5 Electrostatic Precipitators (ESP)

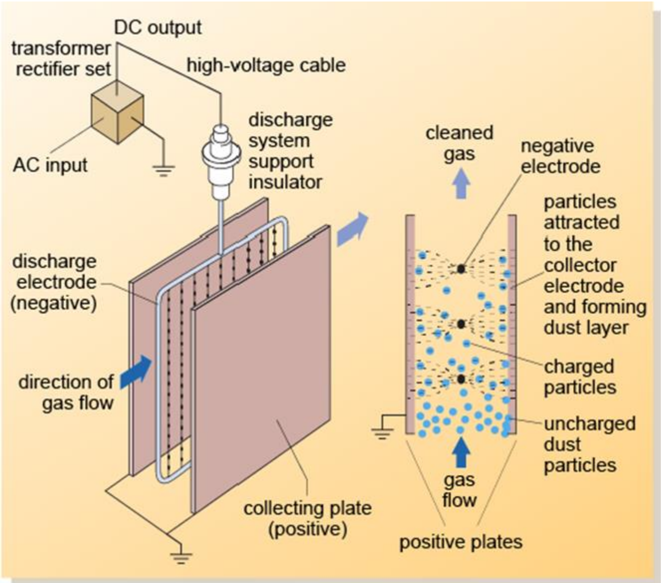
5.1 Collection Mechanisms

Introduction

The electrostatic precipitator(ESP) is a particles removal device which uses the intense electric field generated by the DC high voltage power supply to ionize the gas and generate corona discharge, and then separates the charged particles from the gas under the action of coulomb force. It mainly includes the following four physical processes:

- Applying high voltage generates strong electric field to ionize the gas and produce **corona discharge**.
- **Particles** are **charged**.
- The charged particles **migrate to** the dust **collecting pole** and deposit under the action of electric field force.
- **Electrode cleaning**.

In figure 5.1, a sufficiently high DC voltage is applied to a pair of poles, where **one pole** (generally the **cathode**) is a **thin wire** or an arbitrary shape with a small radius of curvature, and the **other pole** is a **tube or plate** (generally the **anode**), so that **an electrostatic field** is **established** between the two poles. Obviously, the electric field is non-uniform. **Near the wire area,** the electric field lines are very dense, and the corresponding **field strength is** also very **strong**. When walking away from the wire to the other pole, the electric field lines are gradually sparse, and the field strength is gradually weakened.



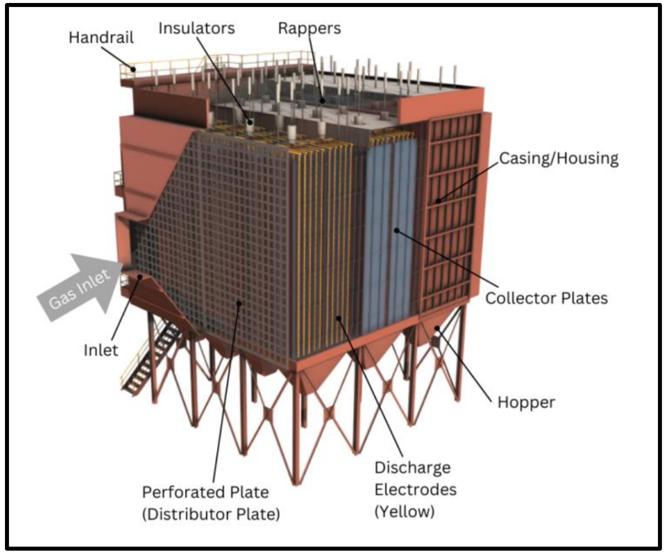
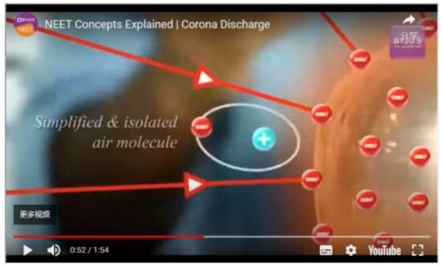


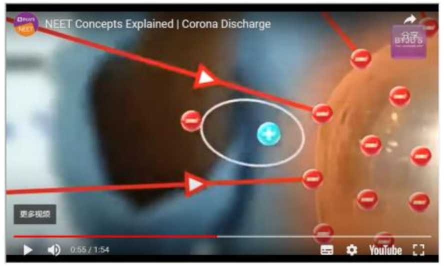
Figure 5.1 Removal of dust by an electrostatic precipitator(Air quality management, John Wiley & Sons Ltd)

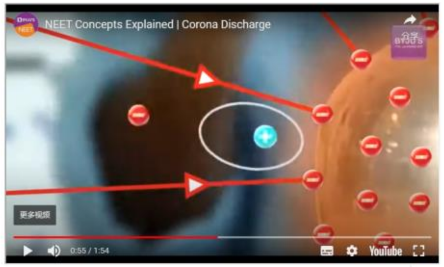
Generation of the Corona

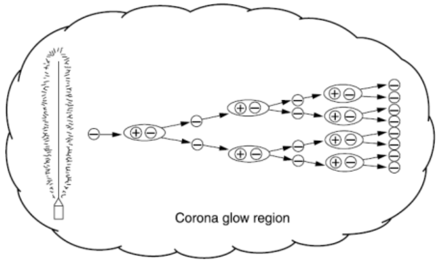
The dust-containing gas is passed into the electric field, the electrons in the gas molecules close to the cathode under the repulsive force (Coulomb force), out of the gas molecular orbit into the electric field, so that the gas molecules become electrons and positive ions, because the electric field strength is large enough, when the electrons move towards the positive pole, the acceleration is large, and the speed is instantly high. It accumulates a lot of kinetic energy in a very short time, and once the high-kinetic energy electrons collide with the neutral gas molecules, they will release electrons and become electrons and positive ions, which is called collision ionization. Under the action of electric field force, the new and old electrons collide with other neutral gas molecules and regenerate electrons and ions. Such new electrons and positive ions are produced continuously like an "avalanche", so that the gas continues to ionize, producing a large number of electrons and positive ions near the discharge electrode. This is called corona discharge.

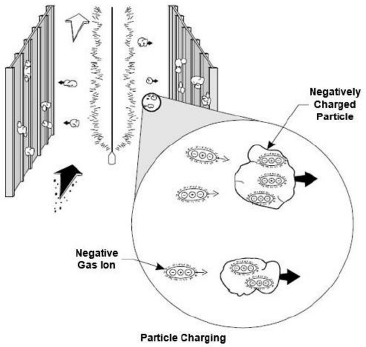
Corona discharge is a kind of self-excited discharge, which generally only occurs in a small area near the surface of the discharge electrode in a non-uniform electric field, that is, the so-called corona glow region. Outside the corona region, the electric field intensity decreases rapidly and is not enough to cause the collision ionization of gas molecules, so the corona discharge stops. Electrons leaving the corona region, due to the rapid reduction of electric field strength, can not obtain a very high speed in a short time, and their kinetic energy is not enough to cause gas molecules to impact ionization, so when they collide with gas molecules again, a completely inelastic collision occurs, adhesion together, forming a negatively charged group (ion).











5.2 Collection Efficiency

Consider a dusty airflow in a rectangular channel defined by two parallel plates as shown in Figure 5.3.

With a few assumptions, we can derive the basic equation used in ESP design-the Deutsch equation (first derived in 1922). The assumptions are

- Gases (and particles) move in the x direction at constant velocity u, with no longitudinal mixing.
- The particles are uniformly distributed in the y and z directions at every x location.
- The charging and collecting fields are constant and uniform; the particles quickly attain terminal velocity ω in the y direction.
- Re-entrainment of collected particles is negligible.

In a channel, the gas flow direction is x, the velocity of both gas and dust in the x direction is v(m/s), and the gas flow rate is Q_c(m^3/s). The total area of dust collecting plate is A_c(m^2). The length of electric field is L(m). Diameter of d_{pi} particles has a drift velocity ω_i (m/s), and its concentration in the gas is c_i (g/m^3).

In dt time, **the amount of dust captured** by a space of **length dx** is:

$$dm = 2 \cdot H \cdot dx \cdot \omega_i \cdot dt \cdot c_i = -B \cdot H \cdot dx \cdot dc_i \qquad (5.1)$$

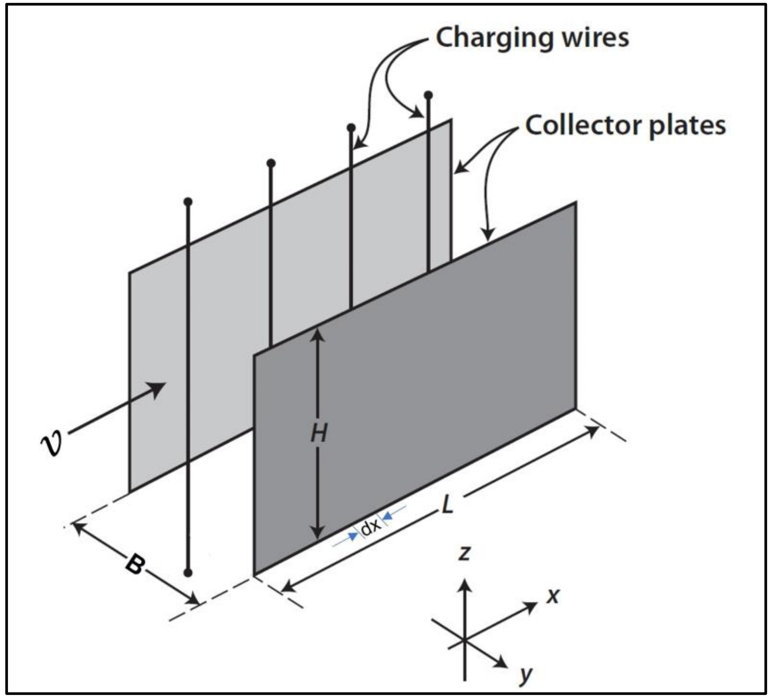


Figure 5.3 Schematic diagram of airflow between two ESP plates.

$\because dt = \frac{dx}{v} \qquad Q_c = v \cdot B \cdot H \qquad A_c = 2LH$

$$\therefore \frac{A_c \omega_i}{Q_c} \cdot dx = -\frac{dc_i}{c_i} \qquad (5.2)$$

Equation (5.2) can be separated and integrated from 0 to L (channel length, m) to give

$$\frac{A_c \omega_i}{Q_c} \int_0^L dx = -\int_{c_{\text{ini}}}^{c_{\text{outi}}} \frac{dc_i}{c_i} \qquad (5.3)$$

$$\frac{A_c}{Q_c} \omega_i = -\ln \frac{c_{\text{outi}}}{c_{\text{ini}}} \qquad (5.4)$$

$$\eta_i = 1 - \frac{c_{\text{outi}}}{c_{\text{ini}}} = 1 - exp\left(-\frac{A_c}{Q_c}\omega_i\right) \qquad (5.5)$$

where η_i = fractional collection efficiency .

The collecting efficiency of other channel is the same as that. For the whole ESP, we can use the total collection area and the total gas flow rate, and Eq. (5.5) can be written as the **Deutsch equation**:

$$\eta_i = 1 - exp\left(-\frac{A}{Q}\omega_i\right) \qquad (5.6)$$

$$\eta = \sum \eta_i m_i \qquad (5.7)$$

where η = overall collection efficiency; m_i = mass fraction of particles in the ith size range.

The **drift velocity *ω*** in an electrical force field can be calculated in a manner similar to that used in Chapter 3 for calculating the terminal settling velocity in a gravitational field.

in ESP ,particle is mainly subject to two forces: one is the **electric field force** qE_{co}, and the other is the **fluid resistance** $3\pi\mu\omega dp$. The equation of motion of the particle is:

$$m\frac{d\omega}{dt} = qE_{co} - 3\pi\mu d_p\omega \quad (5.8)$$

$$\int \frac{m d\omega}{qE_{co} - 3\pi\mu d_p\omega} = \int dt \quad (5.9)$$

$$\frac{-m}{3\pi\mu d_\mathrm{p}} ln\left(qE_{co} - 3\pi\mu d_p\omega\right) = t + C \quad (5.10)$$

When t=0, ω=0, substituting into the above formula, we get:

$$C = -\frac{m}{3\pi\mu d_p} \times \ln qE_{co} \quad (5.11)$$

$$\frac{-m}{3\pi\mu d_\mathrm{p}} ln\left(qE_{co} - 3\pi\mu d_p\omega\right) = t - \frac{m}{3\pi\mu d_p} \times \ln qE_{co} \quad (5.12)$$

$$qE_{co} - 3\pi\mu d_p\omega = qE_{co}e^{-\left(\frac{3\pi\mu d_p}{m}\right)t} \quad (5.13)$$

$$\omega = \frac{qE_{co}}{3\pi\mu d_p}\left[1 - e^{-\left(\frac{3\pi\mu d_p}{m}\right)t}\right] \quad (5.14)$$

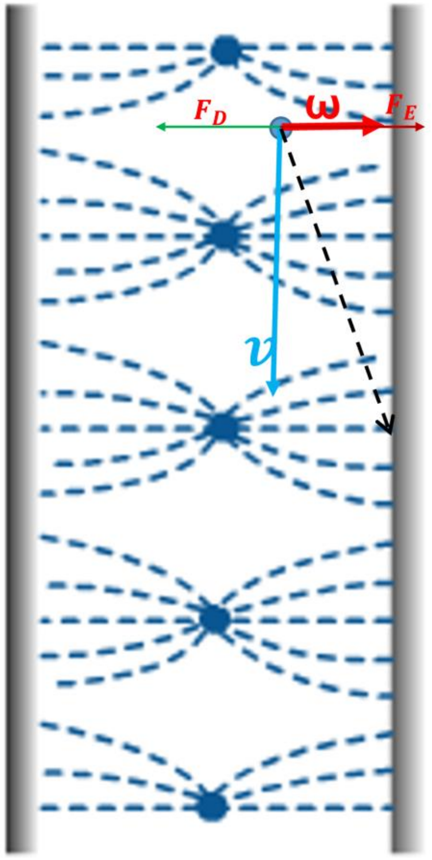


Figure 5.4 Schematic diagram of airflow between two plates in ESP.

where m = mass of the particle, kg ; q = charge on the particle, coulombs (C); E_{co} = collecting field strength, V/m; μ = gas viscosity , kg/m · s.

In all electrostatic precipitators, the exponent of $\frac{3\pi\mu d_p}{m}$ is a large value, for example, for a spherical particle with a density of $1 g/cm^3$ and a diameter of 10μm, in the air there is:

$$3\pi\mu d_p/m = 3\pi\mu d_p/\left(\frac{1}{6}\pi d_p^3\rho_p\right) = \frac{18\mu}{d_p^2\rho_p} = \frac{18\times 1.8\times 10^{-5}}{(10\times 10^{-6})^2\times 1000} = 3240$$

If $t > 0.01s, e^{-\left(\frac{3\pi\mu d_p}{m}\right)t} \le 8.5\times 10^{-15}$,completely negligible. That is, when charged particles move toward the collecting plate under the action of electric field force, the electric field force and air resistance quickly reach a balance, and move toward the dust collecting plate at an equal speed, and the displacement velocity of the particles is:

$$\omega = qE_{co}/(3\pi\mu d_p) \qquad (5.15)$$

As we will see ,the migration velocity ω depends on the number of charges on the particle and particle size as well as the local electric field strength. Particles in the ESP are charged by two mechanisms: **Field Charging** **Diffusion Charging**. In **field charging**, the negative ions are driven by the electrical field onto dust particles that intercept the field lines, this is more effective for particles larger than **$0.5\mu m$** . Particles smaller than about **$0.2\mu m$** are charged more effectively by **diffusional charging**; that is, the charging of small particles is a result of collisions of gas ions and small particles due to the random motions of each.

The theoretical saturation charge on a spherical particle($d_p \ge 0.5\mu m$) is given by

$$q = 3\pi \mathrm{d_p^2}\varepsilon_0\left(\frac{\varepsilon_p}{\varepsilon_p+2}\right)E_{ch} = \pi \mathrm{d_p^2}\varepsilon_0 K E_{ch} \qquad (5.16)$$

where $d_p =$ particle diameter, m;$\varepsilon_0 =$ permitivity of free space, $8.85\times 10^{-12}\mathrm{C/V\cdot m}$; $\mathrm{K} = \frac{3\varepsilon_p}{\varepsilon_p+2}$, $\varepsilon_p =$ dielectric constant for the particle relative to free space(for many particles, the constant K ranges from 1.5 to 2.4 .);

$E_{ch} =$ charging field strength, V/m.

Combining Eqs. (5.13), (5.14), we can solve for the theoretical drift velocity of a spherical particle in an ESP as follows:

$$\omega = \frac{Cd_p}{3\mu}\varepsilon_0 K E_{\mathrm{ch}} E_{\mathrm{co}} \qquad (5.17)$$

where $C =$ the Cunningham correction factor(for $d_p \le 1\mu m$).

Example 5.1

Determine the total collection efficiency of the electrostatic precipitator for collect cement kiln dust. The electrostatic precipitator has 3 electric fields, each field plate is 3.6m long and 4m high, composed of 10 rows of plates, and the plate spacing is 300mm.The discharge electrode voltage is 48kV; the particle size distribution is log-normal distribution, the median particle size d_{50}=12μm, the geometric standard deviation σ_g=3.08, and the particle relative dielectric constant ε_p=6.14; the gas flow rate at 121℃ and normal pressure is 6.278m^3/s, and the gas viscosity is 2.25×10^{-5}Pa·s.

Solution From the particle size distribution,

$$f(d_p)=\frac{1}{d_p\ln\sigma_g\sqrt{2\pi}}exp\left[-\left(\frac{\ln(d_p/d_g)}{\sqrt{2}ln\sigma_g}\right)^2\right]=\frac{1}{d_p\ln3.08\sqrt{2\pi}}exp\left[-\left(\frac{\ln d_p-\ln 12}{\sqrt{2}\ln 3.08}\right)^2\right]=\frac{1}{2.819d_p}exp\left[-\left(\frac{\ln d_p-2.485}{1.591}\right)^2\right]$$

cumulative percent less than 0.5μm

$$D=\int_0^{0.5}\frac{1}{2.819d_p}\exp\left(-\frac{\left(\ln d_p-2.485\right)^2}{2.531}\right)d(d_p)=0.0024$$

It can be seen that the particles smaller than 0.5μm are less than 1%, so the particle collection efficiency can be calculated using formula (5.6).

Area of collection plate A=4×3.6×（10-1）×2×3=777.6m^2

Particles drift velocity $\omega=\frac{d_p}{3\mu}\varepsilon_0 KE_{\mathrm{ch}}E_{\mathrm{co}}=\frac{d_p\times8.85\times10^{-12}\times2.263\times3.2\times10^5\times3.2\times10^5}{3\times2.25\times10^{-5}}=0.03\ d_p$ (d_p units μm, $\mathrm{K}=\frac{3\varepsilon_p}{\varepsilon_p+2}=\frac{3\times6.14}{6.14+2}=2.263, E_{\mathrm{ch}}=E_{\mathrm{co}}=\frac{48000}{0.15}=3.2\times10^5$)

fractional collection efficiency $\eta_i=1-exp\left(-\frac{A}{Q}\omega_i\right)=1-\exp\left(-\frac{777.6}{6.278}\times0.03d_p\right)=1-\exp(-3.716d_p)$

collection efficiency(Eq.5.7) $\eta=\int_0^\infty f(d_p)\times\eta_i=\int_0^\infty\frac{1}{2.819d_p}\exp\left(-\frac{(\ln d_p-2.485)^2}{2.531}\right)\times(1-\exp(-3.716d_p))d(d_p)=0.9987$

particles size distribution as given below, calculate the overall collection efficiency.

Particle Size Range, μm	Mass Percent in Size Range
0 – 2	1.0
2 – 4	9.0
4 – 6	10.0
6 – 10	30.0
10 – 18	30.0
18 – 30	14.0
30 – 50	5.0
50 – 100	1.0

	A	B	C	D	E	F	G	H	I	J
1	dp_i(um)	1	3	5	8	14	24	40	75	
2	ΔD(%)	1	9	10	30	30	14	5	1	100
3	ω_i(m/s)	0.03	0.09	0.15	0.24	0.42	0.72	1.2	2.25	
4	ω(m/s)	0.0003	0.0081	0.015	0.072	0.126	0.1008	0.06	0.0225	0.4047
5	η_i	0.975665	0.999986	1	1	1	1	1	1	
6	η	0.009757	0.089999	0.1	0.3	0.3	0.14	0.05	0.01	0.999755

You can also use the **effective drift velocity** ω_e and use the same form of equation(6.6) to calculate the **overall collection efficiency**

$$\eta = 1 - e^{(-\frac{A}{Q}\omega_e)} \qquad (5.18)$$

where η = overall collection efficiency ; A=the total area of collecting plate,m²; Q=the gas flow rate m³/s; ω_e = the effective drift velocity , m/s.

Effective drift velocity ω_e indicates the trapping performance of a certain structure electrostatic precipitator for a certain type of dust under a specified set of operating conditions. It is calculated according to the total collection efficiency measured by the electrostatic precipitator, so it is the performance parameter of the electrostatic precipitator. The value of ω_e depends on the characteristics of dust, particle size distribution, airflow velocity and its distribution, the structure type of electrostatic precipitator, the mode of particle removal and power supply.

Example 5.2

(a)An ESP with a total plate area of 5000 m^2 treats 8000 m^3/min of air containing particulate, the effective drift velocity is 10 cm/ s. calculate the efficiency of the ESP.

(b) Calculate the total collection area for a 98% efficient ESP that is treating 10,450 m^3/min of air. The effective drift velocity is 6.0 m/ min .

Solution **(a)** $\eta = 1 - e^{\left(-\frac{A}{Q}\omega_e\right)} = 1 - \exp\left(-\frac{5000\ \mathrm{m}^2}{8000\ \mathrm{m}^3/\mathrm{min}} \times \frac{0.1\mathrm{m}}{\frac{1}{60\mathrm{min}}}\right) = 97.6\%$

(b) $\mathbf{A} = \frac{-Q}{w_e}\ln(1-\eta) = \frac{-\frac{10{,}450\ \mathrm{m}^3}{\mathrm{min}}}{\frac{6.0\ \mathrm{m}}{\mathrm{min}}}\ln(1-0.98) = 6813m^2$

5.3 Pressure Drop

The pressure drop in an ESP is due to four main factors:

- Diffuser Plate (usually present) — (perforated plate at the inlet)
- Transitions at the ESP inlet and outlet
- Collection plate baffles (stiffeners) or corrugations
- Drag the flat collection plate

The diffuser plate is used to equalize the gas flow across the face of the ESP. It typically consists of a flat plate covered with round holes of 5 to 7 cm diameter having an open area of 50 to 65 percent of the total. Pressure drop is strongly dependent on the percent open area, but is almost independent of hole size.

The pressure drop, due to gradual enlargement at the inlet, is caused by the combined effects of flow separation and wall friction and is dependent on the shape of the enlargement. At the ESP exit, the pressure drop caused by a short, well - streamlined gradual contraction is small.

Baffles are installed on collection plates to shield the collected dust from the gas flow and to provide a stiffening effect to keep the plates aligned parallel to one another. The pressure drop due to the baffles depends on the number of baffles, their protrusion into the gas stream with respect to electrode - to - plate distance, and the gas velocity in the ESP.

The pressure drop of the flat collection plates is due to friction of the gas dragging along the flat surfaces and is so small compared to other factors that it may usually be neglected in engineering problems.

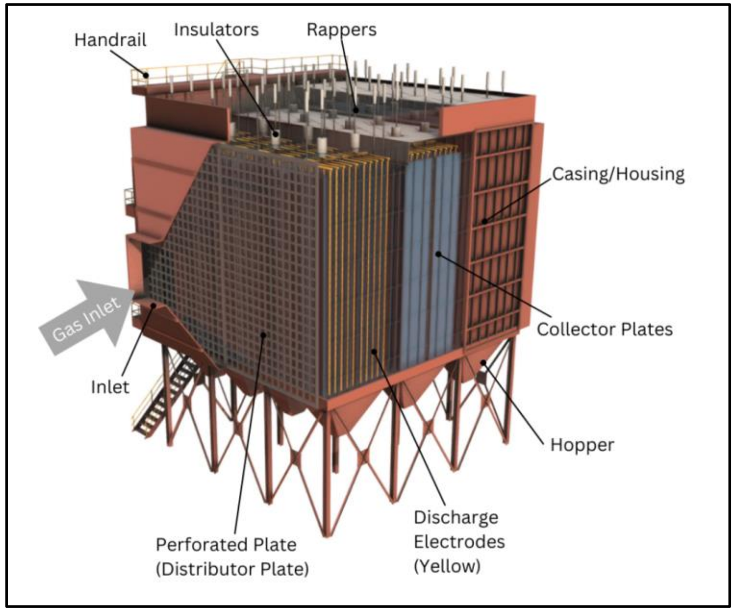


Table 4.1 **Components of ESP Pressure Drop**

component	Typical Pressure Drop(Pa)	
	Low	High
Diffuser	2.49	22.41
Inlet Transition	17.43	34.86
Outlet Transition	1.74	3.74
Baffles	1.49	30.63
Collection plates	0.75	1,99
Total	22.41	94.82

5.4 Design

Plate Sizing

According to the gas flow rate, collection efficiency and particle drift velocity, the total collecting plate area is calculated by equation 5.18.

$$\mathbf{A} = -\frac{Q}{w_e}\ln(1-\eta) \qquad (5.19)$$

Gas velocity

In ESP, if the gas velocity is too large,it runs a risk of reentrainment. The maximum acceptable velocity is about 1m/s for flat plate ESPs. For low–resistivity applications, design velocities of 1m/s or less are common to avoid reentrainment. So,The across area of the ESP must be chosen to keep gas velocity low and to accommodate electrical requirements (e.g., wire - to - plate spacing) while also ensuring that total plate area requirements are met.

Across area

$$F = \frac{Q}{v} \qquad (5.20)$$

where F = The across area of the ESP ,m^2; Q=the gas flow rate m^3/s; v = the gas flow velocity , m/s.

Channels

The plates in an ESP are placed in parallel. The gas flows through the channel is the spaces between the plates.

$$Z = \frac{F}{BH} = \frac{F}{2bH} \qquad (5.21)$$

where Z = The number of channel in the ESP ; B= The distance between the plates,m; b= The distance between the plate and the wire,m; H = the height of the plate, H = $\sqrt{F}$, m.

Length and width of field

$$L = \frac{A}{n'nZh} \quad (5.22)$$

where L = The length of field, m ; n' = number of chambers; n= number of mechanical fields .
The final length and width of the electric field need to be adjusted according to the size of a single plate.

Example 5.2

Design a ESP treating 119946 m^3/h gas and remove 99.3% of particles. Drift velocity is 5.34cm/s. Gas velocity is 0.6m/s. Each plate is 385mm width . the plate spacing is 350mm. estimate the overall width, length, and height of the field in the ESP.

Solution

Due to the large amount of gas ,Choosing 2-chambers&3-Field.
the total collecting plate area

$$\mathbf{A} = -\frac{Q}{w_e}\ln(1-\eta) = -\frac{119946/3600}{5.34/100} \times \ln(1-0.993) = 3096m^2$$

Across area $F = \frac{Q}{v} = \frac{11946/3600}{0.6m/s} \approx 56m^2$

The height of plate H $= \sqrt{F} = \sqrt{56} = 7.48\text{m} \approx 7.5m$

The number of Channels $Z = \frac{F}{BH} = \frac{56}{0.35\times7.5} = 22$

Two chamber 22 channels, one chamber 11 channels.
So, each chamber has 12 rows of collecting plate and 11 rows of corona poles(wire).

The length of field $\text{L} = \frac{A}{n'nZH} = \frac{3096}{2\times3\times22\times7.5} = 3.13m$

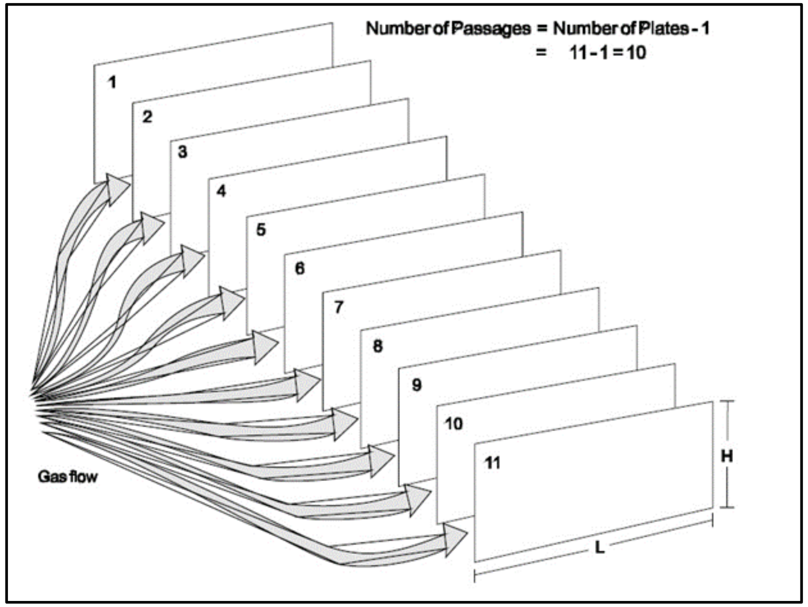


Figure 5.5. Collection plate area calculation
(**Control of Particulate Matter Emissions** APTI Course 413 **EPA**)

385Z型板+板间隔15mm=400mm，那么每个电场集尘极由8块板构成，电场长度为：3.2m，实际集尘极面积为：$0.385 \times 7.5 \times 8 \times 3 \times 22 \times 2 = 3049m^2 < 3094m^2$,显然不能满足要求，因此每个电场需安装9块集尘板，电场实际长度为：3.6m，实际集尘极面积为：$0.385 \times 7.5 \times 9 \times 3 \times 22 \times 2 = 3430m^2 > 3094m^2$，满足要求。

电场（双室）实际宽度：D= $Z \times B = 22 \times 0.35 = 7.70\ m$

最终结果：采用双室三电场，每个电场长度3.6m，电场宽度3.85m，电场高度7.5m。