2. THEORY

2.1 Electrostatic Precipitator

Electrostatic Precipitator (ESP) is a particulate collection device which uses electrostatic force to remove or separate the particles from a gas stream. Initially, ESP has been used to control fly ash from coal fired power plants to eliminate the fine particles of non-combustible minerals that remain suspended in the combustion gases after burning pulverized coal. Principle of electrostatic precipitator is to give electrostatic charge to particles in a gas stream and then pass the particles through an electric field that drives them to a collecting electrode. Finally, the particles are adhered to the electrode and collected. The process of electrostatic precipitation involves

1. Ionizing the air molecules flowing between electrodes to give or create charge to particles.

2. Transporting the charged particles to the collecting surface.

3. Removing the dust (or collected particles) from the collecting surface.

The electrostatic precipitators require maintenance of a high potential difference between the two electrodes, one is a discharging electrode and the other is a collecting electrode. The discharging electrode, which has a small radius of curvature, e.g. a sharp point or thin wire, is held at a high voltage. The collecting electrode, which has a much larger radius of curvature, e.g. a flat plate or a cylinder, is electrically grounded (Chen, 2002). Because of the high potential difference between the two electrodes, a powerful ionizing field is formed.

2.2 Types of Electrostatic Precipitators

Electrostatic precipitators can be grouped, or classified, according to a number of distinguishing features in their design. These features include:

i. Structural design e.g. operation of the discharge electrodes (wire or sharp point) and collection electrodes (tube or plate)

ii. Method of charging (single-stage or two-stage)

iii. Operating temperature (cold-side or hot-side)

iv. Method of particle removal from collection surfaces (wet or dry)

Tubular and Plate ESPs

Tubular precipitator consists of a cylindrical collection electrode (tube) with a discharge electrode (wire) located in the center of the cylinder, as shown in Fig. 1. The tube may be formed as a circular, square, or hexagonal honeycomb with gas flowing upward or downward. The tubular ESP is tightly sealed to minimize leaks of collected material. Tubular precipitators are generally used for collecting mists or fogs, and are most commonly used when collecting particles are wet or sticky. They have been used to control particulate emissions from sulfuric acid plants, coke oven byproduct gas cleaning (tar removal), and iron and steel sinter plants.

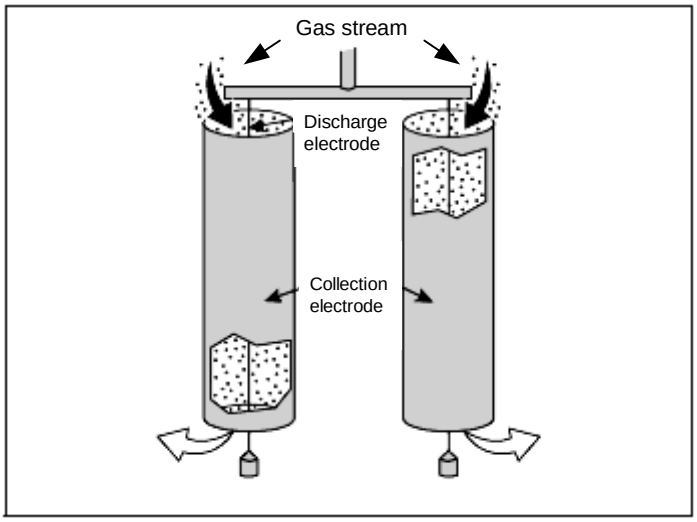

Figure 1. A tubular precipitator (Katz, 1979).

Plate electrostatic precipitator (Fig. 2) has a wire or a series of wire discharge electrodes as in tubular precipitator but its plate is used as a collection

electrode. Plate ESPs are typically used for collecting fly ash from industrial and utility boilers as well as in many other industries including cement kilns, glass plants, and pulp and paper mills.

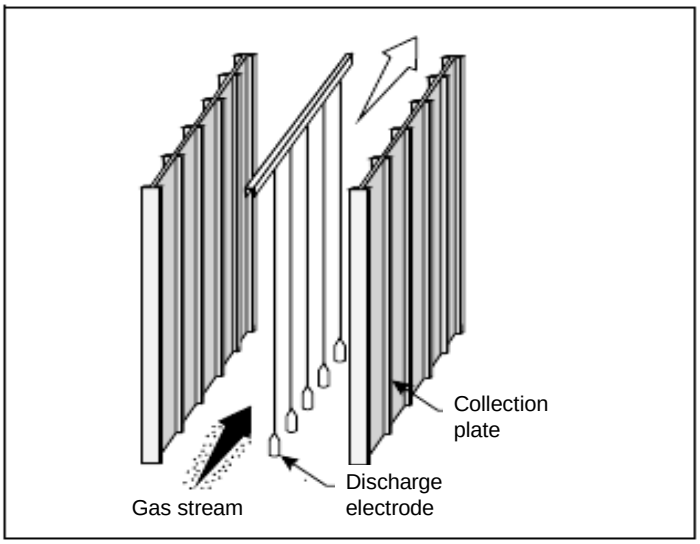

Figure 2. A plate precipitator (Katz, 1979).

Single-Stage and Two-Stage ESPs

Another method of classifying ESPs is by the number of stages used to charge and remove particles from a gas stream. A single-stage precipitator uses high voltage to charge the particles, which are then collected within the same chamber on collection surface of opposite charge, as shown in Fig. 3. In a two-stage precipitator, particles are charged by low voltage in one chamber, and then collected by oppositely charged surface in the second chamber, as shown in Fig. 4.

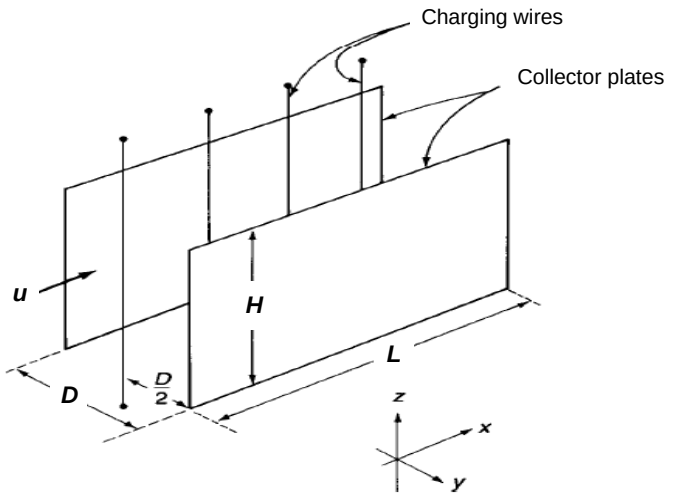

Figure 3. A single-stage wire-plate precipitator (Davidson, 2000).

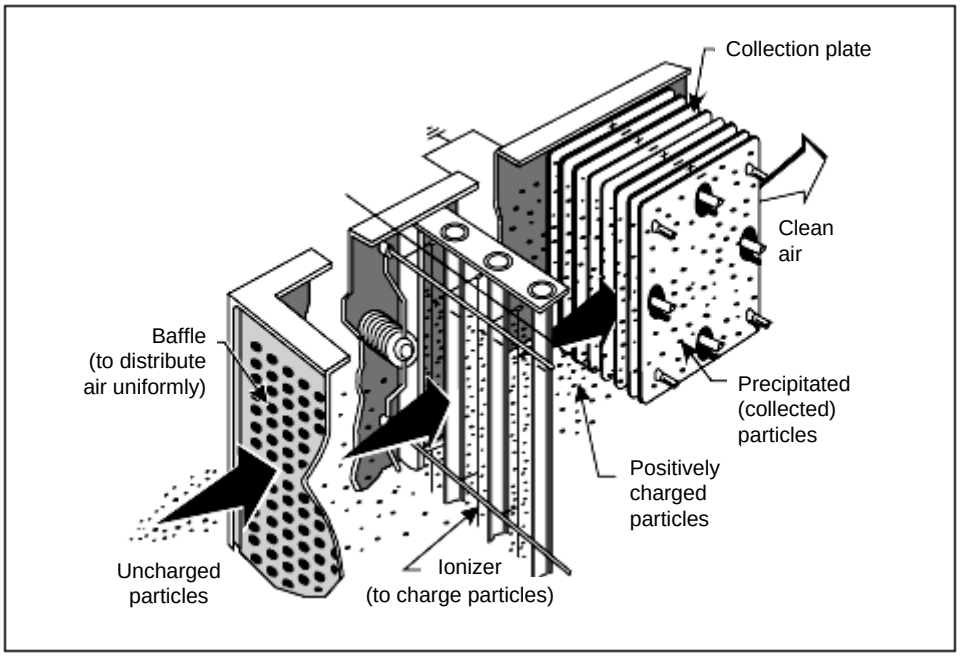

Figure 4. A two-stage wire-plate precipitator (Katz, 1979).

Cold-side and Hot-side ESPs

Electrostatic precipitators are also classified according to the temperature of the flue gas that enters the ESPs. Cold-side ESPs are used for flue gas

having temperatures of approximately 200°C or less, however, hot-side ESPs are used for flue gas having temperatures greater than 300°C.

Wet and Dry ESPs

Wet ESPs, shown in Fig. 5, can be operated with a wet spray to remove collected particles. Usually, the wet ESPs are used for industrial applications where the potential for explosion is high such as collecting dust from a closed-hood basic oxygen furnace in the steel industry, or when dust is very sticky, corrosive, or has very high resistivity. The water flow may be applied continuously or intermittently to wash the collected particles from the collection electrodes. The advantage of using the wet ESP is that it does not have problems with rapping re-entrainment or with back corona.

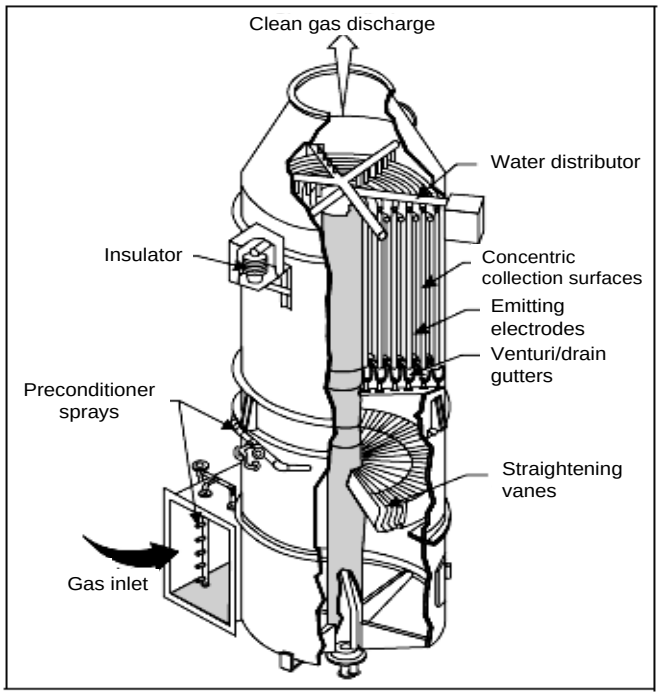

Figure 5. A circular-plate wet ESP (Katz, 1979).

Dry ESPs (most electrostatic precipitators) are operated in dry condition, as shown in Fig. 6. Particles are charged and collected in a dry state and are removed by rapping as opposed to water washing which is used in wet ESPs. The dry ESPs are used for collecting dust from many industries including steel furnaces, cement kilns and fossil-fuel-fired boilers.

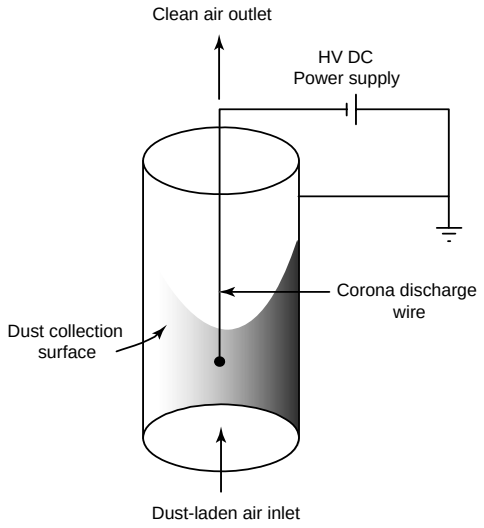

Figure 6. A wire-cylinder dry ESP.

2.3 Principles of Electrostatic Precipitation and Corona discharge

Every particle either has or can be given a charge, positive or negative. If all particles in the gas stream have a negative charge and the collection plate is positively charge, the negatively charged particle will migrate to the grounded collection plate and be captured. The particles will quickly deposit on the plate, and a dust layer is creating. The dust layer will accumulate and needs to be removed, either by rapping the plate or by spraying it with a liquid. Charging, collecting, and removing particles are important procedure of the ESP.

The discharges can be grouped, or classified, according to their temporal behavior, pressure range, and appearance (Eliasson et al, 1991)

1. Glow discharge
2. Corona discharge

3. Silent discharge
4. Radio frequency (RF) discharge
5. Microwave discharge

1) The glow discharge or the staionary glow discharge is a low-pressure discharge, usually between flat electrones encapsulated in a tube. Since the pressure is tpically smaller than 10 mbarr, the reduced field can therfore be quite high. Due to the high energy of electrons, they excite the neutral atoms and molecules, easily producing for each gas a typical grow (therefore the name). This is the discharge of the fluorescent tube. Typical parameter of glow discharges are summerized in Table 1.

Table 1. Characteristic parameters of glow discharges

Pressure, mbar	< 10
Electric field, V/cm	10
Reduced field, Td	50
Electron energy, eV	0.5-2
Electron density, cm^{-3}	$10^{8} – 10^{11}$
Degree of ionization	$10^{-6} – 10^{-3}$

2) The corona discharge is an essential part of the electrostatic precipitation process because it is where the ions are created and the particles are charged. Usually, corona discharge refers to a self-sustaining discharge produced in a gas.

At higher pressures and fields, the discharge becomes highly unstable and turns into a high-current arc discharge if the power supply provides enough current. However, one way of stabilizing the discharge at high pressure is the use of inhomogeneous electrode geometries. A stable discharge requires the presence of two electrodes, one with a much smaller radius of curvature than the other e.g wire-plate or wire-cylinder. The wire-plate and wire-cylinder types are commonly used electrode geometries. As the electrical potential is raised between the electrodes, the

gas in the immediate vicinity of the wire is ionized. The corona is termed positive or negative according to the polarity of the electrically stressed electrode. Positive corona discharge is usually a diffuse and uniform glow, while negative corona discharge is localized discharge from the high voltage electrode.

A typical corona discharge consists of a corona plasma region and a unipolar ion region. The ionization process only takes place in the corona plasma region. Outside the plasma region, the electric field is not strong enough for ionization and unipolar ions drift under the applied electrical force. The electric potential at which the corona is initiated is called the "breakdown" or "threshold" potential. The exact value of this voltage depends on the geometry of the discharge electrode, the distance between electrodes and the composition of the gas.

The electric field strength at which corona begins has been studied extensively. Theoretically, the field required to initiate corona is that when it produces electron energy sufficient to cause ionizing collisions in the gas species present. Obviously, the field required for the initialization of corona discharge depends on the ionization potential of the gas and the mean free path between collisions. The semi-empirical equation for the required electric field to initiate corona discharge in air is given by (Hinds, 1999)

$$E_b = 3000 + 127 d_w^{-1/2} \quad \text{kV/m} \tag{1}$$

where d_w is wire diameter in m.

Moreover, the gas composition also determines the type of ions that are formed in the corona. Then the species with the lowest ionization potential will normally appear in the greatest concentration. The voltage used to generate the corona discharge is as high as several to tens of kilovolts but the resulting corona current is low (in the order of μA per centimeter of length of wire). The main characteristics of corona discharges are listed in Table 2.

Table 2. Characteristic parameters of corona discharges

Pressure, bar	1
Electric field, KV/cm	0.5-50
Reduced field, Td	0-200 (variable)
Electron energy, eV	5 (variable)
Electron density, cm^{-3}	10^{-13} (variable)
Degree of ionization	small (variable)

3) The silent discharge is predestined for applications in volume plasma chemistry. It has inherent advantages over the discharges which have been treated until now. It combines the large volume excitation of the gloe discharge with the high pressuer of the corona discharge. Typically parameters of silent discharges are shown in Table 3.

Table 3. Characteristic parameters of silent discharges

Pressure, bar	1
Electric field, KV/cm	0.1-100
Reduced field, Td	1-500
Electron energy, eV	1-10
Electron density, cm^{-3}	10^{14}
Degree of ionization	10^{-4}

4) The radio frequency discharges or RF discharges are used extensively in the laboratory to produce plasma for optical emission spectroscopy and for plasmachemical investigations. One advantage of RF discharges is that the electrodes can be kept outside of the discharge volume, thus avioding electrode erosion and contamination orf the plasma with metal vapor. RF discharges work well at low pressure, but are used also at atmospheric pressure.

5) The microwave discharges is the use of microwaves to induce surface-wave-sustained discharges. They can operate over a large frequency and pressure range and can produce large-volume nonequilibrium plasmas of reasonable homogeneity.

2.4 Fractional Collection Efficiency (Davidson, 2000)

Precipitator design is based on the expression for the particle capture efficiency which can be evaluated experimentally from

$$\eta = 1 - \frac{C_{exit}}{C_{inlet}} \tag{2}$$

where C_{inlet} and C_{exit} are the concentrations of particles at the inlet and exit of the device, respectively.

In general, Deutsch-Anderson equation is widely used to determine the collection efficiency of the precipitator (Nóbrega et al, 2004). This equation was first derived in 1922 by referring to the simple wire-plate precipitator in Fig. 7, and the following assumptions as.

- Gas and particles move in the x-direction at constant velocity *u*.
- The particles are uniformly distributed in the y- and z-directions at all x location.
- The charging and collection electric fields are constant and uniform, i.e. the particles attain an electric drift velocity *w* in the y-direction very quickly. The determination of *w* will be discussed later.
- Once particles reach the collection plate, they remain there.

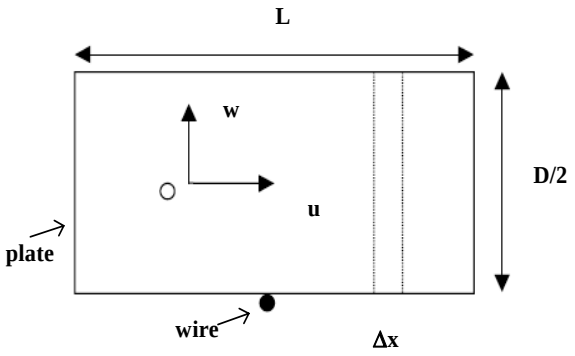

Figure 7. Top view of a one-half of flow channel of a wire-plate precipitator. The length of the collection plate in x-direction is L, and the height of the precipitator in z-direction is H.

With these assumptions, a mass balance on an element Δx can be written as

$$\left[u\frac{D}{2}H\right]C_x - \left[u\frac{D}{2}H\right]C_{x+\Delta x} = wC_{x+\Delta x/2}H\,\Delta x \tag{3}$$

This equation simply states that the difference between the mass of particles flowing into and out of the slice must equal the flux of particles in the y direction times the area normal to the flux. The right hand side of the equation is the mass removed. Dividing by Δx and taking the limit as Δx goes to zero, we obtain

$$\frac{-uHD}{2}\frac{dC}{dx} = wHC \tag{4}$$

Separating variables and integrating, yields

$$\int_{C_X=0}^{C_X=L}\frac{dC}{C} = \int_0^L \frac{w2H}{uHD}dx \tag{5}$$

or

$$\frac{C_L}{C_0} = \exp\left[\frac{-wA}{Q}\right] \tag{6}$$

where A is the plate area in one channel ($2HL$), Q is the volumetric gas flow (uHD) evaluated at the temperature and pressure inside the precipitator, and w is the migration velocity of the particle that will be explained in section 2.5. Thus the collection efficiency is expressed as

$$\eta = 1 - \frac{C_{exit}}{C_{inlet}} = 1 - \exp\left[\frac{-wA}{Q}\right] \tag{7}$$

This equation, known as Deutsch-Anderson equation, shows the relationship between collecting plate area and volumetric flow rate and it can be used to evaluate collection efficiency of an electrostatic precipitator. The ratio A/Q is called specific collection area (SCA).

2.5 Particle Migration Velocity

The particle migration velocity is the speed at which a particle, once charged, migrates toward the grounded collection electrode. Variables affecting particle velocity are particle size, the strength of the electric field, and the viscosity of the gas. How readily the charged particles move to the collection electrode is denoted by the symbol, w, called the particle migration velocity, or V_{TE}, called the electric terminal setting velocity. The migration velocity parameter represents the collection ability of the particle within the confinement of a specific ESP. The migration velocity is expressed by (Hinds, 1999)

$$w = V_{TE} = \frac{neEC_c}{3\pi\eta d} \tag{8}$$

where n is the number of charges

e is the charge of electron

η is the viscosity of air at 293 K

d is the particle diameter

C_c is the Cunningham correction factor which can be written as

$$C_c = 1 + \left(\frac{2.52\lambda}{d} \right) \quad \text{for} \quad d \rangle 0.1\ \mu\text{m} \tag{9}$$

E is the field strength inside a cylinder tube with a wire along its axis, expressed by

$$E = \frac{\Delta W}{R \ln\left(d_t / d_w\right)} \tag{10}$$

where ΔW is the algebraic difference in voltage between the wire and the tube

d_t is the diameters of the tube

d_w is the diameters of the wire

R is the radial position

2.6 Particle Charging Mechanisms

The remaining parameter in Eq. (8) is the number of charges on the particles. In this section, negative corona discharge of the ESPs will be explained. Particles are charged by negative gas ions moving toward the collection plate by one of these two mechanisms: field charging or diffusion charging. In field charging, particles capture negatively charged gas ions as the ions move toward the grounded collection plate. Diffusion charging, as its name implies, depends on the random motion of the gas ions to charge particles.

In field charging (Fig. 8), when particles enter the electric field, they cause a local dislocation of the field. Negative gas ions travelling along the electric field lines collide with the suspended particles and impart a charge to them. The ions will continue to bombard a particle until the charge on that particle is sufficient to divert the electric lines away from it. This prevents new ions from colliding with the charged particle. When the particle no longer receives an ion charge, it is said to be saturated. Saturated charged particles then migrate to the collection electrode and are collected. The number of charges, $n_F(t)$, acquired by a particle during time t in an electric field E can be described by (Hinds, 1999)

$$n_F(t) = \left(\frac{3\varepsilon}{\varepsilon+2}\right)\left(\frac{Ed^2}{4K_E e}\right)\left(\frac{\pi K_E e Z_i N_i t}{1+\pi K_E e Z_i N_i t}\right) \quad (11)$$

where ε is dielectric constant of particle

Z_i is the mobility of the ions

e is the charge on an electron

N_i is the concentration of ions

t is residence time

K_E is electrostatic constant = 9×10^9 N m^2/C^2

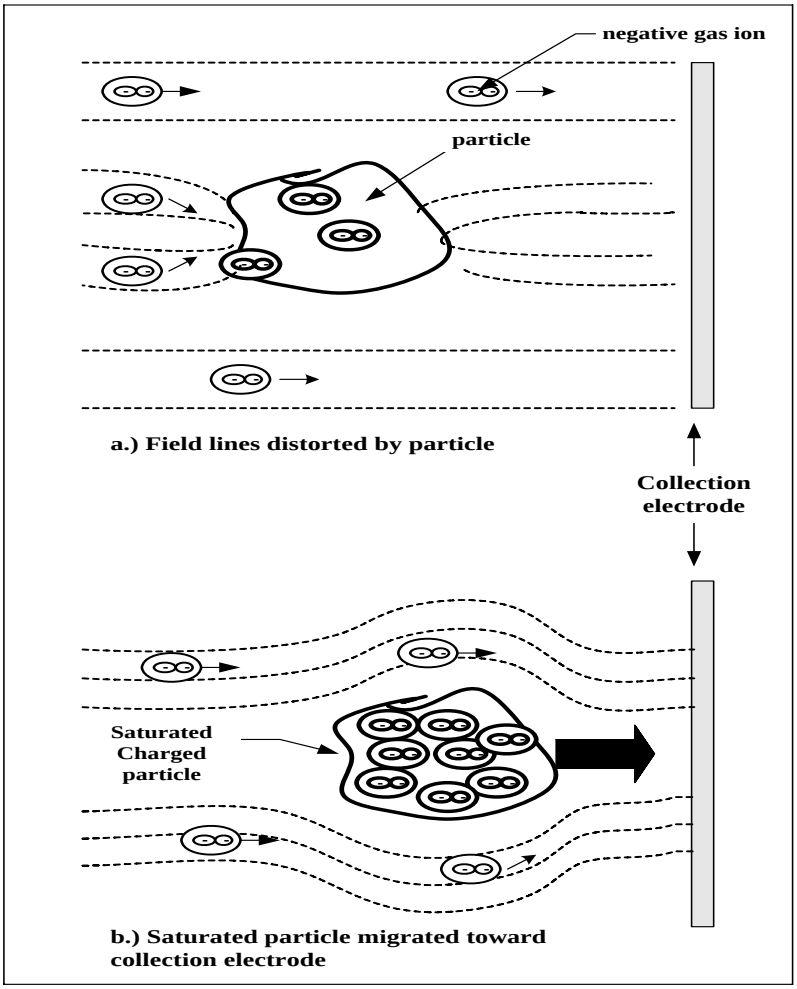

Figure 8. Field charging mechanism for a particle in an electric field (Katz, 1979).

Diffusion charging is, in turn, associated with the random or Brownian motion of the negative gas ions. The random motion is related to the velocity of the gas ions due to thermal effects: the higher temperature, the higher velocity. Negative gas ions collide with the particles because of their random thermal motion, and impart a charge on the particles. Since the particles are very small (submicrometer), they do not cause the electric field to be dislocated, as in field charging. Thus, diffusion charging is the only mechanism by which these very small particles become charged. The charged particles then migrate to the collection electrode. An approximate expression for the number of charges $n_D(t)$ acquired by a particle of diameter d_p by diffusion charging during a time t is (Hinds, 1999)

$$n_D(t) = \frac{d_p kT}{2K_E e^2} \ln\left[1 + \frac{\pi K_E d_p \overline{c_i} e^2 N_i t}{2kT}\right] \tag{12}$$

where d_p is particle diameter, m

k is Boltzmann constant, J/K

T is absolute temperature, K

K_E is electrostatic constant = 9×10^9 N m^2/C^2

e is the charge on an electron, C

$\overline{c_i}$ is the mean thermal speed of ions, m/s

t is residence time, t

N_i is the concentration of ions which can be written as (Asbach, 2004)

$$N_i = \frac{I}{eZ_i E A_c} \tag{13}$$

where I is corona current

Z_i is the mobility of ions = $1.7 \times 10^{-4}\,\mathrm{m^2/(Vsec)}$ for negative ions

A_c is the collection surface

Each of these two charging mechanisms occurs to some extent, with one dominating depending on particle size. Field charging dominates for particles with a diameter >1.0 micrometer because particles must be large enough to capture gas ions. Diffusion charging dominates for particles with a diameter less than 0.1 micrometer. A combination of these two charging mechanisms occurs for particles ranging between 0.2 and 1.0 micrometer in diameter. Then the total number of charges can be described by

$$n_t = n_F(t) + n_D(t) \tag{14}$$

Overall collection efficiency can then be calculated from Eq. (7) together with Eqs. (8)-(14).

2.7 Particle Collection

When a charged particle reaches the grounded collection electrode, the charge on the particle is only partially discharged. The charge is slowly leaked to the grounded collection plate. A portion of the charge is retained and contributes to the inter-molecular adhesive and cohesive forces that hold the particles onto the plates (Fig. 9). Adhesive forces cause the particles to physically hold on to each other because of their dissimilar surfaces. Newly arrived particles are held to the collected particles by cohesive forces; particles are attracted and held to each other molecularly. The dust layer is allowed to build up on the plate to a desired thickness and then the particle removal cycle is initiated.

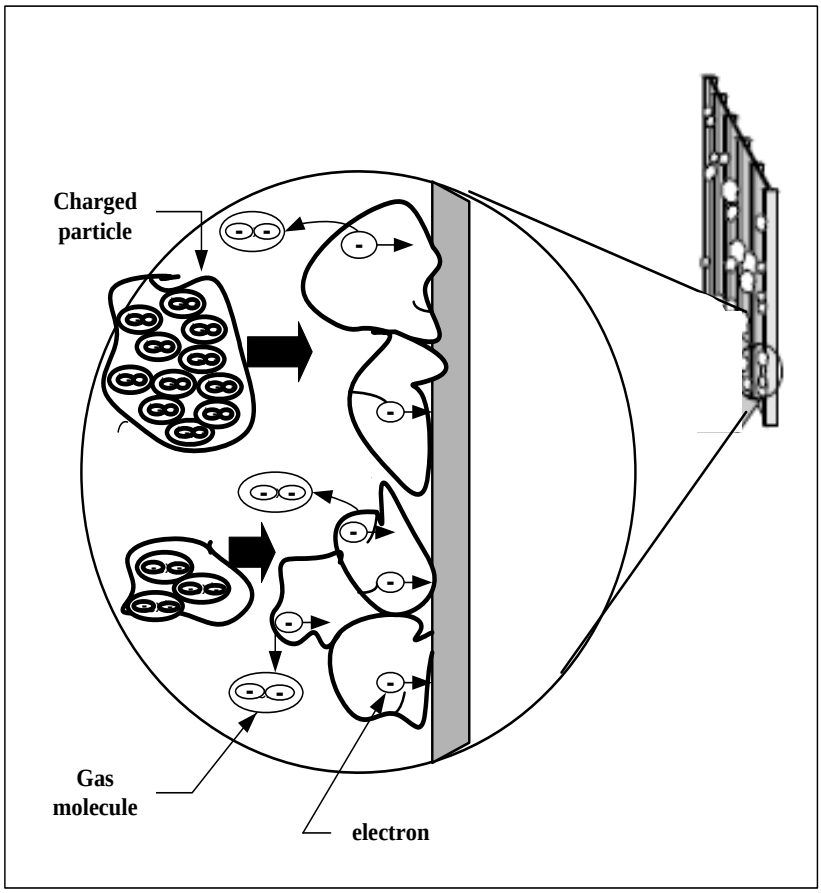

Figure 9. Particle collection at collection electrode (Katz, 1979).