Quality of Gas Flow and Role of Turbulence

•The dominant role played by conditions of gas flow in electrostatic precipitation cannot be overemphasized.

•Disturbed flow in the form of uneven distribution,jets or swirls,not only increases reentrainment losses from electrodes and hoppers,but is responsible for poor collection initially.

•This is because if longitudinal gas velocity varies from duct to duct across a precipitator-and there may be dozens of ducts in parallel- the application of $\eta = [1-\epsilon^{-(A\omega)/Vg}]$to each duct individually will reveal a decay in overall efficiency.

•It is common experience to improve efficiency from 60 or 70% to 95% or better by corrections in gas flow.

- Characteristic solutions to the problems presented by large-scale gas-flow disturbances involve the development of appropriate equipment(e.g., turning vanes,diffusion screens,transitions, and plenum chambers).
- But in addition,it must be recognized that poor gas flow is a system problem in total plant design.
- The trend of future work in precipitation gas dynamics lies not in a further refinement of the criteria for good large-scale gas flow but rather in (1) understanding the small-scale process of particle diffusion as it affects precipitation,(2) assessing the importance of turbulence and convection due to the electric wind, and (3) attempting to harness, as far as possible,these various particle-transfer mechanisms to reenforce electrostatic collecting forces.

Recent Theories of Precipitation

- A number of recent attempts have been made to incorporate into a modified precipitator efficiency equation particle diffusion and other mechanisms ignored in the Deutsch analysis.
- In each case, a condition essential to the Deutsch derivation is abandoned: uniformity of particle concentration over the precipitator cross section.
- The modified derivations assume that the dust is uniformly distributed over the cross section only at the inlet of the precipitator duct.
- As the gas proceeds downstream,the action of the wallward migration velocity promptly tends to clear the midstream section of the duct in the neighourhood of the plane of the wires.
- Opposing this,however, is eddy diffusion,which sweeps particles from the zone of high concentration near the walls back into the depleted midstream region.

- This turbulent eddies continuously redistribute over the cross-section particles which the electric field tends to concentrate nearer the walls.
- Efficiency of collection is governed by the dominance of the latter effect over the former.
- Detailed consideration of the problem is further complicated by reentrainment of collected particles form the walls.This process contributed to raising the particle concentration in the gas close to the walls and so also enhances back diffusion.
- The various theoretical treatments of this problem, and the conflicting assumptions that have been made, reflect the lack of experimental data besetting the investigator who tries to develop a precipitation theory more comprehensive than that of Deutsch.

- Observed results are particularly scanty regarding the nature of the cross-sectional particle distribution profile and the effect of the electric wind of the corona discharge in modifying “normal” aerodynamic turbulence.It should be noted that none of the more sophisticated theoretical approaches described previously has so far been developed to a point of practical utility.
- The few experimental dust-concentration profiles that have been reported confirm the presence of a relatively dust-free zone in the region of the discharge wires, the width of the zone progressively broadening as the gas moves downstream.
- The extent if the central clear zone and its tendency to widen with downstream travel appear to depend on the level of turbulence, on particle size, and in duct precipitators, on the wire-to-wire spacing.
- Knowledge of the particle concentration very close to the collecting wall is of prime importance in establishing the boundary conditions in any theory of precipitation, but this concentration is very difficult to establish experimentally.

The Electric Wind

- The observation that smoke particles could be borne along in the electric wind- the movement of gas induced by the repulsion of ions from the neighourhood of a corona-discharge electrode-was made as long ago as the eighteenth century.
- But except for a flurry of interest in the early 1930s the role of the electric wind has been only ocassionally considered by precipitation workers.
- Studies using gas- and particle-tracer techniques to follow gas-flow patterns suggest that the particle migration velocity relative to the electrodes includes and electric-wind component superposed on the velocity of the particles relative to the gas.
- Strong objections have been raised to this conclusion,however,on the grounds that(1) it is not necessary to propose a major electric-wind contribution to the particle transport rate to explain observed particle-migration velocities and (2) requirements of flow continuity are not clearly satisfied.
- The question remains unsolved.

Particle Adhesion and Reentrainment

- The behavior of dust particles on and near the collecting electrode is a subject of prime practical importance that has received insufficient attention.
- Observation of individual particle trajectories reveals that, contrary to assumptions usually made in theoretical efficiency calculations, impact phenomena at the collecting electrode or precipitate surface cannot be neglected,particularly for particles greater than about 10μm.
- These larger particles may rebound on impact without losing their charge,or they may erode agglomerates of previously precipitated dust.
- Dust on the collecting electrodes tends to acquire a like charge by induction and, if dislodged under low current conditions, can be forcefully accelerated away form that electrode.
- The repulsive force acting on the dust layer is opposed by an attractive electrical force due to the ion current.

- The net electrical force per unit area of dust surface F'(N/m^2) is

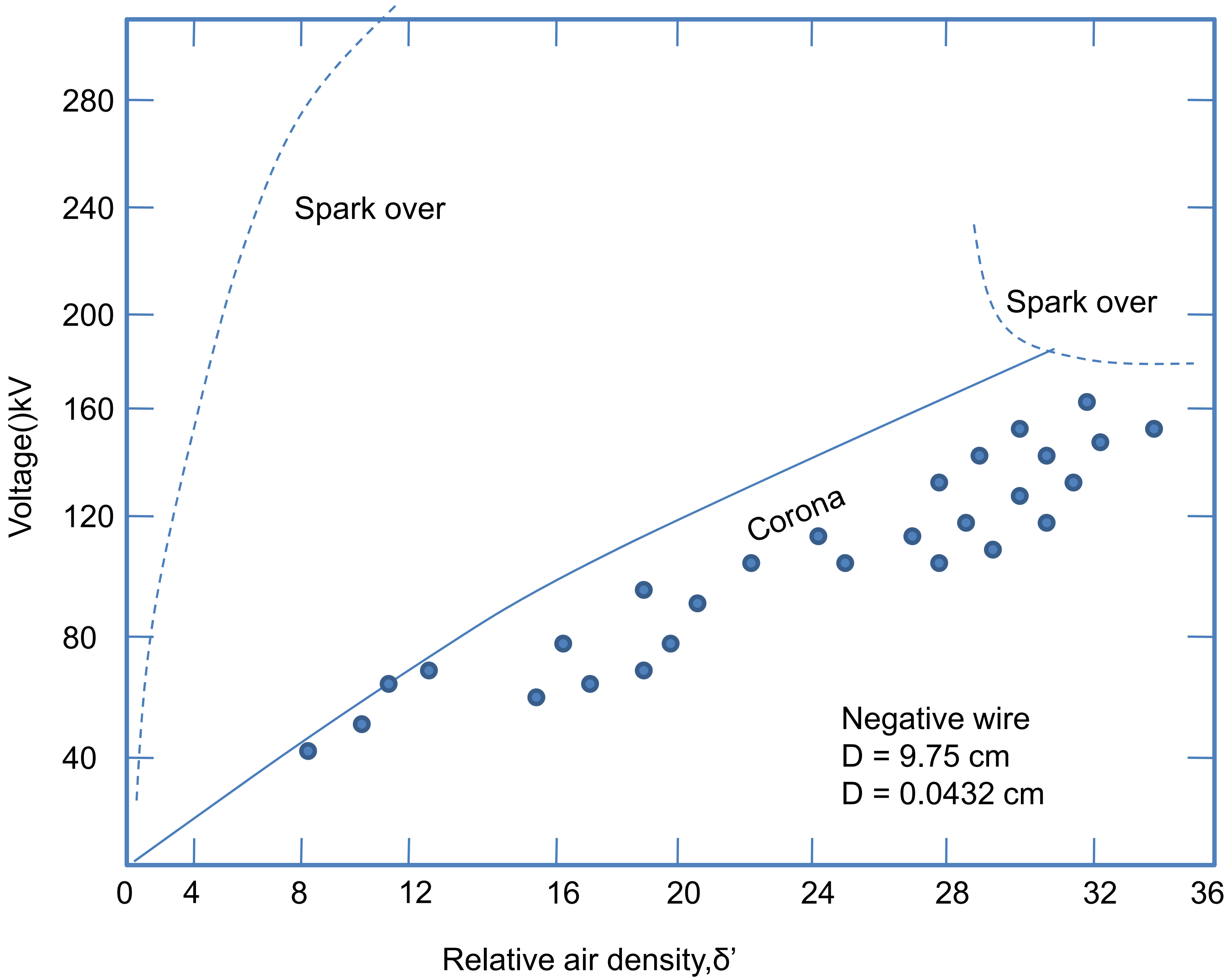
$$F' = \frac{1}{2}\varepsilon_0\left[\left(k_p j\rho_d\right)^2 - E^2\right]$$

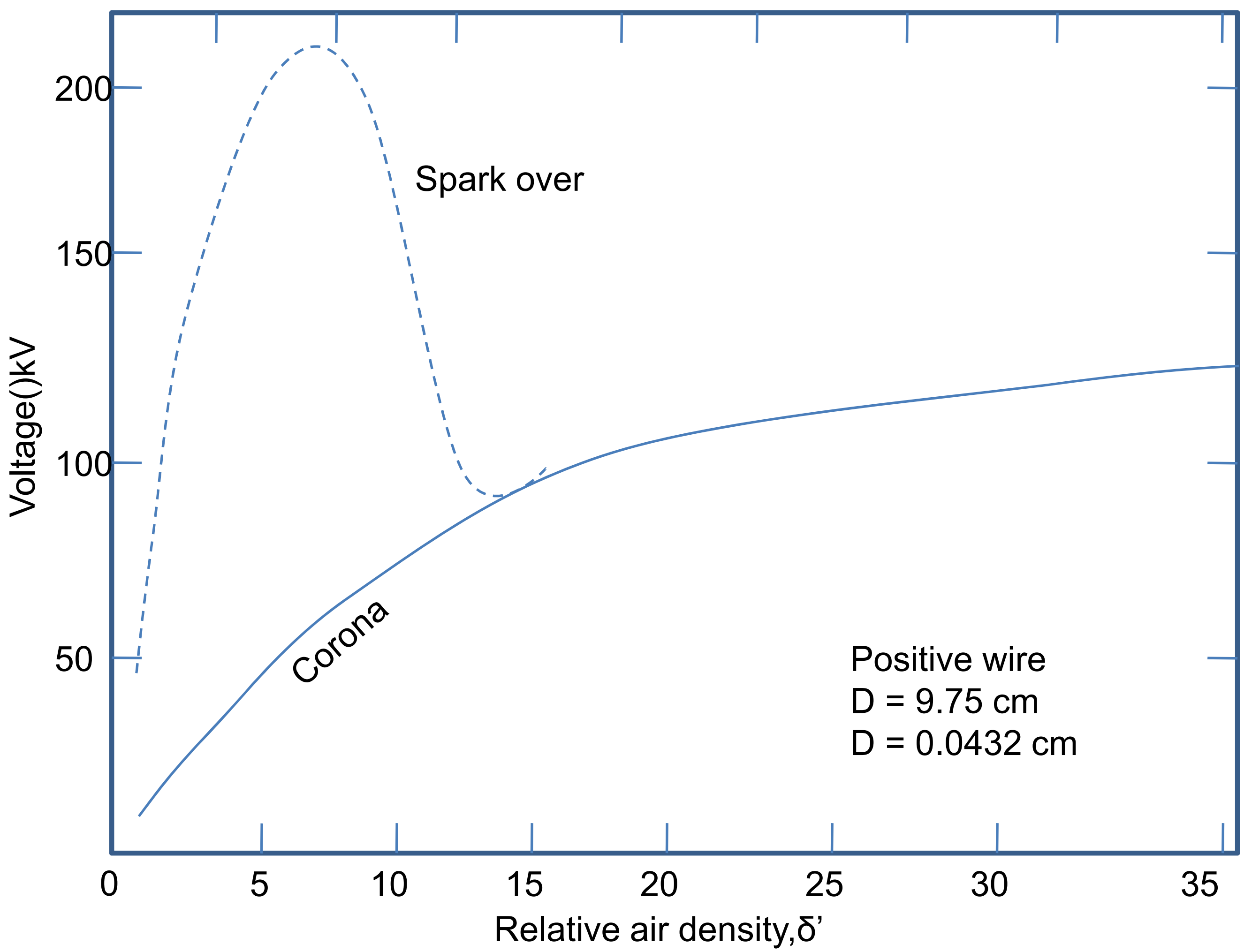
- whereE(V/m) is the field in the gas adjacent to the dust layer and F' is positive when attractive.In addition, various "mechanical" surface forcs must be considered(e.g., Van der Waals forces, adhesion due to moisture films, and reentraining forces due to wind drag).
- A subject of principal concern in electrostatic precipitation is the removal of collected dust from the passive electrode and its transfer,with minimal reentrainment, to the hoppers.In modern precipitators, dust may fall as much as 12m through a transverse gas stream before reaching the hoppers; 15-m high plates are under consideration.
- American and European plate- rapping practice generally exhibits a fundamental difference in outlook.
- The tendency in the united states toward continuous rapping(i.e. every few minutes or less) aims at the elimination of visible rapping puffs in the stack discharge,psychologically so objectionable.
- Higher long term collection efficiencies are, however,more likely when the rapping is intermittent(i.e., at intervals of as much as several hours).
- Ideally, the rapping interval should be adjusted to the needs of different parts of the precipitator.
- A number of collecting- electrode configurations are in use,the various designs purporting to increase efficiency by (1) providing baffles to the shield deposited dust from the reentraining forces of the gas stream,(2) providing catch pockets which convey precipitated dust into a quiescent gas zone behind the collecting plate,and(3) minimizing protrusions from the plate surface in order to raise sparkover voltage.

Precipitation Under Extreme Conditions

- In recent years,electrostatic precipitations have been used in chemical-processing, power-generation, and mass-transport applications involving temperatures and pressures well in excess of conventionally accepted limits.
- Successful pilot or full-scale trials have been run at pressures up to 55 atm and temperature(not simultaneous) to 800^0C.
- Operation at elevated temperatures or pressures must take into account unique corona phenomena not encountered in ordinary paractice.
- For example, at high pressure, the negative corona threshold occurs unpredictably over a band of voltages;Eq.31, giving the corona-starting field,applies only to the upper limit of the band(Fig.9.10).with positive corona, however,Eq.31 remains valid(Fig.9.11).
- Both polarities exhibit a critical gas density at which corona- starting and sparkover curves intersect.
- A reduction in wire diameter or an increase in the size of the interelectrode gap raises the critical density.
- Conventional precipitation is possible only at gas densities below the critical level for the gas and electrode geometry in question

Negative corona- starting and spark over voltages for coaxial wire-ipe electrodes in air(25^{0}C)




200
150
100
50
Voltage()kV
Spark over
Corona
Positive wire
D = 9.75 cm
D = 0.0432 cm
0
5
10
15
20
25
30
35
Relative air density,δ'

- Upper Temperature limits to the precipitation process also exist.
- In very hot gases the corona will be overwhelmed by thermal ionization,with resultant currents so high, and associated fields so low,that effective precipitation is impossible.
- Thermal ionization rates usually depend on trace quantities of the alkali metals(elements of low ionization potential) rather than on the principal gaseous constituents.
- To some extent,raising the pressure together with the temperature helps to maintain a stable corona.

High-Resistivity Precipitate

- ***Back-Corona Formation:*** In the precipitation of high-resistivity dusts it is generally observed that, after a brief initial period of operation, collection efficiency deteriorates, current increases, and the sparkover voltage – assuming negative corona- drops.
- The current increase is due to secondary emission, so-called back corona, which originates in the dust deposit on the collecting electrode and assumes the form of a luminous sheath of tuftlike discharges of polarity opposite to that of the primary discharge.
- The porous dust dielectric appears to serve as a condenser which, first charged by primary ions, discharges when the voltage attains the breakdown value of the gas in the pores. In most practical cases, the breakdown strength E is of the order of 10^6 .

- Industrial corona-current densities j are generally less than about 10^{-3} A/m^2(Table 9.1).At first thought, we should not expect back-corona disturbances to appear until the dust resistivity exceeds

$$\rho_d = \frac{E}{j} = \frac{10^6}{10^{-3}} = 10^9 \Omega - m$$

- a figure somewhat greater than the “critical” resistivity of about $10^8 \Omega$-m widely quoted in industrial practice.
- Definition of the back-corona threshold in terms of particle resistivity, however, is a complex matter that cannot be fully accounted for in terms of Eq. 51. Furthermore, dust resistivity is generally dependent on applied voltage, duration of the test, and other experimental incidentals.

Particle Charging in a Bi-Ionized Field

- In the presence of back corona and the resultant bi-ionized inter-electrode field(the total corona current consisting of negative ions migrating in one direction and positive in the other), the equations given earlier governing particle charging are no longer applicable.Assuming that the oppositely charged ions are uniformly interspersed in the gas, it may be shown that Eq.35 is to be replaced by
- Where

$$Q = Q_{\max} \frac{1 - e^{-\alpha t}}{1 - [(1-\xi)/(1+\xi)]e^{-\alpha t}}$$

$$\alpha = \frac{1}{\varepsilon_0}\left(b_f \rho_f b_b \rho_b\right)^{\frac{1}{2}}$$

$\xi = (b_b\rho_b/b_f\,\rho_f)^{1/2} = (jb/jf)^{1/2}$ $\quad\quad 0 \leq \xi \leq 1$

and the limiting charge Q_{max} is given by

$$Q_{max}=4\prod \varepsilon_0 p a^2\, E_0(1-\xi)/(1+\xi)$$

Ion mobility b, space-charge density ρ, and current density j due to “forward” and back corona are distinguished by the respective subscripts f and b.Unlike monopolar ion bombardment, which effectively ceases after a few time constants τ (Eq.36), bipolar ion bombardment continues indefinitely. A maximum charge Q_{max} is approached because positive and negative ion currents to the particle tend to become equal and so neutralize each other

- The debilitating effect of back corona on an electrostatic precipitator is strikingly illustrated by considering a case in which the back-corona current is only one-third of the total current
- $J_i = j_b + j_f$. We then have § = (0.5) ^{½} = 0.71, and Q_{max} (whence, the particle- migration velocity w) is reduced by a factor (1- §)/(1+ §) = 0.17. According to the Deutsch equation, precipitator length must be increased by 1/0.17 = 5.8 times to restore collection efficiency to the level corresponding to zero back corona. Other considerations, such as the reduction of applied voltage by sparking and the lowering of the interelectrode field by increased voltage drop across the high – resistivity precipitate, are likely to reduce efficiency still further.
- Poisson's equation for a wire-pipe system containing bipolar space charge is
-
- $1/r\ d(rE)/dt = 1/\epsilon_0(\rho_f - \rho_b)$ --------------(56)
- Experimental observations with a negative forward corona justify the assumption that the component forward- and back – corona currents per unit length, jfl and jbl(A/m), respectively,
-
- $J_{fl} = 2\pi r b_f E \rho_f$ ---------------------------(57)
- $J_{bl} = 2\pi r b_b E \rho_b$ -----------------------------(58)

- Are conserved between wire and cylinder. That is, $J_{fl} + J_{bl}$ give the total current per unit length jtl as meassured directly. The parameter § of eq 54 is thus independent of the radius vector r for a given set of operating conditions. Eliminating ρf and ρb from eq 56 we have,

$rE\, dE/dr + E^2 + j_{t1}/ 2\pi\epsilon_0[b_b - \xi^2 b_f/(1+ \xi^2)b_f b_b]=0$

hence

$E = \{j_{t1}/ 2\pi\epsilon_0(b_b - \xi^2 b_f/ b_f b_b(1+\xi^2)) + (r_0/r)[E_c^2 - j_{t1}/2\pi\epsilon_0(b_b - \xi^2 b_f/ b_f b_b(1+\xi^2))]\}^{1/2}$

For j_{t1} and r not too small (cf. Eq. 10), we can write

$E = [j_{t1}/ 2\pi\epsilon_0(b_b - \xi^2 b_f/ b_f b_b(1+\xi^2)]^{1/2}$

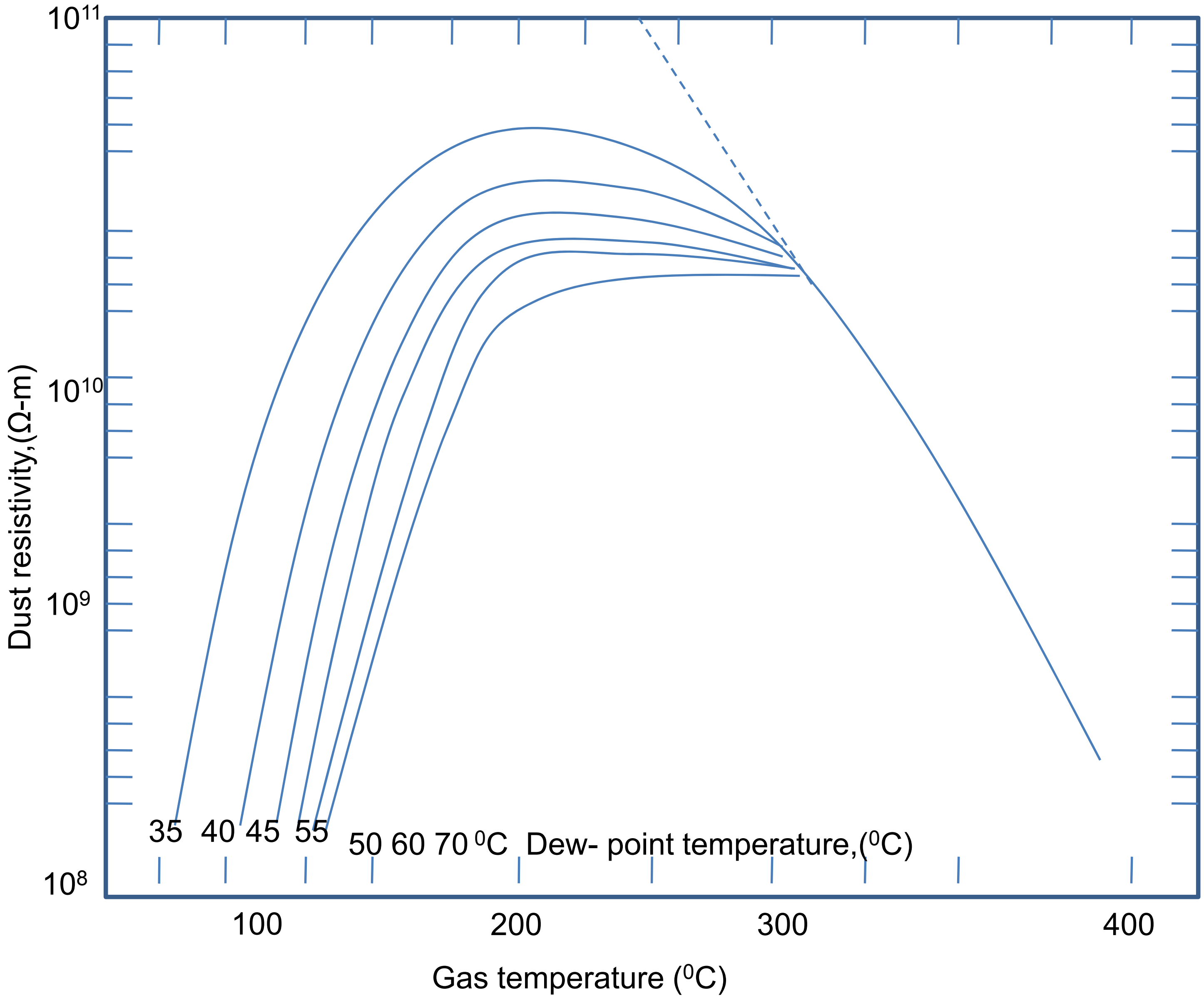
- Analysis of experimental data shows that the negative primary current in the presence of back corona is greater than it would be without back corona. This condition is partly due to the bombardment of the central electrode by back-corona ions and partly due to photoionization originating both at wire and at the surface of the precipitate.

Conditioning: Sulfur Oxides in Flue Gas

- The passage of an electric current through a layer of precipitate occurs both over the surface and through the volume of the individual particles. Surface conductivity is dependent on surface moisture and chemical films adsorbed on the particles, whearas volume conductivity is a property inherent in particle composition. For semiconducting materials usually of interest in electrostatic precipitation, volume resistivity $\rho_v(\Omega m)$ is a decreasing function of temperature in reasonable agreement with the relation
- $\rho_v = \rho\infty^{eE/kTA}$ ---------------------------- (62)

- Where the quantity $\rho_\infty(\Omega m)$ and the activation energy E(J) are constants of the material. Depending on the nature of the dust, the validity of Eq 62 in a humid gas may not become apparant until the temperature exceeds 100 to 300°C or more and conducting surface films are driven off. Fig 9.12, illustrating the transition from surface to volume conduction, is qualitatively typical of curves for numerous substances.

Fig 9.12 resistivity of a cement-Kiln dust as a function gas temperature and dew point.



- Control of particle resistivity by conditioning the carrier gas plays an important role in many applications of electrostatic precipitation. The availability of moisture alone in some cases, or moisture with small particle resistivity by one or more orders of magnitude. In this fashion, by eliminating back-corona disturbances, precipitator performance can be dramatically upgraded. Inlet gas can most economically be humidified by water atomization in a spray chamber installed immediately ahead of the precipitator.
- The physical absorption of a moisture film on a chemically inert surface is characterized by relatively low binding energies. A water film alone consequently produces less effective conditioning than does a chemical binder that is strongly absorbed on the particle surface and, in turn, strongly absorbs moisture. This activated adsorption effect is often accomplished for weakly basic particles by strong acids(H_2SO_4) and for weakly acidic particles by strong bases(eg NH_3)
- Sulfate deriving entirely from sulphuric acid in flue gas provides a natural conditioning substance in the combustion of coal, in which sulfur is normally present in quantities ranging from a small fraction of 1% to about 5%. Although the actual concentrations of sulfur oxides produced in combustion vary depending on the coal, the furnace design, and the operating conditions, the usual orders of magnitude are 0.1% for sulfur dioxide and 0.001% for sulfur trioxide.
- The conditioning of low- sulfur flue gas by the injection of sulfur trioxide, viewed unfavorably- but progressively less so- by American public utility companies, has been successfully employed on a commercial scale in Great Britain and Australia. The small amount of sulfur trioxide supplied, generally less than 50 ppm, is completely adsorbed by the dust and does not lead to increased emission of sulfur compounds into atmosphere.

Corona Quenching

- The heavy particle space charge often resulting in treating very finely divided dust tends to elevate the corona threshold and thus dpress the current is carried essentially by free
- icons (unattached to aerosol particles), the treatment given in Sections 9.2.1.2 and 9.2.2.2 remains applicable. In other words, it is valid to assume that
- $J_t = j_i + j_p = E(p_i b + p_p\ b_p) \cong Ep_i b$
- Where j_t (A/m$^{2)}$ is the current density at a point, the subscripts t, I, and p designating total, free – icon, and particle, respectively. Particle mobility b_p(m/sec)/(V/m)] is commonly 2 or 3 orders of magnitude less than the icon mobility b; therfore, although p_p may be larger than pi,jp is ordinarily no greater than a few percent of jt.
- The mild corona quenching described previously gives way to a severe variety when the particle concentration is to dense that all free icons are captured. Equation then takes the form
- $$j_t = Ep_p b_p$$
- In this event, the current consists soley of icons riding on slowly migrating dust particles and jt is characteristically reduced to 1% or less of its former value. The maximum charge Q that a particle can acquire is dtermined not by the relevant law of charging but by the limited availability of free icons. Specifically
- $$Q = \rho_p / N_p = \rho_i / N_p$$
-

•Where Pt (C/m3) is the limited density of icons available for charging and Np (particles/m3) is the particles number density. With particularly severe quenching, thus, the charge per particle may be far below that attainable in ordinary circumstances, and the associated particle – migration velocity and collection efficiency may be correspondingly low. Over that length of the precipitator in which severe quenching prevails

- $w = ws\rho_i / N_p Q_s \qquad \rho_i \leq NpQs$ ----------------------------(66)

- $\eta = E_p \rho_i A / 6\pi\mu V_g (N_p)_{in}$
-
-

•Where $(N_p)_{in}$ is the inlet particle number concentration. Despite severe quenching, particle collection still occurs, albeit at a reduced rate.

•The deposition of a coat of highly resistive dust ($p_p > 10^8 \Omega$-m) on the discharge electrodes sometimes accounts for still another type of corona suppression. Fine particles(<10μm), whose motions is largely controlled by turbulence, can be acquire an opposite – ion charge in the corona region, whereupon close they are precipitated onto the discharge electrode. As the resultant dust larger builds, the potential drop across it increase, and if the particle resistivity is high enough, the inter electrode field will drop sufficiently to materially reduce the current. Conditioning of the gas to lower the particle resistivity offers the most promising in such cases.

Applications

- Coverage of the numerous practical aspects of electrostatic precipitation presents a two-fold difficulty which cannot be resolved in this chapter. First, an adequate treatment requires a compilation and critical evaluation of operational data. Much of this comes from sources of indeterminate reliability scattered throughout the literature. Second, much of the essential design data-particle-migration velocities, for instance-are regarded as confidential proprietary information by manufacturers who have accumulated it at considerable cost in time and effort. This is why published descriptions of industrial precipitators, no matter how detailed in certain respects, are commonly deficient in revealing certain critical variables of the process.
- The degree to which a full-scale precipitator performs in accordance with theory is highly variable; therefore, no substitute exists in industrial precipitation practice for diversified, long term experience. However, approaches to precipitator design that are governed by empiricism are likely to lead to confusion. Observations in the field, which by their nature often lack adequate controls or other experimental safeguards may, when presented injudiciously, be cited in support of almost any conclusion. Furthermore, the subjective approach that unfortunately goes hand in hand with much field work provides a very limited base for new developments and fails to permit the analysis of design and performance in terms of fundamental physical relationships.