and heart diseases. There is both primary particulate matter emission and secondary particulate matter emission. Secondary emission is from the volatile organic compounds (VOCs) emitted by cars and truck tailpipes that eventually get converted into particulate matter after chemically reacting in the atmosphere. The size of the particles is directly linked to the potential for causing health and environmental problems. The size of particulate matter plays a major role in deciding the extent of pollution it can cause because the smaller particle it is, the more damage it causes as these particles are easy to be carried by the winds for long distances and they will settle on the water bodies making them less acidic and disturbing the aquatic ecosystem and these particles are easy to enter the human body causing breathing problems. Particulate matter is basically a mixture of both sold and liquid particles suspended into the atmosphere which primarily consists of soot particles of diameter less than 40 nm, polynuclear aromatic hydrocarbons (PAH) and minute particles like pollen and liquid droplets. The emission rate of particulates for an engine is calculated by particulate matter (PM) mass (mg/km) and total particle number (1/km). The figure 2 gives the comparison of the emission rates of particulates from various engine technologies such as CNG, Gasoline, GDI and Diesel.

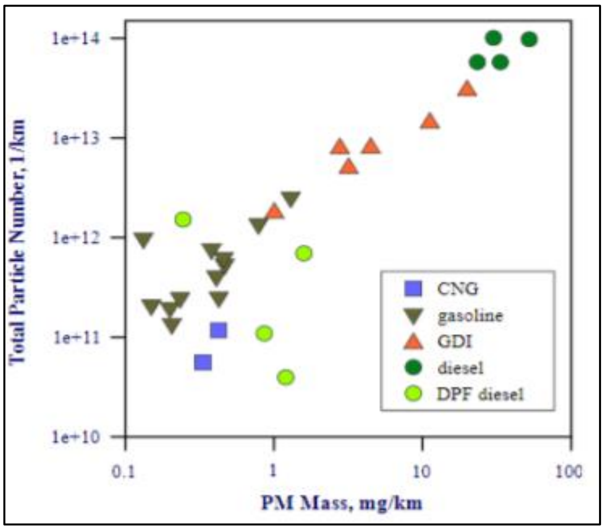

Fig. 2: Particulate matter (PM) emission rate in different fuel engines.

A. How Carbon Monoxide is converted into CO_2 and the Effects of CO_2 on Atmosphere:

The pollutant gases made by car engines include a poisonous gas called carbon monoxide, as well as VOCs (volatile organic compounds) and nitrogen oxides. Carbon monoxide is one of the most toxic gases emitted by vehicle exhaust into the atmosphere. Being very harmful for humans, eliminating this is a must but is a big task which is done by the catalytic converter. The gas is made by harmful molecules, but it need not be made of harmful atoms. A typical catalytic converter found on most newer cars and trucks combines oxygen with carbon monoxide to form non-poisonous carbon dioxide (CO_2) reducing the high concentrations in the exhaust manifold typically 30,000 ppm or more to low concentrations typically below 1,000 ppm after the catalytic conversion, but CO_2 gas percentage in the atmosphere should also be in check because of its property to increase the temperature of the atmosphere. CO_2 causes 20% of the Earth's greenhouse effect and hence the name greenhouse gas for CO_2. Due to increase in Earth's temperature, there is meltdown of glaciers which is disturbing the habitat of many animals. Exposure to CO_2 can have ill-effects on human health, too. Hence it is required to cut down on the percentage of carbon-dioxide released into the atmosphere, which can be effectively done by retrofitting the Electrostatic Precipitator into the exhaust system that uses the principle of precipitation using high voltage.

IV. INPUT TO THE ESP

A high voltage generator voltage inverter transformer boost module is used to obtain a very high voltage which can go up to 400kV. This is helpful in the size and weight reduction as it will be installed into the automobile. A typical conventional ESPs have a step-up transformer, a high frequency switched mode power supply or a voltage multiplier circuit like Karl Marx circuit or Cockcroft-Walton multiplier, but this will usually require a sinusoidal input which is generally utilized in large-scale industries and power plants but for a pilot-scale module, a transformer and multiple-staged voltage multiplier circuit cause the issue of space, size, heaviness and cost. Also, the input here is taken from the automobile or can be supplied from an external source which varies from 3.3V to 12V.

V. SIZE AND MATERIAL OF ELECTRODES

Selection of the electrodes in an ESP plays a very important role in maintaining the efficiency of the system. In case of treating the wet and corrosive flue gas, the collecting electrode should be made of stainless or alloy steel to avoid corrosion and when it's dry and non-corrosive, the collecting electrode is usually made of carbon steel with 0.3 to 0.6% carbon. The shape of discharge or emitting electrode also has a major role to play as it's the heart of an ESP. It can be round, square, twisted-square, mesh-like or barbed (successful in encountering fine particles) shaped electrodes that are uniformly spaced. Star shaped are also preferred when the corona discharge must be high. Wires are generally straight although spiral electrode increases the total discharge surface. Also, sharper the discharge electrode, lower is the voltage required for the corona formation. Here the collecting electrode chosen is an alloy steel plate and the discharge electrode chosen is the mesh-like copper plate.

VI. METHOD OF ELIMINATING CO_2

The negative terminal of the high voltage supply coming from the voltage booster module is connected to the discharge or emitting electrode of the ESP, which is a thin meshed copper plate and positive terminal of the supply is connected to the collecting electrode which is an alloy steel plate (it's not carbon steel because it may have to encounter with the corrodible particles). The CO_2 coming from the catalytic converter gets charged after passing through the discharge electrode and further phenomenon leads to carbon and oxygen getting separated and only oxygen gas is let out to the atmosphere through the exhaust outlet, while the carbon particles are collected by the collecting electrode which is later on removed with the help of miniature rappers and hoppers and collected waste can be used for various requirements. Hence this process will reduce the emission of CO_2, a greenhouse gas.

VII. MECHANISM OF REMOVING PARTICULATE MATTER

When the automobile is running, the fuel is being spent and therefore the ESP which is powered on will encounter with the engine exhaust gases and it will first pass through the negative electrode, which is the mesh-like copper plate and now due to very high voltage across the emitting electrode, the exhaust gases will breakdown once the corona discharge occurs, that is the gas molecules will be ionized. During the corona discharge, due to ionization of gas molecules, free electrons are generated, and these free electrons repel away from the negative electrode, i.e. meshed plate and because the repelling force is strong, these free electrons will bombard with the other gas molecules, emitting more free electrons and this reaction goes on and on to have an effect of chain reaction leading to many free electrons and these electrons will attach to the solid soot or particulate matter that comes with the gas and this will give the PM a negative charge becoming heavy. They move toward the positive electrodes, i.e. the collecting electrode. As the negatively charged particulate matter reach near the positive electrodes, thy get attracted and hence get accumulated on the positive electrode. The size of particulate matter also plays an important role because the number of particulate matters that get adhered to the electrons will depend on the size of PM. And hence as a result of this process, the gas that passes out of the exhaust outlet is with very minimum or free from the particulate matter and the miniature rappers and hoppers attached will take care of the collected waste and periodic cleaning of them is required.

VIII. TEST RESULT

Weight of Positive Electrode	
Before Powdering (gm)	After Powdering (gm)
55.83	61.25

IX. CONCLUSION

The paper deals with effective reduction of CO_2 and PM emission from the automobile engine exhaust into the atmosphere using the principle of Electrostatic Precipitation. It is observed that the efficiency of the ESP is achieved more when the exhaust gas entering the device is charged by negative electric field. The collected waste on the collecting electrode is 5.42 grams/hour when tested on the running diesel engine and the solid particulate matter collected from the running petrol engines will be much lower. Hence with the help of ESP and its principle we can cut down on the air pollution caused by the increasing number of automobiles. There is a scope for further optimization of the device.

X. FUTURE CHALLENGES

When ESPs are used to remove the suspended particles, the corona discharges generate NO_x (NO_2 and NO) or oxidize NO in contaminated air, making it more toxic. This drawback of ESP can be improved by attaching a non-woven sheet made of activated carbon fiber (ACF) on the collection electrodes of an ESP, which will improve the collection efficiency of suspended particles. Positive discharges usually generate more NO_x than the negative discharge and most part of NO_x generated by DC corona is NO_2. Also, higher humidity enhances the NO_x generation. Therefore, the temperature and humidity of the flue gas entering the ESP is a matter of concern. Ozone generated in corona discharge, is consumed for oxidation of NO from exhaust of vehicles to NO_2 which is more harmful to human bodies.

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