CHAPTER 2

THEORY

In this Chapter present the some basic operation of electrostatic precipitator (ESP) and theories to enhancement of submicron particle collection. The first part of this Chapter covers some operational properties of ESP and the second part describes briefly on non-thermal plasma (NTP). In the last part of the chapter describe a review on pulsed corona plasma.

2.1 Electrostatic Precipitator

2.1.1 Operation Properties of ESPs

Electrostatic precipitator is a device used for gas cleaning by removing particulate matter from the gas steam with electrical forces. It has five steps in operation, as shown in Figure 2.1 which are corona discharge, particle charging through combined diffusion and field charging, particle transport by electrical and gas flow forces, formation of dust layer on collecting electrode, and removal of collected dust by rapping techniques. After that, the charged particles will move towards the collecting electrode due to the introduced electrical force. When the charged particles reach the collecting electrode, they will transfer their charges to the collecting electrode and form a dust layer that will be further removed to the hopper by other dust removing techniques. The overall collection efficiency of any gas cleaning device can be determined from

$$\eta_t = 1 - \frac{M_{out}}{M_{in}}.$$
(2.1)

Where M_{out} and M_{in} are particle mass concentrations at the outlet and the inlet of the device, respectively.
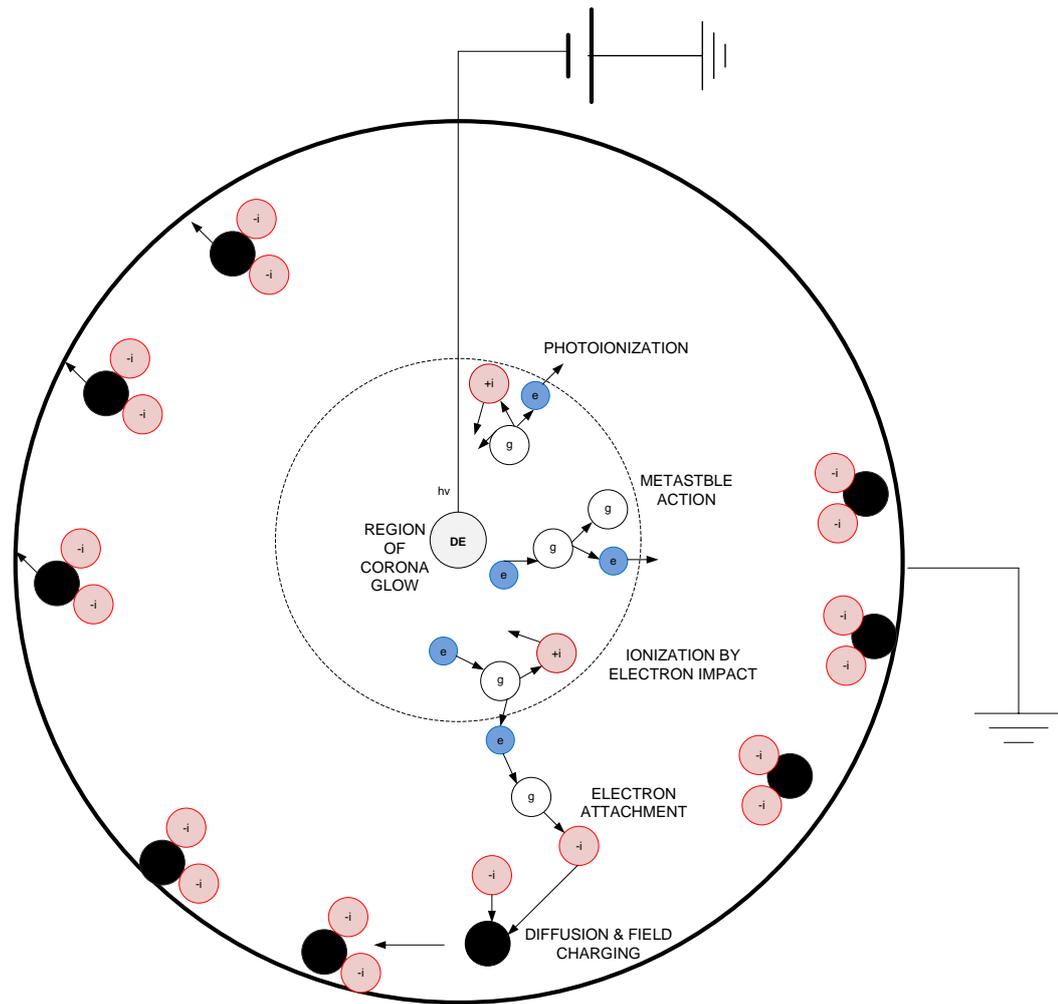
Figure 2.1 Schematic of corona discharge, particle charging and dust
collection process in an ESP.

2.1.2 Corona Discharge

L.B. Loeb (1961) and J.S. Chang *et al*. (1991) studied corona
discharges for many years. They found that corona discharges could exist in several
forms, depending on the applied voltage characteristic, gas condition and electrode
geometry (J.S. Chang *et al*. 1991; J.S. Chang 1996). Most industrial ESPs operate
with negative voltage due to its higher permissible operating current and voltage, and
higher breakdown potential compared to the positive voltage operation. The corona
discharge starts when the electric field in the vicinity of the discharge electrode
reaches the threshold value for ionization of the gas molecules by electron collision.

The initiating electron could be produced from the surface of the discharge electrode. After that, an electron avalanche starts to develop away from the discharged electrode in the direction of the electric field lines. When avalanche is growth, more electrons and photons are produced at the avalanche head and more positive ions are left in the avalanche wake. The avalanche will continue to grow until it reaches the ionization-zone boundary where photo-ionization occurs. The ionization or corona zone extends only a few millimeters from the discharge electrode. Due to the high mobility of electrons, the electrons will be further transported by the electric field outside the ionization zone. Outside the corona zone negative ions are formed by electron attachment (T.G. Beuthe *et al*. 1995) and further transported by the electric field.

Corona onset field is the critical electric field intensity value for the discharge electrode to initiate a self-sustaining discharge. The corona onset field depends on the radius and curvature of the discharge conductor and its surface condition as well as to that of the gas temperature and pressure. In general, the corona onset field of a cylindrical conductor can be calculated from (White 1963)

$$E_c = mE_0\delta\left[1 + \frac{K}{\sqrt{\delta r_c}}\right]. \qquad (2.2)$$

Where E_0 and K are constants depending on the voltage is apply to discharge electrode (Maruvada 2000). For DC voltages, corresponding values according by Whitehead (1929) are E_0=33.7 kV/cm and K=0.24 for positive polarity and E_0=31.0 kV/cm and K=0.308 for negative polarity. r_c is conductor radius in cm and m is conductor surface irregularity factor, which is equal to 1 for smooth and clean conductors. δ is relative air density factor which is given as

$$\delta = \frac{T_0}{T} \cdot \frac{P}{P_0}. \qquad (2.3)$$

Where T and P are temperature and pressure of the ambient air, T_0=25 °C and P_0=760 torr are those at a reference condition.
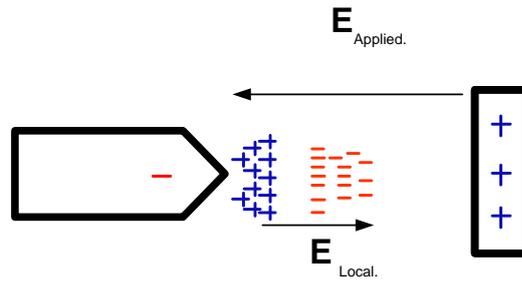
Figure 2.2   A space charge field formed in the vicinity of the emitter
electrode.

For negative corona, a discharge electrode connects to negative
polarity of a high voltage power supply while another electrode is ground, known as
an emitting cathode. When the voltage rises up to the critical field intensity, form
electron avalanches and propagate towards the collecting electrode as anode, leaving
behind positive ions. When electrons enter the low field region, they slow down and
attach to gas molecule form negative ions. The positive and negative ions form local
field or space charge field as shown in Figure 2.2. Here, $E_{Applied}$ is the electric field
generated from the supply voltage while E_{Local} is the local field acting in reverse
direction together. The discharge and ion generation stops when the sum of electric
field intensity ($E_{Applied.} - E_{Local.}$) in the vicinity of the emitter electrode drops below a
critical value. The process will be run continually when the supply voltage increase to
maintain the field intensity is over the critical value. This mode is known as glow
corona. If increasing the supply voltage even further till the discharge occupies a
major portion of the electrode spacing and form streamers. This mode is known as
pre-breakdown streamer corona. Further increase of voltage leads to a complete
breakdown or spark formation.

2.1.3 Particle Charging Mechanisms

When particles immersed between discharge electrode and collecting electrode, the particles could be charged by two mechanisms: diffusion charging and field charging. Diffusion charging occurs due to the attachment of the ions to the surfaces of the dust particles. Field charging occurs when there is a bombardment by moving ions under the influence of the electric field on the particle surfaces. The particle charging mechanisms can be expanded below

(a) Diffusion Charging

When a particle is in gaseous ions region, the particle captures ions leading to the electrical charge on the particle. The ion number depends on a size of the particle, the ion density encountered, and the time that the particle stays in the region. In the non-electric field region, the particle charging is diffusion charging mechanism due to Brownian random motion of the ions. White (1963) and Pui (1976) characterized the average charge number, n_p, caused by the diffusion charging in a time period, t, by a particle diameter d_p, can be founded from (Intra P. and Tippayawong N. 2009)

$$n_p = \frac{2\pi\varepsilon_0 d_p kT}{e^2} In \left(1 + \frac{d_p \bar{c}_i e^2 N_i t}{8\varepsilon_0 k_B T}\right). \tag{2.4}$$

(b) Field Charging

When an uncharged particle is in an electric field region, a permittivity of the particle will be modifying the electric field lines vicinity around it, as shown in Figure 2.3a. Because of Electro static force, an ion will follow the electric field lines and therefore attach to the surface of the particle. When the particle charging proceeds, the charge on the particle surface will transform the surrounding electric field as shown in Figure 2.3b and thus reduce the rate of charging. The particle charging process will continue until no electric field lines move ions attach to the surface of the particle as a saturation charge. The saturation charge, n_s, on the particle diameter, d_p and dielectric constant, ε in an average electric field E is defined from

$$n_s = \left(1 + 2\frac{\varepsilon - 1}{\varepsilon + 2}\right)\left(\frac{\pi \varepsilon_0 E d_p^2}{e}\right). \tag{2.5}$$

Based on the field charging theory, higher the ion concentration and higher the ion mobility, the faster the particle becomes charged. Higher the electric field and the particle size, higher the saturation or limiting charge on the dust particles could be attained.
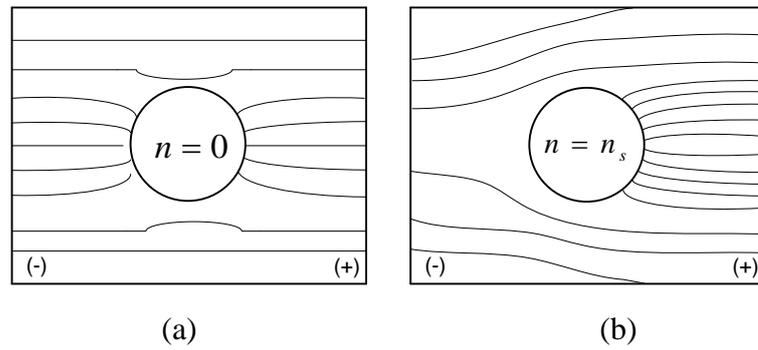

Figure 2.3   The surrounding electric field lines of a) an uncharged particle and b) a charged particle surface area (Hins 1999).

The average number of charge on the particle, n_p, can be defined from

$$n_p = \left(1 + 2\frac{\varepsilon - 1}{\varepsilon + 2}\right)\left(\frac{\pi \varepsilon_0 E d_p^2}{e}\right)\left(\frac{\pi e Z_i N_i t}{4\pi \varepsilon_0 + \pi e Z_i N_i t}\right). \tag{2.6}$$

Where Z_i is an electric mobility of ion.

2.1.4   Particle Transport

The following paragraphs describe the theory of transportation of the particle by electrical and gas flow forces which cover the convective mass transport, the mass transport due to the electrical migration, the molecular and particle velocity, the mean free path and Knudsen number, the particle Reynolds number, the settling velocity, the electrical mobility and the diffusivity of the particle in the flowing gas.

(a) Convection

Convective mass transport usually coincides with the direction of the gas flow streamlines and depends on the gas flow regime and the particle size. The larger particles have a tendency to continue to move tangentially to the gas flow streamlines due to the inertia phenomena. Additionally, the larger particles are subject to the larger drag forces. Smaller particles follow the gas flow streamlines more closely than the larger particles due to the smaller inertial forces. However, the smaller the particles, the larger reduction of the drag force due to the increased particle slip.

When a particle moving with a net velocity corresponding to the carrier gas in which it is suspended, the particle is subject to the gas resistance force or drag force, F_D. This provides the following Stoke's law formulation as

$$F_D = \frac{3\pi\mu U_p d_p}{C_c}. \tag{2.7}$$

Where U_p is a velocity of particle and d_p is a particle diameter, C_c is a Cunningham slip correction factor. The value of C_c was first derived by Cunningham (1910) and later by Allen and Raabe (1982) as

$$C_c = 1 + \frac{\lambda}{d_p}\left(2.34 + 1.05 exp\left(-0.39\frac{d_p}{\lambda}\right)\right). \tag{2.8}$$

For air at 20°C and atmospheric pressure, C_c has a value of 224.332 for a 1 nm particle and 1.155 for a 1 μm particle (Hinds 1999).

The dynamic viscosity for air at 20°C is 1.81×10^{-5}Pa·s. Viscosity can be related to a reference viscosity, μ_0, at a reference temperature, T_0, as the following equation (Willeke and Baron 1993):

$$\mu = \mu_0 \left(\frac{T_0+S}{T+S}\right)\left(\frac{T}{T_0}\right). \tag{2.9}$$

Where *S* is Sutherland interpolation constant (Willeke and Baron 1993). It should be noted that viscosity is independent of pressure.

The free path of gas molecules is defined as the distance that a molecule travels before colliding with another. The mean free path, λ, of gas molecules can be determined from the average mean molecule velocity, $\bar{c}$ and the average number of collisions of a particular molecule undergoes in one second, n_z. The mean free path is defined by

$$\lambda = \frac{\bar{c}}{n_z}. \tag{2.10}$$

Where n_z is an average number of collisions between gas molecules which is given by

$$n_z = \sqrt{2}N_m\pi d_m^2\bar{c}. \tag{2.11}$$

Where N_m is a concentration of molecules, and d_m is a distance between the centers of two molecules at the collision. Combining Equations 2.10 and 2.11 obtains

$$\lambda = \frac{1}{\sqrt{2}N_m\pi d_m^2}. \tag{2.12}$$

For air at 20°C and atmospheric pressure, the mean free path of air is 0.066 μm (Hinds 1999). The mean free path of air as a function of pressure, P, and temperature, T, is given by

$$\lambda = \lambda_o \left(\frac{P_0}{P}\right)\left(\frac{T}{T_0}\right)\left(\frac{1+(115/T_0)}{1+(115/T)}\right). \tag{2.13}$$

Where λ_o is the mean free path at the reference conditions, P_0 and T_0 are pressure and temperature at a reference condition, respectively.

The transportation regime of particle in gas depends on a size of the particle. The ratio of the gas mean free path to the diameter of the particle define as Knudsen number, *Kn,* is given by

$$Kn = \frac{2\lambda}{d_p}.$$ (2.14)

Where d_p is a diameter of the particle, and λ is the mean free path of gas molecules.

(b) Electrical Migration

The transportation of particle due to the electrical migration coincides with the direction of the electric field lines. This type of particle transport is predominantly perpendicular to the gas flow direction, therefore leading to the deflection of the charged particles towards the collecting electrode. It is proportional to the surface charge of the particles and electric field strength. When a charged particle enters the vicinity of an electrostatic field, an electrostatic force, F_E, will be exerted on a charged particle and it can be calculated from

$$F_E = n_p e E.$$ (2.15)

Where n_p is the charge number on the particle, e is the elementary charge, and E is the electric field strength.

When, the charged particles are introduced to the electro static field by gas steam. The Stokes drag force will be balanced by the electrostatic force (i.e. $F_E = F_D$), resulting in the migration velocity of a charged particle, U_m, which is given by

$$U_m = \frac{n_p e E C_c}{3\pi \mu d_p}.$$ (2.16)

The migration of charged particle depends on an electric field and the ability of a charged particle to move in the vicinity of an electrostatic field is referred as the electrical mobility of particles, Z_p, the velocity of a charged particle in an electric field of unit strength which is given by

$$Z_p = \frac{U_m}{E} = \frac{n_p e\, C_c}{3\pi\mu d_p}, \qquad \text{for } Re < 1. \tag{2.17}$$

Particle Reynolds number is an important parameter used in the classification of particle dynamics which describes the aerodynamic properties of the particle. Willeke and Baron define it as the ratio of the inertial forces to the frictional forces acting on the particle which is given by (Willeke and Baron 1993):

$$Re = \frac{\rho U d_p}{\mu}. \tag{2.18}$$

Where ρ is gas density, U is relative velocity between the fluid and particle, d_p is particle diameter, and μ is gas viscosity.

(c) Diffusion

A net flow in a direction of matter from a region of high concentration to a region of low concentration is diffusion. In some sections of ESP, diffusion transport coincides with convection transport and may oppose to electrical migration transport. The net flux of particles, J, is in the direction of lower concentration and characterized by the particle diffusion coefficient, D. This motion is described by Fick's first law of diffusion which is given by

$$J = -D\frac{dn}{dx}. \tag{2.19}$$

Where dn/dx is particle concentration gradient. The diffusion coefficient, D, is given by the Stokes-Einstein equation (Hinds 1999) as

$$D = \frac{K\,TC_c}{3\pi\mu d_p}. \tag{2.20}$$

The diffusion coefficient has unit of m^2/s. Given the diffusivity of a particle, the root mean square net displacement due to the particle Brownian motion is given by

$$dx_{rms} = \sqrt{2Ddt}. \tag{2.21}$$

Where dt is the traveling time.

2.1.5   Particle collection efficiency

Particle collection efficiency is usually based on the Deutsche model that assumes complete turbulent mixing of particles. The model considers an invariant particle profile transverse to the gas flow and a thin boundary layer near the collecting electrode walls. When, the particle flux across the laminar flow boundary and the dust particle flux onto the collecting plate are equating, an exponential function describing the change of the dust concentration along the ESP length can be obtained as (Deutsche 1922)

$$\eta_f(d_p) = 100(1 - e^{-De}) \quad , \tag{2.22}$$

$$De = U_m \frac{A}{Q_g} = \frac{U_m W}{U_g L}. \tag{2.23}$$

Where, De is Deutsch's number, U_m, is migration velocity of the charged particles, W is length of the ESP, L is wire to plate spacing, A is collection surface area, U_g is mean gas velocity, Q_g is gas flow rate. Actually, the collection efficiency is affected by many factors, such as the geometry of electrodes, and the characteristics of particles.

2.2   Non-Thermal Plasma

Plasma is a fourth state of matter. The plasma can be generation by an electric field. When a high voltage (HV) is applied to a gas and electric discharge occurs, the gas can be ionized due to electric energy discharge via the impact of gas molecules or atoms with electrons energized, which results in the formation of discharge plasma. The electric discharge plasma can be classified based on the characteristic of the electric field: a) DC (direct current) discharge; b) AC (alternating current) discharge; c) pulsed discharge.

When an electric field rises to a level which are electrons stripped from their parent molecules to form ions. Due to electrons have a very low mass then their more gaining energy form the electric field than the heavier ions. Results to electrons have a higher thermal-velocity than the ions whereas the ions temperature equals to gas temperature. Thus can generates plasma at near room temperature know as non-thermal plasma (NTP) or cold plasma.

We can classify NTPs into different discharge types. The NTPs along with their energized method and typical applications are listed in Table 2.1.

Table 2.1   the overview of NTP type and their most common applications

Type of discharge	Gap (mm)	Plasma	Energization	Typical application
Corona	10-300	Filaments	Pulsed/DC	Gas cleaning/dust precipitation
Corona with barrier	10-30	Filaments	Pulsed	Gas and water cleaning
	1-5	Filaments	AC	Ozone eneration/large surface treatment/ excimer lamps
Plates/cylinders with barrier	3-10	Filaments	AC	Chemicals conversion
Barrier with packed bed	1-5	Diffuse	AC	Surface treatment/ deposition

Table 2.1   (Continued)

Type of discharge	Gap (mm)	Plasma	Energization	Typical application
Plates with barrier	1-5	Filaments	AC	Surface treatment/ deposition
Surface discharge	1-5	Filaments	Pulsed	Aerodynamic control
Surface barrier	0.5-10	Diffuse	AC/RF	Local surface
Plasma jets	0.1-1	Diffuse	AC/RF	Chemicals conversion/
Microdischarge				light generation

2.2.1   Plasma Streamer

The most important process for electric discharge is the ionization process because it produces an additional electron repetitively, an electron avalanche occurs, as shown in Figure 2.4a. The energy that most neutral molecules require an amount of about 10eV to be ionized, an electric field of about 10kV/mm for discharge formation. The ionization processes remain located in the near of the anode. The space charge builds up and they create their own electric field which counteracts the external field, and stops the avalanche. When space charge acts as the cathode and secondary electrons emit from cathode surface and react with the positive ions to create plasma gas which move away from the cathode to anode. This propagating plasma is called a 'streamer', as shown in Figure 2.4b. The streamer consists of the propagating heads constitute ionization regions , the quasi-neutral plasma channels which left behind by propagating streamer heads, and constitute drift regions where electrons are attached to form negative ions.
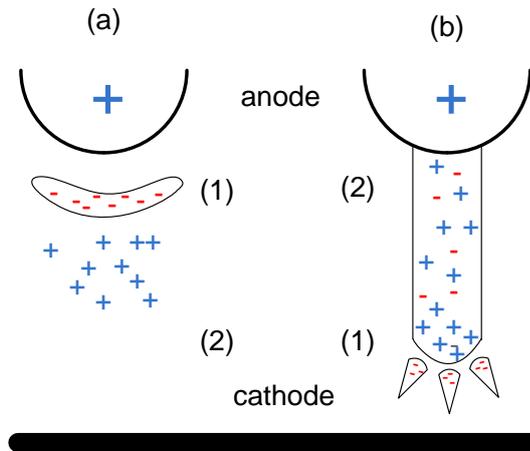
Figure.2.4   Basic discharge modes in positive DC corona (a) glow mode
(b) streamer mode.

      The NTP studied is characterized by its channel-like appearance. The channels, usually referred to as streamers, originate near the active electrode and propagate towards the collecting electrode. To understand the streamer structure it is necessary to distinguish different stages of the dynamics: a) the inception and nucleation of the avalanche, b) the streamer propagation.

(a) The electron avalanche phase

      For a streamer to start, at least one free electron is required. Approximately 10^1-10^3 free electrons·cm^{-3} are always present in the environment as a result of cosmic radiation, radioactivity and/or electron liberation from electronegative gasses. In an electric field, a free electron will accelerate, and hence it gains energy. Upon collision with a molecule, it can liberate an electron; provide it has gained sufficient energy during its acceleration. This is referred as electron impact ionization. As a result of the ionization, two free electrons are now present in the electric field. Both electrons subsequently accelerate in the electric field. During the transit through the electric field, the electron may undergo multiple ionization collisions. In discharge physics, this is usually quantified using the first Townsend coefficient (α). The value for α represents the number of ionization reactions a single electron undergoes upon transiting a centimeter of path in the direction of the field.

As a result of attachment, a portion of the created electrons is lost again. This can be expressed using the attachment coefficient (β), which gives the number of attachments per centimeter of path along the electric field. Both α and β depend on the electric field and the gas density. The difference $\alpha - \beta$ is known as the net-ionization coefficient(α'). If $\alpha'>0$, the number of electrons increases exponentially, resulting in an electron avalanche. If $\alpha'< 0$, the discharge is quench, since the number of free electrons decreases. In air at normal temperature and pressure (NTP: 293 K, 1 bar) the electric field has to exceed 30 kV·cm^{-1} to obtain $\alpha'>$ 0. electron avalanche can be determined from

$$n_e(x) = n_{e0} \exp(\alpha'x). \tag{2.24}$$

Where n_e the avalanche is number over a distance x, and n_{e0} is free electron number.

An electron avalanche will develop a self-induced electric field because the electrons and positive ions move in opposite directions (space charge creation). In the past, analytic studies (J.M. Meek *et al.* 1978, H. Raether 1964), at NTP, showed that if the number of space charge species is $\sim 10^8 - 10^9$, the amplitude of the self-induced electric field becomes of the same order of magnitude as the applied electric field E$_{applied.}$ At that moment the avalanche transits into a streamer. More recent studies (C. Montijn 2006) have shown that besides geometrical considerations, diffusion should also be taken into account to determine the condition for the transition into a streamer. Depending on the value of the diffusion constant, the critical number of space charge species can be substantially different from $10^8 - 10^9$.

(b) The streamer phase

The streamer phase is characterized by the large field enhancement in front of its head, which dominates the streamer propagation. The field enhancement is high enough to ensure a positive net ionization coefficient(α'). Consequently, many new electrons are created directly in front of the streamer head.

The streamer will propagate mainly in the direction of the field enhancement, resulting in the channel-like appearance of the streamer.

a) Cathode directed streamer   b) Anode directed streamer.
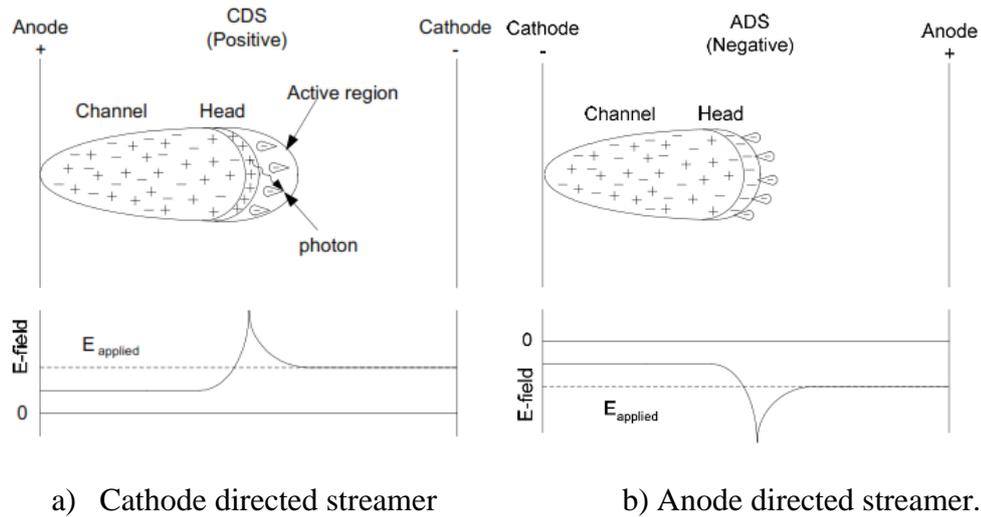
Figure 2.5   Streamer propagations with cathode and anode directed

streamers

(C. Montijn 2006).

The minimum electric field strength required to create a streamer in air-like mixtures is in the order of $10^2 - 10^3$ kV·cm^{-1}. Such high fields can be generated with strongly non-uniform electrode geometries (like wire-plate, wire-cylinder, and point-plate) under high supplied voltage. For the Cathode directed streamer, CDS, as shown in Figure 2.5a, the electrons travel in the direction opposite to the streamer whereas the Anode directed streamer, ADS, as shown in Figure 2.5b, the electrons travel in the streamer direction. To continue propagating, a mechanism is required to generate free electrons in the sheath surrounding the streamer head, which then accelerate towards this head (creating an avalanche).   If the electrons are generated too far from the streamer head, the electric field is too low to obtain a positive net ionization coefficient. The region suitable for new avalanche creation is indicated in Figure 2.6 (S.Badaloni and I. Gallimberti 1972 , I.Gallimberti 1972).

Several possibilities exist for creating free electrons in the active region. For single-shot streamer generation in air-like mixtures, Photo ionization is the dominant process. Photons created in the streamer head can ionize molecules at a small distance. When streamers are generated repetitively, in addition to photo-ionization, it is also possible that background ionization processes are responsible for the creation of the secondary electrons. The streamer will continue propagating in the gap as long as: 1) the local electric field in the streamer head is high enough to ensure a positive net ionization coefficient; 2) the applied voltage is large enough to sustain the quasi-neutral streamer channel left behind by the streamer head. The stability field found in literature was ~5-8.5 kV·cm^{-1} for the CDS in air (N. L. Aleksandrov and E.M. Bazelyan 1996, N.L. Allen and M. Boutlendj 1991, R. Morrow and J.J. Lowke 1997, Y.P. Raizer 1991). For the ADS, the stability field was estimated to be higher which was ~12 kV·cm^{-1} (N. Yu Babaeva and G.V. Naidis 1997). In general, to create an ADS, a higher field should be applied to the reactor (Y.P. Raizer 1991).

Three fundamental differences exist between the ADS and CDS could be concluded as

1) In the ADC, the electron drift velocity in directed outward from the region with the high electric space charge field and parallel to diffusion flow. In The CDS these directions are anti-parallel.

2) In the ADS, the axial component of the drift velocity is parallel to the direction of propagation. In the CDS these directions are anti-parallel.

3) Initial electrons of the in front of the CDS are necessary for its propagation. Initial electrons in front of the ADS may influence its propagation but are not necessity.

2.2.2 Particle charging in plasma

In general, if submicron particles are injected into the plasma, they become negatively charged up to the floating potential by the currents towards the particles. The plasma shielding effect is a unique consequence when the particle is immersed in plasma as shown in Figure 2.6. A measure of the plasma shielding is called the Debye length (λ_D) which is given by

$$\lambda_D = \lambda_{De} = \sqrt{\frac{kT_e}{4\pi n_e e^2}} \quad . \tag{2.25}$$

Where e is electron charge, T_e is electron temperature, k is Boltzmann's constant, and n_e is electron density.
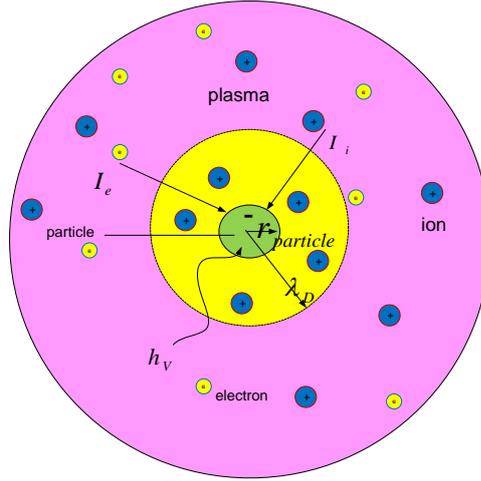

Figure 2.6   Plasma shielding on charged particle.

For the particle having radius r much smaller than Debye length (λ_D), the particle in plasma gains an electric charge and responds to electric forces. The charge can range from zero to hundreds of thousands of electron charges, depending on the particle size and the plasma conditions. It arises from collecting electrons and ions from the plasma and sometimes from emitting electrons. In plasma in which electron emission processes are unimportant, the particle charge is negative because the flux of electrons to an uncharged particle surface is high relative to that of ions. On the other hand, when electron emission is significant, the particle charge is positive.

In Figure 2.7, the electron and ion currents impinging on the particle during charging are (H. Kersten et al. 2004)

$$I_e = 4\pi r^2 n_e \sqrt{\frac{kT_e}{2\pi m_e}} \exp(eV_s/kT_e), \tag{2.26a}$$

$$I_i = 4\pi r^2 n_i \sqrt{\frac{kT_i}{2\pi m_i}} 1 + eV_s/kT_i) \tag{2.26b}$$

Here V_s is defined as floating potential surface which is a potential of the particle relative to the plasma potential, m_e and m_i are electron and ion masses, respectively.
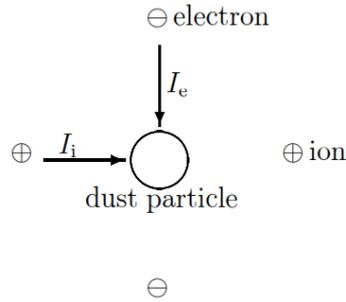

Figure 2.7   Charging of dust particle in plasma field
(H. Kersten et al. 2004).

Electron can be emitted by the particle due to electron impact, thermionic emission and field emission. Electron emission constitutes a positive current with respect to the particle, and if it is large enough, it can cause the particle to be positively charged.

The particle in plasma gains an electric charge (Q) that related to the particle's surface potential (V_s) could be calculated by

$$Q = CV_s. \tag{2.27}$$

Where C is capacitance of a particle in the plasma. For a spherical particle, the capacitance could be calculated from

$$C = 4\pi\varepsilon r. \tag{2.28}$$

A qualitative description and modeling of particle charging is mostly based on the assumption of a spherical capacitor at floating potential as

$$Q = 4\pi\varepsilon r V_s. \tag{2.29}$$

Where ε is particle dielectric constant.

From Equation 2.36, a particle in plasma gains an electric charge, depending on the particle size and plasma conditions. It arises from collection electrons and ions from the plasma and some time from emitting electrons. The process of electrical precipitation depends on the force acting on charged particle in electric field. The bigger the charge and higher the field have the greater the force. In pulsed corona plasma, the electrons are much thermal velocity. They move faster than the ions and then high collision rate to particle. They are thus able to bombard the particles and build up a charge beyond the field charge limit.

2.2.3 Pulsed Corona Plasma

In NTPs, the electron energy is higher than that of the ions and then the energy requirements to remove the pollutants are reduced (Penetrante *et al*. 1993). When a gaseous gap is excited by high voltage pulsed power at an atmospheric pressure results in the production of NTP, which called puled corona plasma.

The NTP is generated by applying high voltage pulsed power supply between two electrodes. When, the applied electric field in between the electrodes exceeds a critical value, streamers start propagating from one electrode toward the counter one. (Wang. D. 2004). The investigation of the streamer propagation across between electrodes considers the electrode impedance, and gas temperature of the discharges. Waveform of The applied voltage and discharge current depend on the electrode impedance.

One of the important factors on the plasma reaction process is gas temperature (Tochikubo F. and Teich, T. H. 2000). In positive pulsed streamer discharge, the emission at the vicinity of the discharged electrode is observed after pulsed voltage application. The streamer heads were generated in the vicinity of the discharged electrode and then propagated toward the ground electrode. After that, the steamer discharge transformed to a glow-like discharge. Finally, the applied pulsed voltage fall to zero and then the glow-like discharge stopped as shown in Figure 2.8 (Namihira et al. 2003), (Wang. D. 2007). Therefore, the pulsed discharge defines two stages. The first stage is the 'streamer discharge', which means the streamer heads

propagation between electrodes. The second stage is the 'glow-like discharge' that follows the streamer discharge.
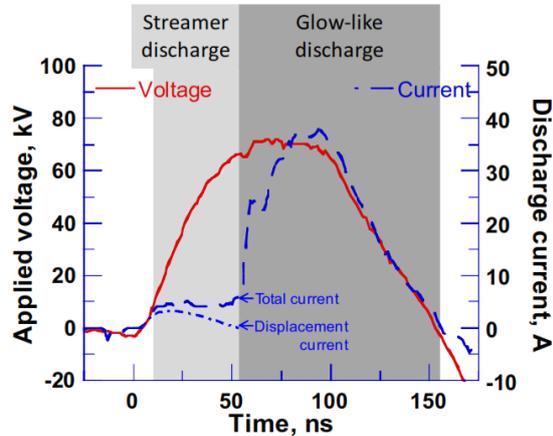

Figure 2.8   Applied voltage and discharge current with time through the electrode gap

(Namhira *et al*. 2009).

The velocity of streamer propagation increases with increase of supplied voltage to the discharged electrode. The velocity of a negative streamer is approximately half from that of positive streamers. The gas temperature increased during the glow-like discharge so that an energy loss occurred in the glow-like discharge phase. Therefore, to improve energy efficiency of a pulsed discharge, a discharge should be ends before it shifts to the glow-like phase. This can be achieved by designing a pulsed power supply with short pulse duration.

The pulse-energized ESP was purposes with both technical and economic advantages over other methods of precipitation (Dinelli *et al*. 1991, Nelson and Salasoo 1987, Porle 1985, Lausen *et al.* 1975). In this type of energization, a pulse voltage was superimposed on top of a DC voltage. But in this thesis uses only pulse power supply to form a pulse voltage and also a DC voltage produced automatically by residual voltage of pulse voltage. The pulse voltage component produces the corona ions necessary for particle charging, while the DC voltage component provides the necessary electric field for particle transport to collecting electrode.

The enhancement of ESP for submicron particle using NTP present in this thesis used pulsed corona plasma to enhance submicron particle charging and agglomerate submicron particle to large size. The used of negative pulsed voltage in non-uniform electrode geometry could be increasing over than breakdown limit of DC voltage for higher collection efficiency. And the used of positive pulsed corona discharge in non-uniform electrode geometry then streamers could propagate across the entire gas volume between electrodes, ionizing molecules and producing free electron. Results, NTP form in a larger active gas volume. The streamers leave positive ions, which do not contribute to the power consumption because no significant movement of the ions occurs within the short pulse period. The result is a large improvement in the power efficiency.