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Application of ESP for gas cleaning in cement industry — with reference to India

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Abstract

Electrostatic precipitators (ESP) are used for gas cleaning in almost every section of cement manufacture. Application of ESP is studied, keeping in view Indian conditions. The characterisation of dust emissions has been done for different units, such as rotary kiln and raw mill, alkali by-pass, clinker cooler, cement and coal mill, in terms of exit gas quantity, temperature, dew point, dust content and particle size. It is seen that all these characteristics have a wide range of variance. The ESP system must effectively deal with these variations. The fundamental analytical expression governing the performance of ESP, i.e. the Deutsch equation, and that for particle migration velocity, were analysed to predict the effect of major operating parameters, namely particle size, temperature and applied voltage. Whereas the migration velocity (and the efficiency) varies directly with the particle size, it is proportional to the square and square root of applied voltage and absolute temperature of the gas, respectively. The increase in efficiency due to temperature is not seen in dc based ESP, perhaps due to more pronounced negative effect on the applied voltage due to the increase in dust resistivity at higher temperatures. The effect of gas and dust characteristics on the collection efficiency of ESP, as seen in the industrial practice, is summarised. Some main process and design improvements effectively dealing with the problem of gas and dust characteristics have been discussed. These are gas conditioning, pulse energisation, ESP-fabric filter (FF) combination, improved horizontal flow as well as open top ESP.

Generally, gas conditioning entails higher operating and maintenance costs. Pulse energisation allows the use of hot gas, besides reducing the dust emission and power consumption. The improved horizontal flow ESP has been successfully used in coal dust cleaning. The open top or vertical flow ESP has a limitation on collection efficiency as it provides for only one electric field.

Keywords: Electrostatic precipitator; Gas cleaning; Cement production; Particulate emission control; Air pollution control equipment

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Table 1
Gas cleaning equipment used in different sections of cement manufacture[a]

Section	Crushing	Raw grinding, blending and storage	Kiln and cooler	Coal grinding	Cement grinding and storage	Packing
Equipment	FF	ESP and FF	ESP	FF and ESP	FF and ESP	FF

[a] FF: fabric filter; ESP: electrostatic precipitator.

1. Introduction

Gas cleaning in the cement industry is an enormous task. The modern process of cement production involves crushing and grinding of carbonaceous and clayey raw materials under dry conditions, thermal processing of finely ground raw meal, i.e. preheating, precalcining and sintering in rotary kiln, cooling of the clinker (sintered material) on a reciprocating grate cooler and further grinding and packaging of the product cement. Besides this, a great amount of mechanical conveying is also involved. All these operations generate a huge quantity of gas and particulates of varying characteristics, such as temperature, moisture content, particle size distribution, chemical composition, abrassiveness, etc. The selection of gas cleaning equipment depends upon these characteristics. The commonly used equipment are settling chambers, conventional and high efficiency cyclones/multi-cyclones, fabric filters (FF) and electrostatic precipitators (ESP). As can be seen in Table 1, FF and ESP are the most commonly used equipment. In this paper, some aspects related to the application of ESP are discussed.

2. Emission limits

On average, considering the different unit operations, nearly 15–16 $N\,m^3$ of gas is generated per kg of cement produced. The dust content may go up to 1000 $g/N\,m^3$ gas. The emission limits stipulated by Indian Air Pollution Control Act 1981 are given Table 2.

The protected areas mentioned in Table 2 are metropolitan areas which already have high levels of air pollution or those in proximity to parks, forests, historical monuments or health resorts. The individual Indian states are free to impose more stringent standards. In a survey conducted in 1993, the Central Pollution Control Board of India found that 57 cement plants are fully complying with the pollution standards. The Board is now considering fixing emission levels for SO_x and NO_x and load based emission standards for cement plants.

Table 2
Emission limits for cement plants in India[a]

Plant capacity (tonnes per day)	Dust emission limit ($mg/N\,m^3$)	
	Protected area	Other areas
≤200	250	400
>200	150	250

[a] The gas volume at the normal temperature and pressure (NTP) is expressed as $N\,m^3$.

3. Characterisation of exit gas and dust

The characteristics of dust emission from different unit operations depend upon the material being processed; type of processing, i.e. heating, sintering, grinding; gas flow rate through the equipment; fineness of the product; type of handling operations, etc. As these characteristics vary widely, section-wise evaluation has been done in the following paragraphs.

3.1. Preheater kiln and raw mill

The ESP has been successfully used to clean gas coming out from the preheater kiln. The gas is often taken through the raw mill for material drying before cleaning in ESP. The design and operation of a cement kiln has undergone substantial improvement over past 30 years. The fuel crisis made the old wet process change to semi-wet/dry to long dry and finally to multistage (4–6) preheater precalciner kiln. These improvements resulted in many changes in operating parameters of the ESP which are summarised in Table 3.

The following observations can be made from Table 3.

1. As a result of the modernisation from wet to dry preheater kiln, the temperature of exit gas has increased and the dew point lowered with a corresponding increase in the dust resistivity (Figs. 1 and 2) [1].
2. The particle size distribution has shifted to a smaller size with 75–80% particles lying below 10 μ.

In addition to the above, it is observed that the alkali content of preheater gas from the modern plant has been considerably reduced. Water-soluble alkalis (Na, K) are known for their property of reducing the dust resistivity. The alkali content of preheater exit gas reduces because most alkalis get condensed at the cold raw meal feed or the top cyclones, unlike long dry kiln processes where they used to condense in ESP.

3.2. Alkali by-pass

The excess quantity of alkali compounds present in the raw material adversely affects the quality of the cement. Most of this alkali is evaporated inside the kiln and gets recycled due to condensation of alkali vapour at the cold raw meal feed or the top cyclones. In order to reduce this recycling a certain quantity of gas is bled off from the back end of the kiln. This gas contains around 80% alkali. As can be seen from the Table 4: (a) the temperature of by-pass gas can go up to 1050°C and the dew point is very low in the range of 35–45°C, (b) the resistivity of dust is not very high due to the presence of alkalis but a large fraction, around 90%, of particles lies below 10 μ.

3.3. Clinker cooler

The sintered material discharged from the rotary kiln is known as the clinker. A reciprocating grate cooler is largely used for cooling of clinker from a temperature of around

Table 3
Variation in the operating parameters of ESP with the modernisation of cement kiln

Kiln type	Exit gas temperature (°C)	Dew point (°C)	ESP operating parameters		
			Dust content (g/N m^3)	Dust resistivity (Ω cm)	Particle size distribution (%, <10 μ)
Wet kiln	150–250	65–70	20–25	10^{11}–10^{12}	20–50
Dry kiln with 5 stage preheater, gas directly going to ESP	250–300	35–40	50–70	10^{13}	75–85
Dry kiln with 5 stage preheater, gas through conditioning tower/raw grinding mill	100–150	50–60	30–50 (Ball mill), 300–1000 (air swept/vertical roller mill)	10^{11}–10^{12}	65–75

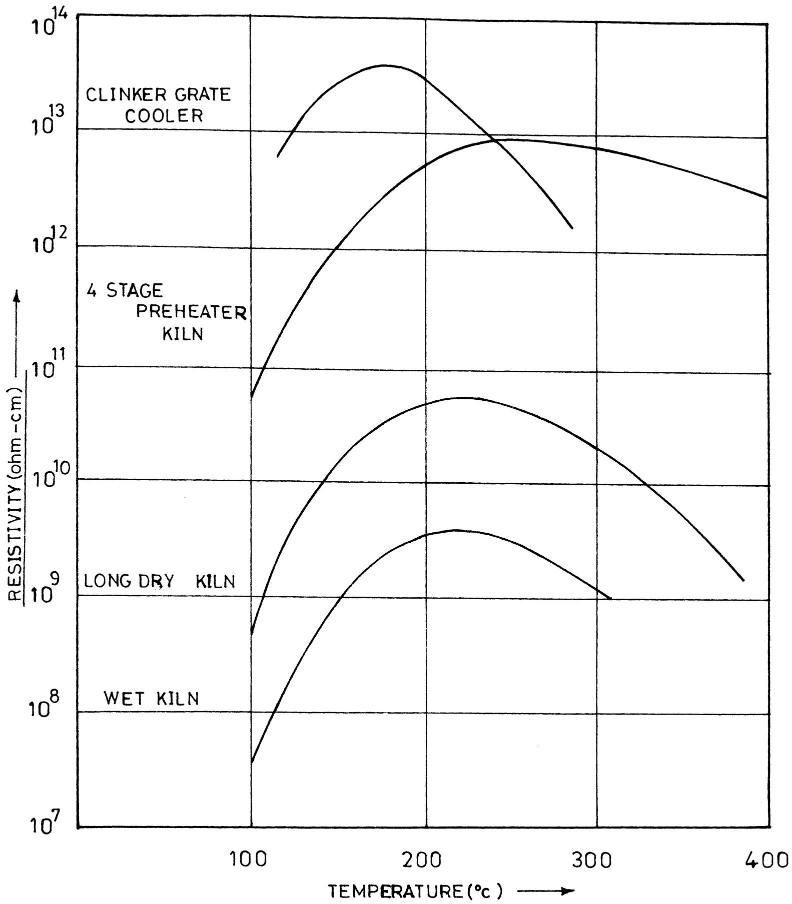

Fig. 1. Dust resistivity vis-à-vis temperature.

1200°C–70°C. This is done by blowing air, cross-current, through the grates. A part of the hot air coming out from the grate cooler is used as secondary combustion air in the kiln or for raw meal drying in the grinding mills, the rest is cleaned in ESP. On the basis of data tabulated in Table 4 and other laboratory/plant observations, the following dust characteristics can be delineated.

1. The dust particles are coarse and abrasive with the majority lying above 10 μ size.
2. Under normal operation, the dust content of exit gas is in the range of 15–20 g/N m^3. However, under kiln upset conditions, excessive material may pass through the cooler. Under such conditions, exit gas temperature may reach 400–425°C and the dust content up to 50 g/N m^3.
3. The dust resistivity is very high (10^{13}–10^{14} Ω cm). The peak reaches around 150–200°C (Fig. 1).

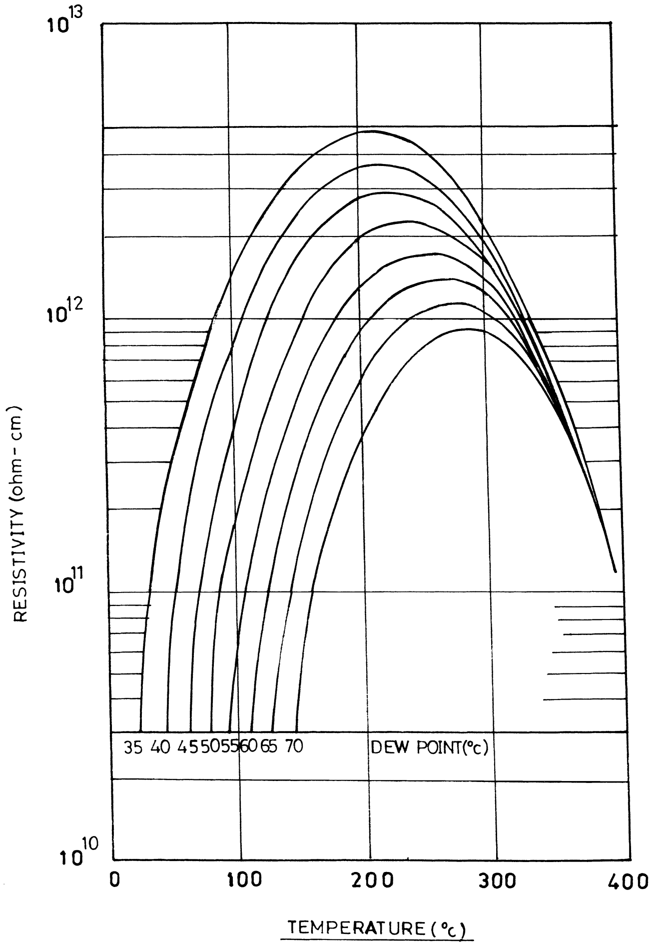

Fig. 2. Resistivity of kiln dust vis-à-vis dew point [1].

3.4. Cement mill

Modern cement grinding units consist of a ball mill in closed circuit with an air separator. The energy efficiency of the ball mill is very low, as only about 5–10% of the power supplied to the mill is used in grinding work, the rest is wasted in friction. The power lost in friction mostly gets converted into heat and increases the temperature of the product, cement. The cement temperature is not allowed to go beyond 100°C otherwise the gypsum, an additive to cement, will dehydrate. The cooling of cement inside the mill is achieved by air and water injection maintaining the dew point of exhaust gas at 50–60°C. Table 4 and laboratory/plant data provide the following information on the gas and dust emissions.

1. Water injection in the mill increases the dew point of exhaust gas and reduces the dust resistivity. Some typical values of dew point vis-à-vis resistivity are given in Table 5 [2].

Table 4
Exit gas and dust characteristics in cement industry

Serial number	Section	Exit gas			Dust	
		Quantity ($N m^3$/kg product)	Temperature (°C)	Dew point (°C)	Content ($g/N m^3$)	Particle size (%, <10 μ)
1	Crusher	0.03–0.06	25–45	20–45	15–20	20–30
2	Raw mill		90–100	20–60		65–75
	Ball mill (gravity discharge)	0.3–0.8			25–60	
	Air swept ball mill/vertical roller mill	1.5–2.5			300–1000	
3	Cement mill	0.3–0.8	65–75	20–60	20–80	15–50
4	Packing plant	0.06–1.2	35–45	20–25	20–40	15–50
5	Kiln (dry)	1.7–2.0	200–240	45–50	50–75	75–85
6	Coal mill (air swept ball/vertical roller mill)	1.2–2.6	60–80	30–50	100–500	60–75
7	Clinker cooler (grate type)	2–2.1	220–260 400–425[a]	20–55	15–20 Up to 50[a]	4–5
8	Kiln by-pass	1.2–1.4	1000–1050	35–45	75–150	80–95

[a] Under kiln upset conditions.

Table 5
Variation in the resistivity of cement mill dust with dew point

Dew point (°C)	26	30	42	50
Dust resistivity (Ω cm)	10^{12}	3×10^{11}	6×10^{10}	10^{10}

2. When air separator is added in close circuit with the mill, a part of the warm bleed air from the separator circuit goes to the ESP along with the mill vent air. The addition results in an increase in dust loading, gas temperature and reduction of dew point and a corresponding increase in dust resistivity. However, when the separator arrangement incorporates cement cooling, a separate dust collector is normally used to clean the separator gas [3].

3.5. Coal mill

High gas temperature as well as dust content in air-swept ball mill or vertical roller mill (VRM) and small particle size can create explosive conditions in the dust collector in coal mill circuit (Table 4). Thus, any dust collector used in this section must have the necessary provisions to prevent the explosion.

4. Theoretical considerations

The analytical expression for efficiency of ESP is given by the famous Deutsch Equation [4]

$$\eta = 1 - \exp\left[\frac{-AV_e}{Q}\right] \tag{1}$$

where A is the collector surface area, m^2; V_e the particle migration velocity, m/s; Q the volume flow rate of gas, m^3/s and η is the ESP fractional collection efficiency, dimensionless.

The collection efficiency of ESP increases with the migration velocity. The relationship for migration velocity is given by Eq. (2)

$$V_e = \frac{qEC}{3\pi \mu D_p} \tag{2}$$

where q is the electrical charge on particles, coulombs; E the electric field strength, V/m; C the slip correction factor, dimensionless; μ the gas viscosity, kg/m s and D_p is the particle diameter, m.

For particles larger than 1 μ size, the field charging mechanism is predominant and the charge is given by Eq. (3)

$$q = \left[\frac{3k}{(k+2)}\right] \pi \varepsilon E D_p^2 \tag{3}$$

where k is the dielectric constant, dimensionless and ε the permittivity of free space, C/m V.

Substituting q from Eq. (3) into Eq. (2), migration velocity is given as

$$V_e = \left[\frac{k}{(k+2)}\right]\left[\frac{\varepsilon E^2 C}{\mu}\right] D_p \tag{4}$$

Eq. (4) shows that V_e is proportional to D_p for $D_p > 1\,\mu$, all other parameters remaining constant. Thus, above 1 μ size, increasing particle size distribution on higher size will result in increase of migration velocity and collection efficiency. As can be seen from Eq. (4), variation of migration velocity with temperature will depend upon the variation of slip correction factor (C) and the gas viscosity (μ) with temperature. The variation in dielectric constant need not be considered as it comes both in numerator and denominator. The relationship between gas viscosity and temperature is given by Glasstone and Lewis [5] as follows:

$$\mu \propto T^{1/2} = C_1 T^{1/2} \tag{5}$$

where T is the temperature, K and C_1 the proportionality constant, kg/m s $K^{1/2}$.

The slip correction factor C is given by Flagan and Seinfield [4] as follows:

$$C = 1 + C_2 \left[\frac{2\lambda}{D_p}\right] \tag{6}$$

where λ is the mean free path of gas molecules, m and C_2 the constant, dimensionless.

The mean free path λ is directly proportional to the temperature. Hence,

$$C \propto T = C_3 T \tag{7}$$

where C_3 is the proportionality constant, K^{-1}.

Substituting Eqs. (5) and (7) in Eq. (4) and further simplifying, we can write

$$V_e = C_4 T^{1/2} \tag{8}$$

where C_4 is the proportionality constant, m/s $K^{1/2}$.

Thus, we get an important finding that for a given particle size the migration velocity increases with the square root of absolute temperature. This, however, is not seen in practice. The efficiency is seen as going down with temperature. This is due to the increase in dust resistivity with temperature in the beginning. When the dust resistivity exceeds about 10^{10} Ω cm, the potential across dust layer increases and the effective voltage maintained across the ESP decreases, resulting in a decrease in the collection efficiency. It should be noted that the migration velocity varies with the square of electrical potential (Eq. (4)).

5. Effect of gas and dust characteristics on ESP performance

5.1. ESP operating principle

The operating principle of the ESP is illustrated in Fig. 3. An industrial, single stage, ESP consists of, high voltage, negatively charged (above −50 kV) discharge electrodes placed between grounded collecting electrodes. The discharge electrodes are normally wires or rods and the collecting electrodes are vertically hung plates. Under the influence of corona, generated due to high negative voltage, dust particles get negatively charged, migrate towards and get collected on the collecting electrodes. The path of the migrating particles is normal to the gas flow. The forces acting on the migrating particle, namely electrical, viscous, inertial and gravitational are indicated in the Fig. 3. Upon collection, dust particles

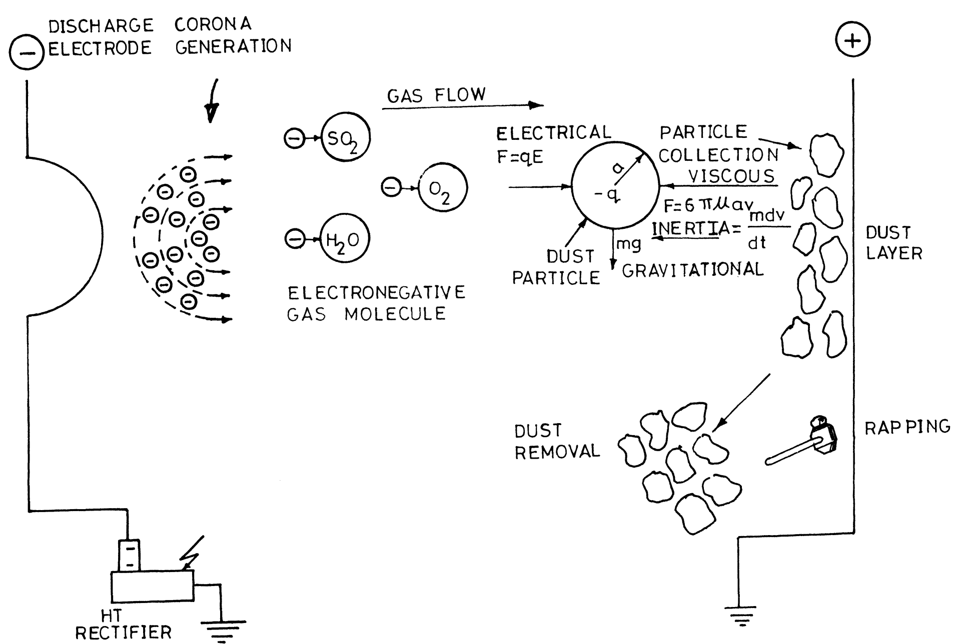

Fig. 3. Operating principle of ESP.

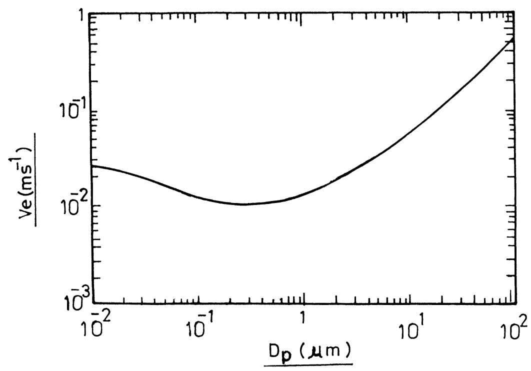

Fig. 4. Variation of migration velocity with particle size [4].

discharge their charge to the collecting electrode. The dust layer formed on the collecting plates is dislodged by rapping and collected in hoppers at the bottom of the ESP.

The gas and dust characteristics affect ESP's dust collection efficiency. The choice of appropriate ESP design and other equipment in the dust collection process depends upon these characteristics. The following paragraphs briefly summarise the effect of these characteristics on the ESP efficiency.

5.2. Effect of particle size

As already seen in Eq. (1), ESP efficiency is a function of migration velocity which is a function of particle size (Eq. (4)). Fig. 4 shows the variation of migration velocity with particle size. It is seen that the migration velocity is relatively large for very small and very large particles. Even though the particle charge is lower for very small particles, the mobility of such particles is large enough to compensate for lower levels of charge [4], as can be seen in Eq. (9)

$$B_e = \frac{qC}{3\pi\mu D_p} = \frac{V_e}{E} \tag{9}$$

where B_e is the electrical mobility, m^2/V s.

On the other hand, large particles acquire such a substantial charge that even the increased Stokes drag cannot overcome the charge effect. This is due to the fact that particle charge increases as D_p^2 whereas the Stokes drag increases only as D_p, leading to overall increase in migration velocity with D_p.

5.3. Effect of gas temperature and dust resistivity

The variation in the resistivity of dust deposit with temperature, for the dust emanating from different sources can be seen in Fig. 1. The plot shows a peak at certain temperature. In the ESP, at temperatures below 100°C, the dust layer is covered with a thin layer of moisture. This moisture also contains soluble alkalies. Most electricity that the dust conducts, passes over its surface and these two constituents, namely water and alkalies, assist conduction. As the temperature increases, moisture gets evaporated. As it rises above 100°C, the alkali content also gets depleted. Thus, we see a gradual rise of dust resistivity with temperature. At temperature above 150°C, the surface becomes completely dry and conduction through the core of particles becomes important. At higher temperatures, core conductivity increases and resistivity decreases, as evident in Fig. 1.

The particle layer on the precipitator collection surface must possess, at least, a small electrical conductivity to allow passage of ion currents from corona to the ground. The minimum conductivity required is about $10^{-10}/\Omega$ cm or a resistivity below $10^{10}\ \Omega$ cm. Dust deposits having resistivity in the range of 10^{8}–$10^{10}\ \Omega$ cm, discharge their charge to the collecting electrode and still retain sufficient agglomeration to avoid re-entrainment of particles in the gas flow. Particles of very low resistivity, discharge very quickly, assume the charge of collecting electrode and get repelled to the discharge electrode, resulting in higher re-entrainment. When the resistivity of the dust deposit exceeds $10^{10}\ \Omega$ cm, the potential across the deposit increases and the effective voltage difference maintained across the ESP decreases, resulting in the reduction of collection efficiency. This is illustrated in Fig. 5. Higher voltage drop across the dust deposit can result in flashover and recharging of already collected particles. This phenomenon is known as back corona or back ionisation, reversing the normal precipitation with particles tending to collect on negative discharge electrode. The main factors affecting the occurrence of back corona are dust resistivity, breakdown strength of gas and current distribution.

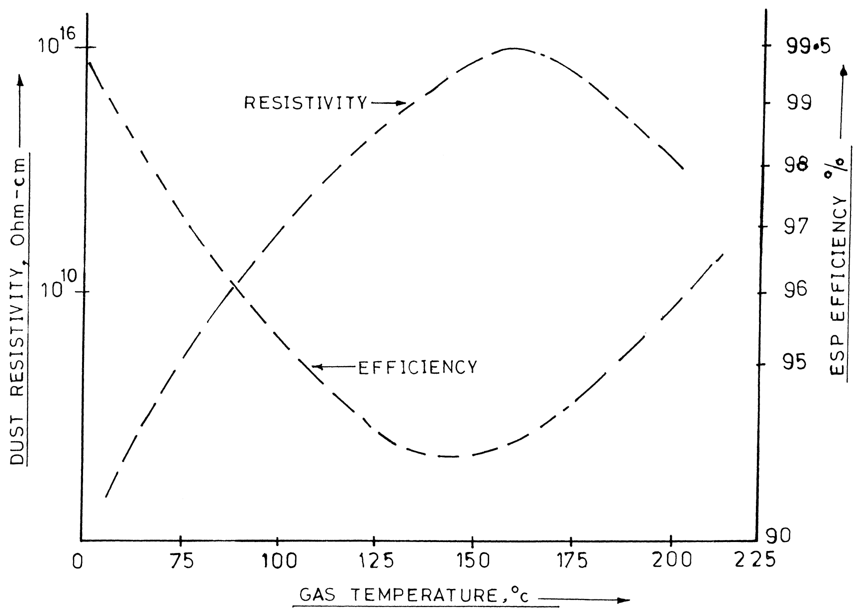

Fig. 5. Variation of ESP efficiency with dust resistivity.

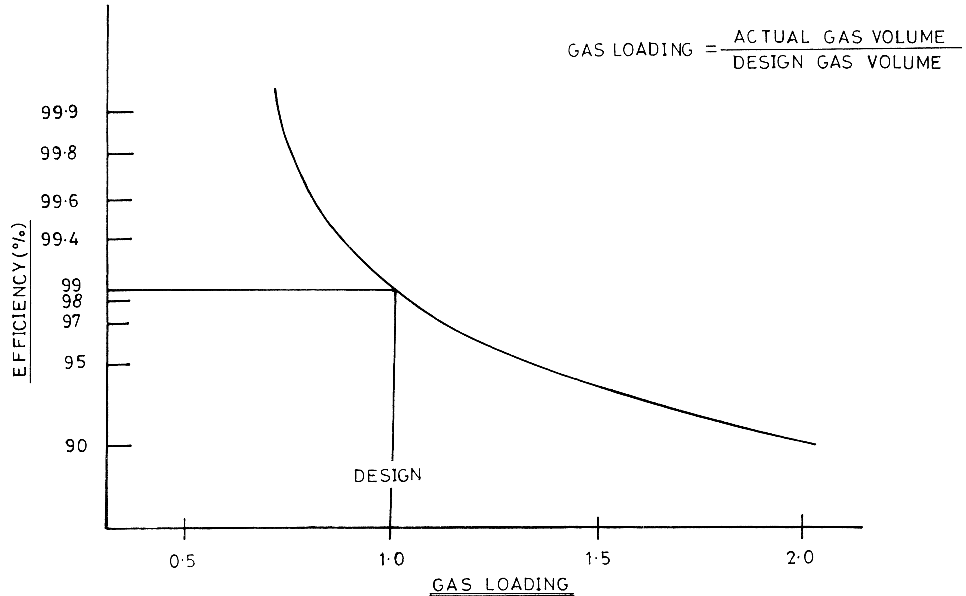

Fig. 6. Variation in ESP collection efficiency with gas loading.

5.4. *Effect of gas volume*

The gas flow has a direct bearing on the ESP size and performance. Gas flow rates are often overstated to ESP suppliers, to take care of variations in operating condition including upset conditions. This results in substantial increase in size and cost of the ESP as evident from the rearranged Deutsch Eq. (1) given as follows:

$$A = -\left[\frac{Q}{V_e}\right]\ln(1-\eta) \tag{10}$$

Sometimes gas flow rates increase due to changes in the process conditions such as capacity enhancement. Increase in gas flow rate beyond design limits reduces the collection efficiency [6] as can be seen in Fig. 6. This is because an increase in gas velocity increases dust re-entrainment during rapping (electrode cleaning process). Re-entrainment is more pronounced for fine particles and those which have little tendency to agglomerate.

5.5. *Effect of dust concentration and chemical composition*

The observations reported in [7] show that the major portion of dust is collected in the initial stages of an ESP. Therefore, a small change in dust concentration will not affect the performance of the ESP significantly.

The alkalis, sulphur and chlorine compounds often found in dust, affect the performance of ESP. The resistivity of dust is reduced by the presence of water soluble alkalies and sulphur compounds. High chloride content makes the dust sticky and it becomes difficult to shake it off the precipitator plates and discharge electrodes.

The variations in coal quality, changes in burning characteristics and upsets in rotary kiln operation, can result in substantial increases in concentration of dust in exit gas as a whole and that of unburnt coal particle in particular. High concentrations of unburnt coal particles in the exit gas increases the risk of explosion in dust collecting equipment. Therefore, an ESP is very often tripped to avoid possible explosions during such conditions. The tripping of ESP results in very high dust emissions at the outlet.

6. Practical considerations

The ESP has been successfully used in the cement industry for gas cleaning by making various process and design modifications, to tackle the effect of gas and dust characteristics. In the following paragraphs some ESP applications focusing upon these practical considerations shall be discussed.

6.1. Gas conditioning

In Section 5.3, it was seen how gas temperature and dust resistivity affect the ESP performance. Gas conditioning is one of the means to tackle this situation. It comprises any one or the combination of the following.

1. Reducing gas temperature.
2. Increasing gas moisture content.
3. Diluting gas by cold air.
4. Increasing the concentration of hydrophilic compounds, such as K_2SO_4, in the gas.

The moisture content of the gas is increased in equipment called a "gas conditioning tower" (Fig. 7). Gas enters at the top of the tower, flows down and exits at the bottom. Water is introduced in the gas stream at the top in the form of tiny droplets produced by spray nozzles. As they flow down, water droplets absorb heat from the gas and get evaporated. The gas gets cooled and its moisture content is increased. The in-flow of water is controlled such that the entire quantity introduced at the top gets evaporated and no water reaches the tower bottom. The handling of dust collected at the tower bottom, thus becomes easy. The control of water flow is achieved by continuous measurement of outgoing gas temperature. For example, in the Kiln section, exit gas temperature is brought down from 280–330 to about 150°C and the dew point is raised from 40 to about 60°C. The following constraints on the use of gas conditioning tower have been reported [1].

1. Gas cooled to 150°C cannot be used for further heat recovery.
2. High cost of electric power and water.
3. Dependence on the availability of water of acceptable quality.
4. Additional maintenance and unreliability due to system failures.

The conditioning of gas using cold air and water injection is practised in cleaning of kiln by-pass gas. When the raw mix (used for cement manufacture) contains higher percentages

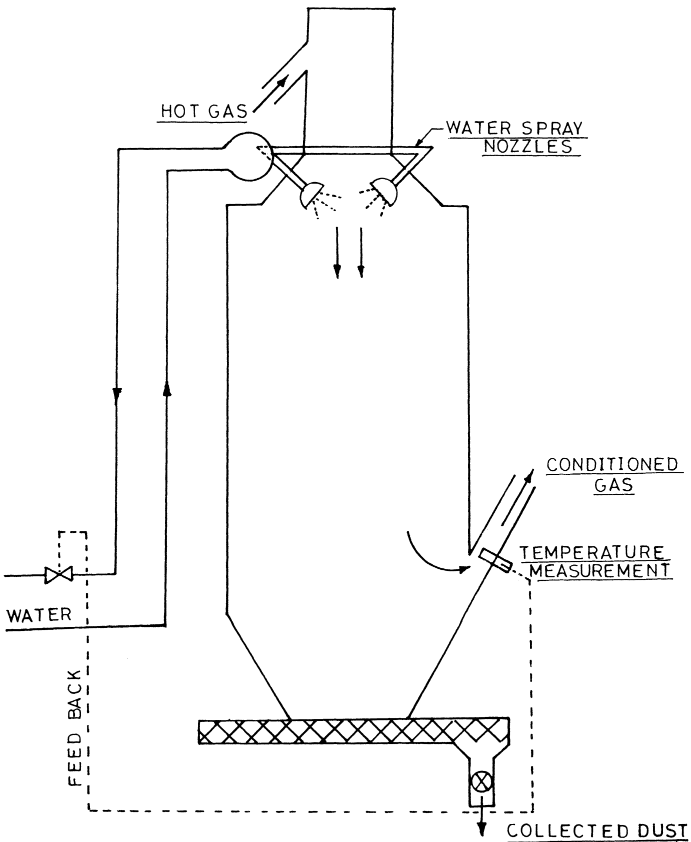

Fig. 7. Gas conditioning tower.

of alkalies, a small quantity of exhaust gas is by-passed from the back-end of the kiln. This is done to reduce the alkali circulation. The temperature of by-pass gas is in the range of 900–1000°C with a dew point around 35–40°C. The gas temperature is first brought down to about 500°C by ambient air dilution and further to around 200°C in the conditioning tower. Although, the dust resistivity is not so high in this case (due to the presence of water soluble alkalies), increasing moisture content helps agglomeration and better collection of sub-micron alkali particles. Besides, temperature reduction in conditioning tower helps reduce the gas volume.

As seen in Section 3.3, the temperature of exhaust gas from the grate type clinker cooler can go above 400°C under kiln upset conditions. Evaporative cooling is sometimes used to bring down the temperature. Injecting water spray near the cooler outlet [8] does this cooling.

Gas conditioning by increasing the concentration of hydrophilic compounds is relatively new to the cement industry and more investigations are required in this area. Addition of small quantities of potassium sulphate (K_2SO_4) considerably reduces the requirement of a water in the conditioning tower [7]. The effect of K_2SO_4 conditioning on dust resistivity

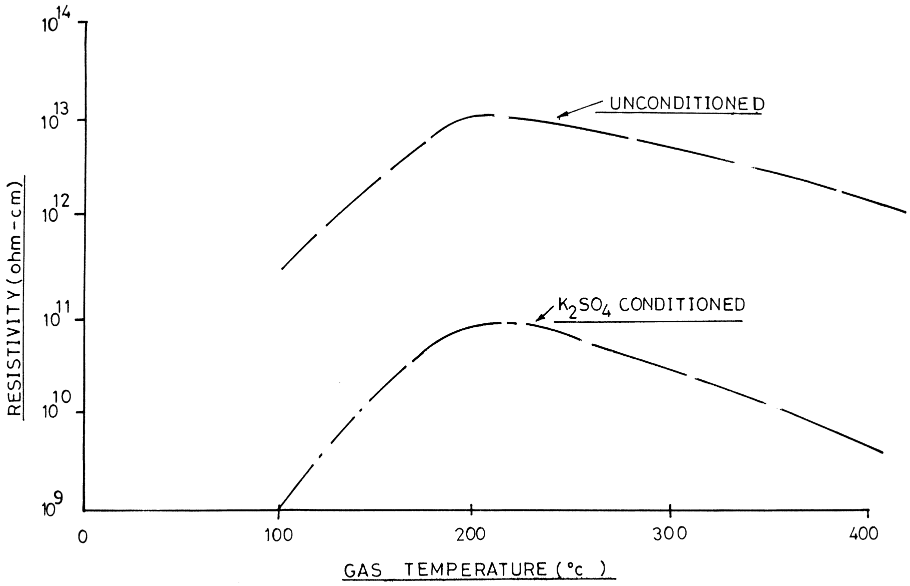

Fig. 8. Effect of K_2SO_4 conditioning on dust resistivity.

can be seen in Fig. 8. However, the effect of such additions on the quality of cement is required to be seen.

6.2. Pulse energisation or hot ESP

As seen in Section 6.1, gas conditioning results in the loss of vital heat from gas, high power and water consumption due to conditioning tower requirements and high maintenance. Therefore, a gas-cleaning technique allowing the use of hot, unconditioned gas is welcome. This is achieved in ESP by pulse energisation. It allows the application of high voltage across the electrodes for efficient collection of high resistivity dust, without causing back corona. ESP using pulse energisation is also called “hot ESP”, for it allows the passage of hot gas.

As the name indicates, the pulse energisation technique raises electrode voltage to a high level for a very short time (ms or μs). The short time duration prevents building up of ionised path for high current or spark-over. Thus, the advantages of high voltage, namely the creation of a dense cloud of ions and high field strength are obtained without affecting the ESP performance, as no back-corona is created. Pulse energisation is done in the following two ways.

1. Intermittent (ms) pulse charging.
2. Multipulse (μs) charging.

For pulse energisation Eq. (4) for the migration velocity can be written as

$$V_e = \left[\frac{k}{k+2}\right]\left[\frac{\varepsilon E_p E_q C}{\mu}\right] D_p \qquad (11)$$

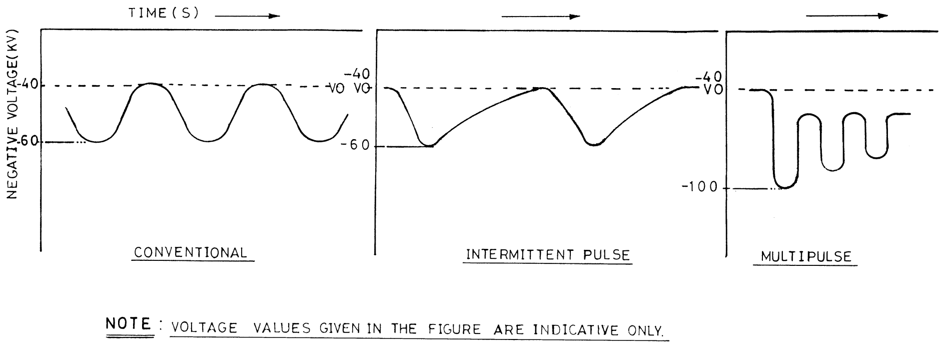

Fig. 9. ESP voltage wave forms for different types of charging.

where E_p is the peak field strength in pulse energisation, V/m and E_q the average field strength, V/m.

From Eq. (11) it can be seen that the migration velocity increases due to a substantial increase in the peak voltage E_p in the pulse energisation.

6.2.1. Intermittent pulse charging

A comparative picture of ESP voltage waveforms obtained by two types of charging is shown in Fig. 9. In the case of conventional ESP, the transformer-rectifier (T/R) set controlling thyristers is fired for each half cycle of the line power. In the intermittent pulse charging, the frequency of firing is reduced. This is done by allowing only third or fifth half-wave to pass. This can be done by microprocessor control. Thus, while maintaining the amplitude of conventional half-wave, the current is decreased to 1/3 or 1/5 of the original, thereby reducing the possibility of back-corona flash over. The voltage waveform has a pronounced ripple and it can be further increased by blocking more pulses. The voltage wave form now becomes a dc base level with pulse superimposed on it. The pulse duration is around 3–5 ms. The ratio of the total number of unblocked pulses to the total number of half cycles is referred to as charging ratio. Reported experience on the operation of intermittent pulse charging in ESP installed after clinker cooler on five ESP's in South Korea [9] and on a 2500 tonnes per day dry process in India [1], shows that while the emission levels are maintained more or less constant, the power consumption was reduced up to 80% in the first case and about 58%, in the second.

6.2.2. Multipulse charging

As the name indicates, high voltage pulses of very short duration are repeatedly superimposed on dc base-corona onset-voltage. The difference with the intermittent charging is illustrated in Table 6, using typical values of pulse width and interval.

The short duration pulses are created by placing a storage capacitor after the high voltage rectifier. The electrical energy oscillates between ESP and the capacitor until an essential portion is used up by ESP. The high voltage waveform created by these oscillations is shown in Fig. 9. As can be seen, pulse amplitude declines progressively as the energy is used to

Table 6
Comparision of pulse energisation techniques

Type of energisation	Pulse width (ms)	Pulse interval (ms)
Intermittent	3–5	30–50
Multipulse	50–100[a]	7–100

[a] Pulse width is measured in microseconds (μs).

form the corona. Peak voltages higher than those for intermittent charging can be used without any sparking.

The cost of multipulse energised ESP is comparable with that of ESP with a gas conditioning tower. This is because the increase in cost due to larger size in the first case is compensated by the cost of the gas conditioning tower in the second. In a typical case reported by Porle and Ekstrom [9], a multipulse energised ESP installed to clean preheater kiln gas at 200–240°C in one of the large dry process cement plants in India, gave the following advantages in comparison to the ESP with conditioning tower: doubling of migration velocity, 3–4 times reduction in emissions and 70–80% power savings. The outlet dust emission is practically independent of temperature (Fig. 10).

The enhancement of ESP performance with pulse energisation is sometimes measured with the help of a "enhancement factor" which is defined as follows:

$$\text{enhancement factor} = \frac{\text{migration velocity with pulse energisation}}{\text{migration velocity with conventional ESP}}$$

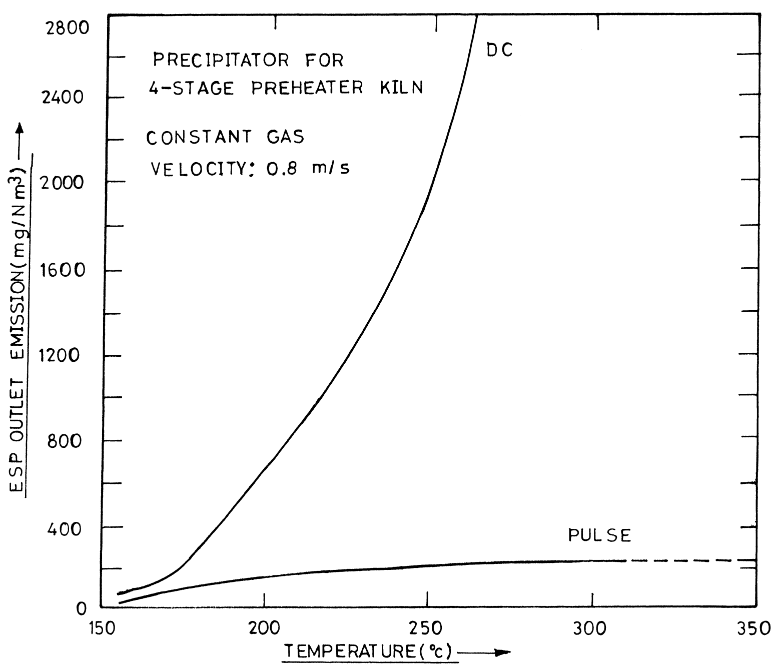

Fig. 10. Variation in outlet emission with temperature for ESP with dc voltage vis-à-vis pulse energisation.

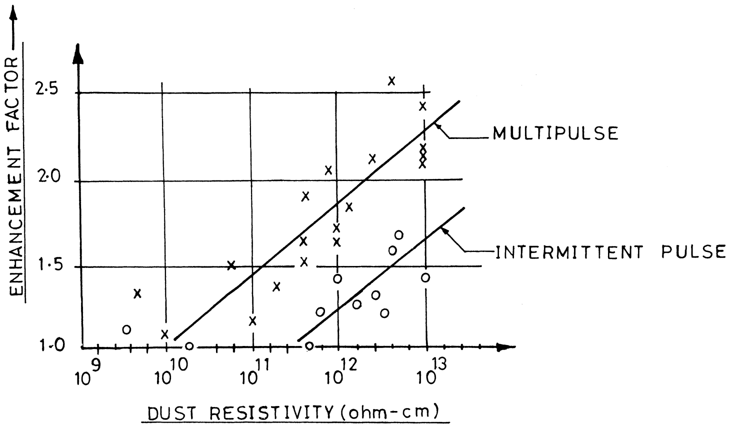

Fig. 11. Variation of enhancement factor with dust resistivity.

Fig. 11 shows a typical trend in variation of enhancement factor with dust resistivity [9]. This phenomenon perhaps explains why the outlet dust emission in pulse energised ESP remains practically unaffected by the rise in temperature (Fig. 10). As can be seen in Fig. 11, enhancement factors for multipulse energisation are higher compared to intermittent pulse. This is due to the comparatively higher peak voltages obtainable in the multipulse energisation (Eq. (11)). The enhancement factor is nearly 1.0 at low values of resistivity which means that the performance of a pulse energised system is similar to the dc based system at lower temperatures. The enhancement factor becomes pronounced at higher values of dust resistivity or higher temperature. This is due to the increase in migration velocity both as a result of the higher peak voltage (Eq. (11)) and the temperature. (Eq. (8)).

6.3. Combination of ESP with FF

The combination of ESP and FF in one unit is considered in some cases as an effective alternative to meet the requirements of stringent emission regulations enforced in some countries. The pollution control regulations in India are also going to be stricter in future. ESP–FF combination is also useful for large size plants, considering large gas volumes emitted by such plants and the requirement of large size ESP for gas cleaning. As an example, a 4000 tonnes per day cement plant will emit approximately 0.5×10^6 m^3/h of gas from its preheater kiln at 250°C. This makes ESP size considerably large, increasing its cost beyond economic limits. As stated earlier, most of the dust is precipitated in the initial stages of the ESP and the last few stages contribute little to the ESP efficiency. This is mainly due to the fine particle size. On the other hand, the efficiency of a FF is practically unaffected by the particle size and is, therefore highly efficient in collecting the dust particles.

This fact is illustrated in Fig. 12. The basis for predicting the collection efficiency of the FF is the efficiency of single fibre element. The figure shows the collection efficiency of a single cylindrical fibre by the mechanisms of diffusion, inertial impaction and interception, as a function of particle diameter [4]. As can be seen, the collection efficiency reaches almost

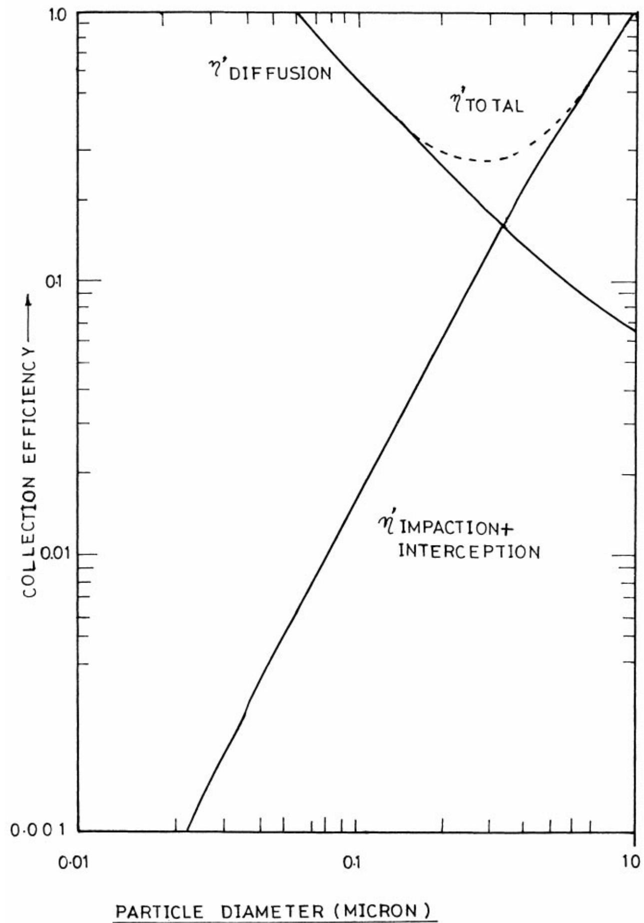

Fig. 12. Collection efficiency of a single cylindrical fibre as a function of particle diameter [4].

100% for the particle size of 1 μ and above. In a typical case reported [10], an ESP installed in the kiln section was partly converted into a fabric filter. The ESP fields were reduced from 5 to 2 and a six compartment pulse jet bag house section was added to it. ESP and FF formed one unit. Poly-tetrafluoroethylene (PTFE) membrane was used as a filter media.

This arrangement can be very effectively used to reduce the alkali content of re-circulated kiln dust, simultaneously with substantial reduction in the dust emission. This is evident from Table 7, which gives typical values of alkali content of dust collected in different sections of ESP system [11]. As can be seen in the Table 7, nearly 12% of the total alkali was removed in just 2% of the dust collected in last sections (serial number: 5–8). When these sections were replaced by FFs, this dust, being a small quantity, could be easily rejected. The chemical separation can be achieved in ESP also but gas cleaning is inefficient especially when the low alkali cement is produced, it is reported [11].

Table 7
Alkali content of kiln dust collected in ESP system

Serial number	Section of ESP system	Alkali content (tonnes per hour)	K_2O content (total %)	Dust collected	
				(tonnes per hour)	(Total %)
1	Settling box	0.009	5.29	1.3	14.5
2	Distribution chambers	0.014	8.24	1.3	14.5
3	First ESP field	0.049	28.82	2.6	29
4	Second ESP field	0.078	45.88	3.6	40.15
	Sub total (1–4)	0.150	88.23	8.8	98.15
5	Third ESP field	0.005	2.94	0.08	0.9
6	Fourth ESP field	0.008	4.71	0.05	0.65
7	Fifth ESP field	0.002	1.18	0.01	0.1
8	Distribution chambers	0.005	2.94	0.02	0.2
	Sub total (5–8)	0.020	11.77	0.16	1.85
	Grand total	0.170	100	8.96	100

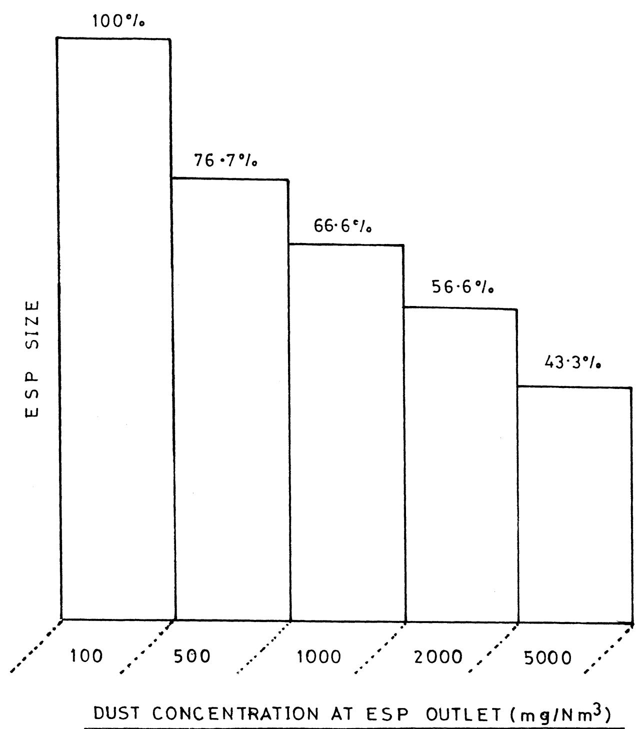

Fig. 13. Effect of dust emission level on size of ESP in combination with fabric filter.

Both, the space requirement and the operating power requirement remained the same as in the earlier unit. The dust emission got reduced from earlier 93–12 mg/N m^3 to 4–5 mg/N m^3 which was well below the new statutory requirements. Ramanan et al. [6] report a reduction in ESP size when used in combination with bag house, considering different dust concentration at the ESP outlet (Fig. 13). The study relates to a thermal power plant with an inlet dust concentrations of 100 g/N m^3.

6.4. Horizontal flow and vertical flow (open top) ESP

In the modern cement plants, the exhaust gas from the coal mill circuit requires dust control measures. Until a few years back, it was the practice to use coal mill exhaust gas as primary air in the kiln burner and the coal mill capacity was balanced with respect to the kiln requirement. In the modern efficient burner designs, the quantity of primary air has been minimised, hence some air has to be vented out. Secondly, the capacity of mill is kept on the high side to take care of the irregularities in the availability of coal. Horizontal ESP is specially designed for coal mill gas cleaning. It has the following provisions to minimise the risk of explosions [7]:

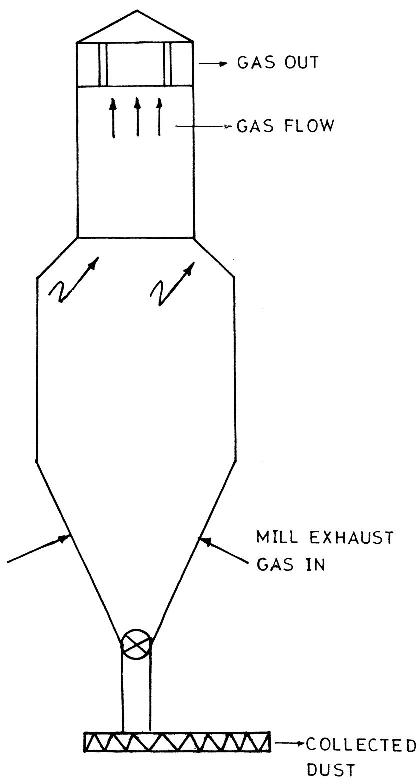

Fig. 14. Open-top ESP for explosive dust.

1. New precipitator design normally employs two electric fields. The internal requirement, such as collecting plates, discharge electrodes and rapping system, is basically the same as in a standard ESP.
2. Precipitator casing is reinforced to withstand up to 2000 mm water gauge (WG) pressure and the explosion relief panels provided at the roof are adjusted to open at 1000 mm WG pressure.
3. Temperature measurement and warning systems are provided at sensitive locations such as inlet/outlet transition pieces and hoppers.
4. Manually operated CO_2 fire extinguishers are installed.

The vertical flow ESP is open to the atmosphere from the top. The gas flows from bottom to the top of the ESP. The discharge and collecting electrodes are arranged horizontally. A schematic of a open top ESP is given in Fig. 14. Besides this special provision to take care of explosions, normal safety measures, such as maintaining gas temperature above dew point, provision of O_2 and CO_2 analyser before ESP with alarm, "trip" set-point, periodic checking of rapping system, are also required to be incorporated.

The vertical flow ESP is effective in dissipating the pressure wave upwards and avoid explosions. However, its design allows the provision of only one separate electric field which puts limit on the achievable efficiency levels.

7. Conclusions

1. The foregoing discussion shows that the characteristics of exhaust gas and dust emitted from different sections of the cement manufacturing process vary considerably in terms of gas quantity, temperature, moisture content (dew point), dust content and particle size distribution. Some typical characteristics are as follows:
   1.1. As a result of modernisation from wet to dry preheater kiln the temperature of exit gas has increased (250–300°C) and the dew point lowered (35–40°C) with a corresponding increase in the dust resistivity (10^{13} Ω cm). The particle size distribution shifted to a smaller size with 75–85% particles lying below 10 μ. The alkali content has gone down considerably.
   1.2. The dust particles in clinker cooler exit gas are coarse, abrasive with majority lying above 10 μ. Under upset conditions, the temperature may reach 400–425°C and the dust content up to 50 g/N m^3. The dust resistivity is very high (10^{13}–10^{14} Ω cm).
   1.3. In case of cement ground in ball mill, water injection in the mill increases the dew point and reduces the resistivity of dust in exhaust gas. The incorporation of air separator in the mill circuit affects the dust characteristics.
   1.4. When coal is ground in VRM or air-swept ball mill, the high temperature (60–80°C) and the high dust content (100–500 g/N m^3) and the fine particle size (60–75%, <10 μ) can create explosive conditions in the dust collector in the mill circuit.
2. The theoretical considerations show that the collection efficiency increases with the particle migration velocity. The particle migration velocity varies directly with the (a) square of electrode potential, (b) particle size and (c) square root of absolute temperature. The positive effect of temperature increase is not seen in the actual practice, in conventional

dc base ESP, perhaps due to the simultaneous negative effect on the electrode voltage due to the increased dust resistivity.

3. The migration velocity or the mobility of the particles is relatively high for very small ($<0.1\ \mu$) and very large ($>1\ \mu$) particles.
4. The resistivity of dust increases with temperature, reaches a peak and falls at higher temperatures. The performance of ESP has been found optimum in the range of 10^8–10^{10} Ω cm resistivity, the efficiency drops below or above that range.
5. The collection efficiency of ESP falls when the gas flow rate is increased beyond the design limits.
6. The performance of ESP is not significantly affected by a small change in dust concentration. The resistivity of dust is reduced by the presence of water soluble alkalis and sulphate compounds. The presence of chlorides makes the dust sticky.
7. In the cement industry, the adverse effects of gas and dust characteristics are effectively countered by making various process and design modifications in the gas cleaning operations. Some of which are as follows:
   - 7.1. Gas conditioning by either or the combination of reducing gas temperature, increasing gas moisture content and diluting gas by cold air. The gas conditioning tower is generally used for the purpose. It faces certain constraints like high cost of operation and maintenance, loss of useful heat and unreliability due to system failures.
   - 7.2. The technique of pulse energisation or hot ESP allows the use of hot, unconditioned gases in ESP. It results in substantial reduction in the dust emission as well as the power consumption.
   - 7.3. The technique of combining ESP with FF has been successfully used in some cement plants. It has been found specially useful for large size ($>10^6$ t/a) cement plants where the size of ESP becomes very large on account of large gas volumes.
   - 7.4. The horizontal ESP has been successfully used in coal mill gas cleaning due to its special design which effectively takes care of the main concern, that of explosion.

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