Abstract

If exhaust gases are to be cleaned from particulate matter at high flow rates and, simultaneously, at low pressure drops, an electrostatic precipitator (ESP) is a suitable device. ESPs are widely used for removal of fly-ash in coal fired power plants commonly operating at moderate temperatures up to about 200°C and ambient pressure. Today, particle collection at high temperatures and/or high pressures is of current interest because of new concepts for electrical power generation systems. However, the capabilities of electrical precipitators under these extreme conditions are only poorly investigated. Therefore, the paper works out the fundamentals of high-temperature and/or high-pressure electrostatic precipitation. It provides a basis for discussion and gives the interested reader several tools to permit estimating the potential for electrostatic precipitators under extreme conditions.

1. Introduction

Particle collection at high temperatures and/or high pressures is of current interest mostly because of new concepts for electrical power generation systems. These are, for example, coal combustion processes (pressurized fluidized beds) or coal gasification processes combined with a more or less conventional steam cycle. In order to achieve high energy efficiencies, the hot exhaust gas is fed directly into turbines which, to guarantee a long service life, can only operate with extremely low particle loadings. Because of this, high performance in dust collection is required which, under moderate conditions, is usually achieved by means of baghouses or electrostatic precipitators. As various investigations show, at high temperatures, rigid ceramic filters appear to be in widespread use, whereas the capabilities of electrical precipitators under these extreme conditions are only poorly investigated.

If exhaust gases are to be cleaned from particulate matter at high volume rates and simultaneously at low pressure drops, an electrostatic precipitator (ESP) is a suitable device. ESPs are widely used for removal of fly-ash in coal-fired power plants commonly operating at moderate temperatures up to about 200 °C and ambient pressure. Electrical particle separation still works effectively at very small particle sizes.

Concerning their capability to operate at temperatures of about 1000°C, only a few experimental results have been published. Therefore, the goal of the following sections will be to outline the fundamentals of ESP design and operating conditions, especially emphasizing the effects of high temperature and/or high pressure.

2. Fundamentals

2.1 Effect of high temperature and/or high pressure

Changing gas temperature and/or changing gas pressure usually leads to a change in gas density. This can easily be seen when regarding the state equation of ideal gases (Eq. 1).

\[ \frac{p}{\rho} = R \cdot T \]  

(1)

For easy handling of different states, it is convenient to introduce the so-called relative gas density \( \delta \) defined by equation 2. It relates the gas density of an interesting state 2 to the gas density of a known state 1. The relative gas density is obviously a function of the pressure ratio and the reciprocal temperature ratio.

\[ \delta = \frac{\rho_2}{\rho_1} = \frac{p_2}{p_1} \cdot \frac{T_1}{T_2} \]  

(2)

Temperature and pressure are usually related to normal conditions, i.e., \( T_1 = T_0 = 273 \) K and \( p_1 = p_0 = 1 \) bar. Figure 1 illustrates the range of the
relative gas density for temperatures from 300 K to 1500 K and pressures from 1 bar to 30 bar represented by corresponding isolines.

A decreasing relative gas density corresponds with an increasing average distance between the gas molecules (which can be deduced from kinetic gas theory) or, in other words: when comparing two different gas states, the mean free path of the gas molecules behaves like the reciprocal of the relative gas density (Eq. 3). At normal conditions, \( \lambda(p_0, T_0) \) is about 0.065 \( \mu \)m. Therefore, under normal conditions for particles smaller than 1 \( \mu \)m, the mean free path of the gas molecules has to be taken into account.

\[
\lambda(p, T) = \frac{\lambda(p_0, T_0)}{\delta} \quad (3)
\]

Closely connected with the mean free path of the gas molecules is the mobility of the gas ions. The mobility of charge carriers is defined as the ratio of mean drift velocity \( v \) of the charge carriers to the electrical field strength \( E \) generating the drift, and a typical value for gas ions at normal conditions is given in equation 4. The mean drift velocity of the charge carriers is determined by the collision frequency with other (neutral) gas molecules; obviously the collision frequency decreases with increasing intermolecular distances, thus the mobility increases in the same way as the mean free path of gas molecules does (Eq. 5). The mobility of gas ions influences the current-voltage relationship, as will be discussed in the following sections.

\[
b(T_0, p_0) = 2 \times 10^{-4} \frac{m^2}{Vs} \quad (4)
\]

\[
b(p, T) = \frac{b(p_0, T_0)}{\delta} = \frac{b(p_0, T_0)}{\delta} \quad (5)
\]

Finally, we have to consider how the viscosity of the gas flow is affected by high temperatures and/or high pressures. It can easily be demonstrated that viscosity is not influenced by pressure but only by temperature, since the \( p, T \)-dependence of gas density and mean free path compensates each other (Eq. 6). Thus the well-known \( \sqrt{kT} \)-dependence of the mean thermal velocity of a gas molecule with mass \( m \) remains (Eq. 7). Therefore, viscosity is not transferring in terms of relative gas density, but in terms of \( \sqrt{T_2/T_1} \) (Eq. 8).

\[
\eta = \epsilon \cdot \lambda \cdot <v> \quad (6)
\]

\[
<v> \sim \frac{kT}{m} \quad (7)
\]

\[
\eta(T) \sim \frac{T}{T_0} \cdot \eta(T_0) \quad (8)
\]

Viscosity of flow is decisive for the migration velocity of the particles which results as a balance between electrical force and drag force. The viscosity therefore determines separation efficiency, while relative gas density and mobility mainly govern the operating conditions.

Finally, some particle properties important for the ESP process are also a function of temperature: electrical resistivity (will be discussed in Section 2.7.1), particle-particle and particle-collector adhesive forces (are discussed elsewhere\(^2\)), and the electrical permittivity \( \epsilon_r \) of particulate material. The electrical permittivity \( \epsilon_r \) is related to the electrical susceptibility \( \chi_e \) according to equation 9, which, in general, shows a temperature dependence as indicated in equation 10. The effect of equation 10 on the particle charge is neglected in all following calculations.

\[
\epsilon_r = 1 + \chi_e \quad (9)
\]

\[
\chi_e = \frac{C_1 + \frac{C_2}{T}}{2} \quad (10)
\]

2.2 Minimum field strength for corona initiation

To generate charge carriers in a gas phase, a critical field strength has to be overcome. This can be
done with the aid of a wire/plate or needle/plate geometry because the electrical field lines are focused onto the top of the needle or wire surface. When $r_{SE}$ describes the radius of curvature or wire, respectively, then the corona initiation field strength $E_0$ at the wire surface can be calculated according to Peek’s empirical relationship$^1)$. When using the relative gas density already introduced, equation 11 emerges:

$$E_0 = A\delta + B\sqrt{\delta/r_{SE}}$$

(11)

where the empirical constants for a negative corona (i.e. the wire is on negative potential) in air are:

$$A = 3.2 \times 10^6 \text{ V/cm} \quad B = 9 \times 10^4 \text{V/m}^{1/2}$$

Figure 2 shows the corona initiation field strength $E_0$ as a function of wire radius and isolines for different relative gas densities. In general, an increase of wire radius leads to a decrease in electrical field strength; this trend weakens for radii $>1$ mm. Relative gas densities $>1$ need higher electrical field values to initiate corona in the same geometry. This seems reasonable because in a denser gas, the mean free path of molecules reduces and with it the time available for acceleration; compensated by higher electrical field values. Obviously, for relative gas densities $<1$, the opposite behaviour has to appear.

2.3 Tube-type ESP

Looking at high temperatures is often in line with high pressures (especially in electrical gas cleaning as demonstrated later); this is why wire-tube geometries might be favourable compared with wire-plate designs. In any case, i.e. without the intention of preferring either design, it will certainly suffice to discuss the effect of high pressure and high temperature for the tube-type ESP, which is in some ways easier to handle. Therefore the discussion of theoretical aspects will be deliberately restricted to the tube-type ESP, and its typical geometry is shown in Figure 3. The important geometric parameters are the wire radius $r_{SE}$, the radius of the collecting tube $r_{NE}$, and its length $L_{NE}$.

2.3.1 Corona onset voltage

According to White$^2)$, the corona onset voltage can be estimated according to equation 12 and its dependence on relative gas density is plotted in Figure 4. For fixed geometries, an increasing relative gas density generally needs higher voltage levels to initiate corona.

$$U_0 = E_0(\delta) \cdot r_{SE} \cdot \ln \frac{r_{NE}}{r_{SE}}$$

(12)

The thick line in Figure 4 refers to a wire radius of 1.0 mm and a tube radius of 150 mm. As shown, a variation of the tube radius only has small effects on the voltage levels compared with changes of the discharge wire radius. Interesting to note is that the smaller the discharge wire, the weaker the dependence of onset voltage on gas density becomes.

2.3.2 Current-voltage relationship

Instead of “current”, it is helpful to take current...
densities $i_{NE}$, i.e. the total current $i$ is related to the total collecting area $A_{NE}$ (Eq. 13). Sometimes, one can find a definition of an unconventional current density $j_{SE}$ where the total current is related to the total length of discharge wire, which for a tube-type ESP, is approximately described by $L_{NE}$ (Eq. 14). Considering this, the current density at the collecting surface can be estimated with equation 15.

$$i_{NE} = \frac{i}{A_{NE}}$$  \hspace{1cm} (13)

$$j_{SE} = \frac{i}{L_{SE}} = \frac{i}{L_{NE}}$$  \hspace{1cm} (14)

$$j_{NE}(\delta) = \frac{j_{SE}(\delta)}{2\pi \cdot r_{NE}} = \frac{4 \cdot \varepsilon_0 \cdot b(\delta) \cdot U \cdot (U - U_0(\delta))}{(r_{NE})^2 \cdot \ln \frac{r_{NE}}{r_{SE}}}$$  \hspace{1cm} (15)

For a discussion of the relative gas density dependence, we have to keep in mind that the corona onset voltage $U_0$ and the mobility of gas ions $b$ are also functions of $\delta$ (Eq. 11/12 and Eq. 4).

**Figure 5** shows the calculated relationships for different relative gas densities for a tube-type design of $r_{SE} = 1$ mm and $r_{NE} = 150$ mm. The higher the relative gas density, the flatter the curve becomes, or in other words, at higher relative gas densities, a constant applied voltage can force less gas ions to pass the gas phase.

**2.3.3 Sparkover voltage**

In reality, the current-voltage relationships will end suddenly at a critical current/voltage level (which is obviously not considered in **Figure 5**). Unfortunately, and as far as the author knows, no analytical formula is available for this electrical breakdown which allows an estimation of the so-called sparkover voltage $U_{crit}$.

![Fig. 5 Electrical current density at collecting wall as a function of applied voltage for different relative gas densities.](image)

As experiments show, this sparkover voltage plays an important role for the operation of electrical precipitators, because stable operation is only possible if an essential difference between corona onset and sparkover ($U_{crit} - U_0$) exists. As the experimental results in **Figure 6** can show\(^5\), the region of stable operation $U_{crit} - U_0$ in a tube-type ESP decreases continuously with increasing temperatures if the pressure is kept constant at 1 bar. However, if the pressure is also increased, then the region $U_{crit} - U_0$ widens up and extends to higher temperatures. For example, at 1 bar and room temperature, $U_{crit} - U_0$ is about 25 kV in **Figure 6**; approximately the same voltage difference is observed at a pressure level of 21 bar at about 800°C. Stable operation of ESPs at high temperatures must therefore be accompanied by an appropriately high pressure level, i.e. high relative gas densities.

Furthermore, the high gas densities enable higher voltages to be applied, i.e. higher electrical fields can be sustained between the electrodes (**Fig. 6**) corresponding to considerable improvements in particle collection, as will be seen later on. Since no reasonable forecast of the sparkover voltage can be made, no reliable forecasts for achievable electrical field strengths are possible and experiments are necessary. For example, **Figure 7** shows $j_{SE}/U$-curves experimentally determined by Bush et al.\(^4\) in a laboratory-scale tube-type ESP, allowing temperatures in the range 533-1366 K and pressures...
of between 3.4 and 35.5 bar ($R_{NE} = 3.63$ cm and $R_{SE} = 0.8-1.6$ mm). In the same way as other authors, they find no investigated general limitations for corona discharge at high pressures and high temperatures, and in most cases, negative corona is superior to positive corona. As is seen in Figure 7, relative gas densities of about $\delta \geq 6$ enable voltage levels of approx. 100 kV; bearing in mind the tube radius of approx. 3 cm, this corresponds to electric field strengths of the order of 30 kV/cm! Regarding standard operation conditions of about 3 kV/cm, this represents, obviously, an outstanding potential for successful particle collection at high temperatures and high pressures.

![Figure 6](image-url)  
Fig. 6 Corona onset voltage (bright dots) together with sparkover voltage (dark dots) as a function of temperature for four different pressures. The measurements were done by Weber in a tube-type ESP with $R_{NE}/R_{SE} = 62.5$.

2.4 Particle charging process

Usually, the charging process is divided into a field charging region for particles about $>1$ $\mu$m and a diffusion charging region for particles about $<0.1$ $\mu$m. Whereas field charging requires the presence of an electrical field and free movable charge carriers, the diffusion process needs the statistical movement caused by temeprature in addition to the charge carriers, but no electrical field at all. Obviously, in an ESP, both mechanisms are active simultaneously, i.e. particles $<0.1$ $\mu$m are also guided by an electrical field. It therefore seems reasonable to look for charging theories which allow continuous description of the charging process from small to larger particle sizes. The analytical equation of Cochet, which allows an easy discussion of basic principles, can be considered a reasonable alternative to published models based on numerical solutions.

![Figure 7](image-url)  
Fig. 7 Current voltage characteristics $i_{SE}(U)$ for dry air measured by Bush et al. Diagrams on the left for $T = 811$ K, diagrams on the right for $T = 1089$ K. Top diagram represents positive corona, bottom diagrams hold for negative corona. The top end of the curves corresponds to electrical breakdown. The value of the relative gas density is written along each curve. The tube radius was $R_{SE} = 3.63$ cm and that of the discharge wire $R_{SE} = 1.17$ mm.

2.4.1 Saturation charge

The particle saturation charge according to Cochet is given by equation 16. For calculations, the electrical field strength $E$ and the electrical permittivity of the particle material $\varepsilon_r$ have to be specified.

$$Q_p^\infty = \frac{2}{1 + 2 \lambda/d_p} \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \right) \times \varepsilon_{0} d_p^2 E$$

The results for $E = 3$ kV/cm and $\varepsilon_r = 10$ are shown in Figure 8 as a function of the particle size for different relative gas densities. With decreasing particle size, the achievable particle charge generally decreases because of decreasing surface area. This is why a straight line emerges for large particles in the log-log scale. Obviously at low relative gas densities, small-sized particles can bear much greater charges than at atmospheric conditions.
According to Figure 1, gas densities <1 correspond e.g. with atmospheric pressure and high temperature. But the charge carriers are also to be generated in a corona discharge which provides for stable operation at high pressure, as discussed before. Obviously, both effects do not fit together, thus we could suppose at this stage that ESPs will work less effectively in the fine particle region at high temperature and high pressure levels; on the other hand, the decrease in separation efficiency might be compensated by higher electrical field strengths.

2.4.2 Time dependence

The time dependence of the charging process is described by equation 17, using the time constant \( \tau_Q \) for the charging process (Eq. 18)

\[
Q_p(t) = Q_p^{\infty} \frac{t}{t + \tau_Q}
\]

(17)

\[
\tau_Q = \frac{4 \varepsilon_0}{c_Q b}
\]

(18)

To find the T/p-dependence of \( \tau_Q \), we first have to look for the T/p-dependence of the charge carrier concentration \( c_Q \). Referring to Ohm’s law, \( c_Q \) can easily be expressed in terms of current density, mobility and electrical field (Eq. 19). As already shown in equation 15, \( j/b \) will only be a weak function of the relative gas density; therefore the T/p-dependence of \( \tau_Q \) will be approximately described by that of the mobility \( b \), i.e. \( \tau_Q \) is proportional to the relative gas density (Eq. 20). Using typical values, the constant in equation 20 is about 2 ms.

\[
j = c_Q \cdot b \cdot E
\]

(19)

\[
\tau_Q(\delta) = \frac{4 \varepsilon_0}{c_Q \cdot b \cdot (T_0, P_0)} \cdot \delta = \text{const.} \cdot \delta
\]

(20)

2.5 Migration velocity

The forces acting on a particle in an ESP are the momentum force \( F_T \) (Eq. 21), the electrical force \( F_el \) (Eq. 22) and the drag force \( F_W \) (Eq. 23). For the drag force, the validity of Stokes’ law is assumed.

\[
\vec{F}_T = -m \vec{a}
\]

(21)

\[
\vec{F}_el = Q_p \vec{E}
\]

(22)

\[
\vec{F}_w = 3 \pi \eta d_p \cdot \vec{v} - \vec{w} \cdot j \cdot \frac{1}{Cu}
\]

(23)

\( Cu \) represents the drag force correction for particles in the size range of the mean free path of the gas molecules (\( \lambda \)) according to Cunningham (Eq. 24). The Cunningham correction is a function of the relative gas density, because of its dependence on \( \lambda \).

\[
Cu = 1 + 1.246 \cdot \frac{2 \lambda}{d_p} + 0.42 \cdot \frac{2 \lambda}{d_p} \cdot \exp(-0.87 \cdot \frac{d_p}{2 \lambda})
\]

(24)

By using equation 3 for the dependence of \( \lambda \) on the relative gas density \( \delta \) the dependence of \( Cu \) on \( \delta \) as a function of the particle size \( d_p \) can easily be calculated; the results are plotted in Figure 9. For constant particle sizes, an increase in relative gas density leads to lower \( Cu \) values, i.e. the influence of \( \delta \) on the Cunningham correction acts in the same direction as its influence on particle saturation charge.

![Fig. 9](image-url)
2.5.1 Steady state

Integrating the equation of particle motion (resulting from a balance of the forces mentioned above) and looking for the steady state solution leads to equation 25, the so-called theoretical migration velocity of an individual charged particle in an electrical field. For all calculations, an electrical field of $E = 3 \text{kV/cm}$ and an electrical permittivity of $\varepsilon_r = 10$ have been applied.

$$w_{th}(\delta) = \frac{Q_c^e(\delta) \cdot E}{3 \pi \eta(\delta) \cdot d_p} \cdot C_u(\delta) \quad (25)$$

Figure 10 illustrates what happens to the theoretical migration velocity as a function of the particle size under atmospheric pressure and raised temperatures corresponding to relative gas densities $< 1$. The absolute value of the characteristic minimum in the migration velocity function is raised weakly and its location is shifted with decreasing relative gas velocity to larger particle sizes. For particles $> 1 \mu m$, the influence of the dynamic viscosity $\eta$ dominates the $\delta$-dependence (compare Figs. 8 and 9), i.e. at higher temperatures or relative gas densities $< 1$, respectively, the gas phase becomes more viscous and hence the particles migrate more slowly. For particles $< 1 \mu m$, this behaviour turns around: here, the $\delta$-dependences of particle charge and Cunningham correction dominate over the viscosity, i.e. at higher temperatures or relative gas densities $< 1$, respectively, particles can penetrate the gas phase more easily, resulting in higher migration velocities.

Here again, this situation is different from the one in an ESP because for a corona discharge, the pressure level also has to be raised (see 2.3.3). Therefore, we consider the migration velocities of particles of fixed size as a function of the temperature, keeping the relative gas density constant. This was done in Figure 11 for 10 $\mu m$ particles, in Figure 12 for 1.0 $\mu m$ particles, and in Figure 13 for 0.1 $\mu m$ particles, respectively.

As seen in Figure 11, the migration velocity of a 10 $\mu m$ particle decreases by about a factor of two when going from room temperature up to more than 1000$^\circ$C with the relative gas density kept constant. In general, almost no $\delta$-dependence can be observed for particles of around 10 $\mu m$ and larger. This changes when looking at 1.0 $\mu m$ particles (Fig. 12). Here, it can be seen that for constant temperatures, an increase in $\delta$ will weakly decrease the migration velocity, while doubling the relative gas density shows a higher effect than reducing it by half. This behaviour increases dramatically for 0.1 $\mu m$ particles or smaller (Fig. 13).

Up to now, we did not consider the possibility or even the necessity of applying much higher electrical field strengths at high relative gas densities. An increase in the electrical field $E$ ultimately leads to an enormous increase of the migration velocity because $w_{th}$ depends quadratically on $E$ (electric charge Eq. 16 and electrical force Eq. 22), as illustrated in Figure 14 for a 1.0 $\mu m$ particle at a relative gas density of $\delta = 4.0$ for electrical field values of $E = 3/6/9/12 \text{kV/cm}$.
2.5.2 Time dependence

The time dependence of the particle velocity is described by equation 26, whereby the instationary particle movement is characterized by the relaxation time $\tau_p$ (Eq. 27).

$$w(t) = w_{th} \left[ 1 - \exp \left( -\frac{t}{\tau_p} \right) \right]$$

$$\tau_p(T) = \frac{m_p (\cdot Cu(\delta))}{3 \pi \eta(T) \cdot d_p} \frac{q_p \cdot d_p^2}{18 \eta(T)} (\cdot Cu(\delta))$$

In determining the T/p-dependence of $\tau_p$, we neglect for simplicity the influence of the Cunningham correction, thus $\tau_p$ is solely a function of temperature. Remembering the viscosity dependence on temperature (Eq. 8) the relaxation time decreases with increasing temperature, i.e. particles reach their steady states faster. For solid spheres of $d_p > 1 \mu m$ with a density of $\rho_p = 1000 \text{ kg/m}^3$, the relaxation time can be calculated with equation 28.

$$\tau_p = 3.09 \cdot 10^{-6} \frac{d_p^2}{\mu m^2} S$$

2.6 Grade efficiency

A well-established model in ESP theory and practice is the one of Deutsch\textsuperscript{10}. In the original form, it allows prediction of the grade efficiency, i.e. efficiency as a function of particle size, on the basis of the main design and operation parameters. For tube-type ESPs, the Deutsch equation is given by:

$$T(d_p) = 1 - \exp \left[ -w_{th} \frac{A_{NE}}{V} \right]$$

$$= 1 - \exp \left[ -2 \cdot w_{th} \frac{(d_p, \delta) \cdot L_{NE}}{V_0 \cdot r_{NE}} \right]$$

In determining the T/p-dependence of $T(d_p)$, we first have to specify the tube design. We choose for further calculations $r_{NE} = 150 \text{ mm}$ and $L_{NE} = 5.0 \text{ m}$ with the operation conditions $E = 3.0 \text{ kV/cm}$ and $V_0 = 1.0 \text{ m/s}$.

Figure 15 illustrates what happens to grade efficiency under atmospheric pressure and raised temperatures corresponding to relative gas densities <1. The efficiencies naturally show the same tendencies as those of the migration velocities in Figure 10; the absolute value of the typical minimum
is strongly increased and the minimum’s location is shifted as before to larger particle sizes for decreasing relative gas densities. As can be seen, reducing the relative gas densities leads to a dramatic improvement in efficiency when one neglects the high pressure levels needed for corona generation. Figures 16 and 17 therefore show efficiency as a function of temperature with the relative gas density as a parameter for particles of fixed size, 0.1 μm and 1.0 μm, respectively.

As can be seen in Figures 16 and 17, particles will be collected less efficiently at high temperatures if the relative gas density is kept constant and assuming a constant electrical field strength. For the 0.1 μm particle and constant temperature, a dramatic breakdown in efficiency can be observed when increasing the relative gas density. For the 1.0 μm particle, the efficiency decrease for constant temperature is less, but compared with Figure 16; the decrease with rising temperature is more pronounced. A plot for 10 μm particles is not given because for the parameter settings investigated, the efficiency values always equals 1.0.

Finally, we have to take into account again the possibility and/or necessity of a higher electrical field strength at raised relative gas densities. Figure 18 shows efficiency values of a 1.0 μm particle, calculated and plotted as a function of temperature as before, for a relative gas density of δ = 4.0 with the applied electrical field strength as the parameter. Obviously, particle collection is extremely sensitive to electrical field strength: e.g. at a temperature level of 1300K, doubling the electrical field strength from 3 to 6 kV/cm, which enlarges the migration velocity by a factor of 4 (compare Fig. 14), reduces penetration (1 - efficiency) by more than a factor of 25!

Experimental results for total mass efficiencies (integrating over all particle sizes occurring) have been published, e.g. by Feldman/Bush and Rinard et al. As was to be expected, they found a strong influence of the electrical field on particle collection. Feldman and Bush refer to a wire-pipe ESP of Union Carbide Olefins Co. operating at temperatures of 870-1000 K, pressures of 3-8 bar and gas velocities of 0.2-1.2 m/s. It consists of 19 pipes of 15.2 cm in diameter, 1.8 m in length and discharge wires of 2.1/3.4 mm in diameter. Rinard et al. refer to a test facility located at the Denver Research Institute with one tube 30.5 cm in diameter and 2.1 m in length, operating at temperatures up to 1200 K, pressures up to 10 bar and with a flow rate of 0.078 m³/s under these conditions.

Fig. 15 Grade efficiencies at atmospheric pressure calculated according to Deutsch (Eq. 29) for three different temperatures; the ESP was designed to $L_{\text{NE}} = 5.0$ m, $r_{\text{NE}} = 150$ mm and operated with $E = 3.0$ kV/cm and $v_0 = 1.0$ m/s.

Fig. 16 Efficiencies according to Deutsch (Eq. 29) for a 0.1 μm particle as a function of temperature; different lines correspond to different relative gas densities. ESP design and operation conditions as before.

Fig. 17 Efficiencies according to Deutsch (Eq. 29) for a 1.0 μm particle as a function of temperature; different lines correspond to different relative gas densities. ESP design and operation conditions as before.
2.7 Particle resistivity

The processes of particle deposition on the collecting electrode and detachment of the dust layer from the collecting electrode are the most important and critical stages of electrostatic precipitation. These processes are governed decisively by the electrical resistivity of the particles for the following reasons:

The charge of the arriving particles is opposite to that at the collecting electrode. As soon as the particles contact the collector, they will more or less quickly discharge depending on their electrical resistivity or conductivity. If the particles discharge rapidly, upon capture they assume the same polarity as the collecting electrode and can therefore be reentrained into the gas stream. This behaviour is well known for particles with resistivities in the range of $10^4 \, \Omega\text{cm}$. At the other extreme, represented by electrical resistivities typically $\approx 10^{10} \, \Omega\text{cm}$, particles cannot lose their charges and cause a continuous charge build-up on the collecting electrode. This will reduce the voltage available for precipitation and the excess of charge within the dust layer can lead to such high electrical fields in the porous system that in extreme cases, a corona discharge is initiated, the so-called back-corona. Therefore both high and low electrical resistivities are detrimental to particle collection.

The electrical conductivity of particles consists of two contributing parts: the first one is the conductivity on the particle surface caused by the adsorption of gas molecules such as water or sulfuric acid; the second one is the conductivity caused by the volume of the material itself. Therefore, the temperature dependence of electrical resistivity can be divided into a surface-dominated and a volume-dominated part.

These tendencies are shown in Figure 19. At a constant temperature, a higher water content in the flue gas increases the surface conductivity, thereby reducing the electrical resistivity. An increase in temperature causes the desorption of water molecules, thereby increasing the surface resistivity. At the temperature where a maximum value in resistivity occurs, the volume conductivity of the particle material begins to predominate. A further increase in temperature reduces the electrical resistivity for most dusts in question. Even when the temperatures are raised up to levels of 1000°C, this behaviour does not change for fly ash, as experimental results of different researchers illustrate\textsuperscript{12-14}. An example is given in Figure 20. Deviations are observed, e.g. for carbonaceous ash, as Shale et al. already found out in 1968\textsuperscript{15}.

Therefore, a first assumption might be that high-resistivity ash—troublesome at common power plants at typical current densities of 0.1-0.2 mA/m$^2$—is easily collected. But it must be remembered that at high temperature and high pressure levels, the current densities can reach orders of 5-10 mA/m$^2$. The combination of low ash resistivity at the operating temperatures, together with the high current densities, probably will not lead to back-corona since the high gas densities should suppress it. On the other hand, electrical re-entrainment of particles might also be caused by the low resistivity values.

![Figure 19](https://example.com/figure19.png)
3. Problems

Apart from eventually reduced resistivity problems (discussed in section 2.7), all problems known from common ESP operations will certainly occur: re-entrainment caused by rapping, by-pass gas flow — so-called sneakage, and dust layers build-up on the discharge electrodes. Problems which are especially attributed to the high temperatures are for example:

- Mechanical stability of material
  The hardness of the materials used at temperatures ≥ 1000°C has to be considered carefully. For long-term applications at elevated temperatures, the creeping behaviour of the material has to be taken into account. Furthermore, the flue gas at high temperature is much more aggressive, therefore corrosion will be a severe problem.

- Rapping
  At temperatures above 700°C, the region of forgeability starts for some materials. This can become a problem if rapping is carried out by conventional hammer systems. Cleaning by means of pulse jets analogous to those used in bag houses or by ultrasonic horns is also under discussion.

- Electrical insulation
  Insulator arrangements commonly used on the roofs of ESP housings have temperatures of about 50°C less than the gas flow and they are stressed thermally, mechanically and electrically. Unfortunately, the electrical resistivity of most insulator materials drastically decreases at temperatures above approx. 200°C. An application of the so-called advanced ceramics as insulating material for extreme requirements might be promising and should be investigated.

- Discharge of hoppers
  To bring the collected dust out of the hoppers means overcoming a pressure barrier of some ten bars. In order to guarantee secure dust handling, a carefully designed pressure sluice is absolutely necessary.

- Electrical power consumption
  The electric power consumption, as a fraction of the total electric output from a PCFB electric generating plant, was observed to be between 1.5 – 2%19. In the case of inadequate efficiencies, the collecting area has to be increased, although this will lead to a probably unacceptable high power consumption. A solution might be to use power-conserving means on the transformer rectifier sets such as intermittent electrical energization.

4. Conclusions

This paper has tried to fundamentally work out the potential of electrostatic precipitation in gas cleaning at high temperatures and high pressures. Ultimately, this was done with special respect to grade efficiency under extreme conditions, resulting in promising trends. Furthermore, laboratory and pilot-plant results of various researchers3, 4, 11-19 have demonstrated the feasibility of ESP operation at pressures up to 20 bars. In general, it is observed that negative corona is far more effective than positive corona. Stable coronas are generated and the current-voltage characteristics can be related to the relative gas density. Therefore, a successful ESP operation at high temperatures needs correspondingly high pressure levels. In this way, the gas can withstand the electrical breakdown much better than at standard conditions leading to much higher electrical field strengths. For the same reason, back-corona is not expected to cause severe problems. Therefore, such high electrical field strengths suggest rather small
specific collecting areas for efficiencies $\geq 99\%$.

Tassicker concludes\textsuperscript{(1)} that "the data available would be sufficient for the commercial-scale of an ESP for conditions of 5-15 bar and 400-700°C. The available data are less definite for a firm design at 850-900°C. More pilot-plant work is needed before a commercial-scale plant in this range could be confidently sized".

Symbols

\begin{itemize}
  \item $a$ acceleration
  \item $A_{NE}$ collecting area
  \item $b$ mobility of gas ions
  \item $c_Q$ number concentration of gas ions
  \item $Cu$ Cunningham correction
  \item $d_p$ particle diameter
  \item $E$ electrical field strength
  \item $E_0$ corona initiation field strength
  \item $F$ force
  \item $i$ electrical current
  \item $j$ electrical current density
  \item $j_{NE}$ electrical current density at collecting wall
  \item $j_{SE}$ electrical current density related to discharge wire length
  \item $L_{NE}$ length of collecting tube
  \item $L_{SE}$ length of discharge wire
  \item $m$ mass of gas molecule
  \item $m_p$ mass of particle
  \item $Q_p$ particle charge
  \item $Q_{sp}$ particle saturation charge
  \item $p$ pressure
  \item $r_{NE}$ radius of collecting tube
  \item $r_{SE}$ radius of discharge wire
  \item $R$ molmass related constant of gas
  \item $T$ temperature
  \item $t$ time
  \item $T_{(dp)}$ grade efficiency
  \item $U$ applied voltage
  \item $U_0$ corona onset voltage
  \item $U_{crit}$ sparkover voltage
  \item $<v>$ mean thermal velocity of gas molecules
  \item $v$ fluid velocity
  \item $w$ particle velocity
  \item $w_{th}$ theoretical migration velocity of an individual particle
  \item $\delta$ relative gas density
  \item $\varepsilon_0$ electrical permittivity of vacuum
  \item $\varepsilon_r$ electrical permittivity of particle material
  \item $\chi_e$ electrical susceptibility of particle material
  \item $\eta$ viscosity of fluid
  \item $\lambda$ mean free path of gas molecules
  \item $\rho$ density of fluid
  \item $\rho_p$ density of particle material
  \item $\tau_Q$ time constant of particle charging process
  \item $\tau_p$ time constant of particle acceleration process
\end{itemize}

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