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VI. REDUCTION OF EMISSION OF POLLUTANTS

Recent advances in electrostatic precipitators for dust removal

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1. Introduction

The first essential in the prevention of atmospheric pollution is to remove the pollutant, or at least as much of it as is feasible, at source. Electrostatic percipitation is a well established process for removing dust from gases and careful attention to the many physical processes which are involved has allowed the development of the very large and highly efficient installations now required by the cement, electricity supply and the iron and steel industries.

For example, a typical 2000 MW power station burning pulverized coal produces about 9.3×10^6 m^3 (330×10^6 ft^3) of flue gas per hour, containing about 100 tons of fly ash. The precipitators are specified to have a dust removal efficiency of 99.3 % at full load. They have a collecting electrode area of the order of 0.157 km^2 (1.7×10^6 ft^2, or 40 acres); their cost, together with that of the associated dust handling plant, is about £3M, i.e. about $3\frac{1}{4}$ % of the complete boiler. The total amount of fly ash removed annually on all the C.E.G.B.'s pulverized fuel stations is between seven and eight million tons.

Most industrial precipitators are now of the 'plate' type. The basic principles are quite simple: gas flows horizontally between a series of parallel, vertical, flat 'collecting electrodes'; the dust receives ionic charge from corona on the 'discharge electrodes' which are interposed between the collecting electrodes and maintained at a high, usually negative voltage—typically −40 to −50 kV; the electrostatic field causes the charges dust to migrate towards the collecting electrodes where it is deposited and subsequently dislodged to fall into hoppers by periodically rapping the electrodes. In some cases where the dust is extremely fine and difficult to handle in a dry form, e.g. blast furnace installations, it is washed into the hoppers by water trickling down the electrodes (Watkins & Darby 1964).

Public insistence on a high standard of cleanliness of effluent industrial gases, reinforced by the Clean Air Act of 1956 and extension of the Alkali Act in 1958, has resulted in many scientific investigations of the precipitation process and of the various difficulties that have arisen in particular applications. These have yielded a succession of refinements of practice, the more recent of which are summarized in this paper.

2. Theory

The basic processes in electrostatic precipitation e.g. particle charging, particle migration, etc., have been extensively studied and the theories reasonably well validated in the laboratory (Cooperman 1956; Hewitt 1957).

The most commonly used equation for particle deposition is that due to Deutsch (1922). It may be expressed:

$$\text{collection efficiency} = 1 - \exp(-Aw/Q),$$

where A is the area of receiving electrodes, Q the volumetric gas flow rate and w the particle migration velocity. There is, however, no doubt that, when applied in the Deutsch formula, theoretical values for particle migration velocity predict very much higher values for efficiency than are actually achieved in commercial installations. Therefore, designers usually resort to using empirical values for the particle migration velocity term which are based on previous experience of similar applications.

Investigators have tried to quantify this discrepancy in terms of re-entrainment from the collecting electrodes, etc. (Robinson 1967), but Cooperman (1968), recognizing that the basic Deutsch assumption of particle motion being dominated by turbulence is invalid in commercial practice, has recently reconsidered the matter. Taking into account diffusion forces arising from turbulence and from particle concentration gradients in both the direction of flow and transverse to it, he has derived an efficiency formula of the same form as that of Deutsch but more pessimistic, particularly at high efficiencies. At high gas velocities, the Deutsch equation is modified by multiplying the particle migration velocity by a factor $(1-f)$, where f is the ratio of turbulent transport away from the collecting electrodes to electrostatic transport towards them. Particle diffusion in the direction of flow becomes important at low gas velocities and divergence from the Deutsch equation is more pronounced. Cooperman's formula offers a plausible explanation for the decrease in effective migration velocity which has been reported by several investigators (see, for example, Dalmon & Lowe 1961; Trevor Busby & Darby 1961; Williams & Jackson 1962; White 1963); it also predicts a significant advantage for low turbulence precipitators. Work on the latter is now proceeding at C.E.R.L. in view of its possible application in the final zone of a plate type installation.

3. DESIGN ASSESSMENT

Concurrently, the wide discrepancy between the simple Deutsch theory and practice has led Barrett (1967) to analyse the performance of power station precipitators in terms of the many variables inherent in the design and operation of the plant.

Using the results of 74 carefully conducted tests, involving several makes of plate precipitator, he deduced that the effective migration velocity, as defined by the Deutsch formula, could be expressed:

$$w = 31.2-(4.8\ln F)-(0.0008P)-(0.7\times 10^{-7}\,g^2)-8.1\exp(-0.5S)-43.3/a, \tag{1}$$

where

a is the content of coal (%)
g the specific surface area of inlet dust ($\mathrm{cm^2\,g^{-1}}$)
w the effective migration velocity ($\mathrm{cm\,s^{-1}}$)
F the collecting electrode area per unit volume of gas per second $(=A/Q)$ ($\mathrm{ft^2\,ft^3\,s^{-1}}$)
P the ratio of collecting electrode area to installed capacity of h.t. supply ($\mathrm{ft^2/kVA}$)
and S the sulphur content of coal (%)

As seen in figure 1, the correlation is remarkably good—bearing in mind the wide range of plant and operating conditions—and, although it offers no explanation for the observed relation, it provides an extremely valuable tool for assessing the performance of new and existing power station installations.

The analysis indicates no correlation between effective migration velocity and inlet dust burden, carbon content of dust, moisture content of fuel, inlet gas temperature, gas velocity, or height of collecting electrodes. The apparent independence of gas velocity and temperature is a little surprising since they have previously been found to be significant parameters in pilot scale experiments (Dalmon & Lowe 1961); likewise, correlation with ash content of coal but not with inlet dust burden is curious since these two quantities would be expected to be closely related.

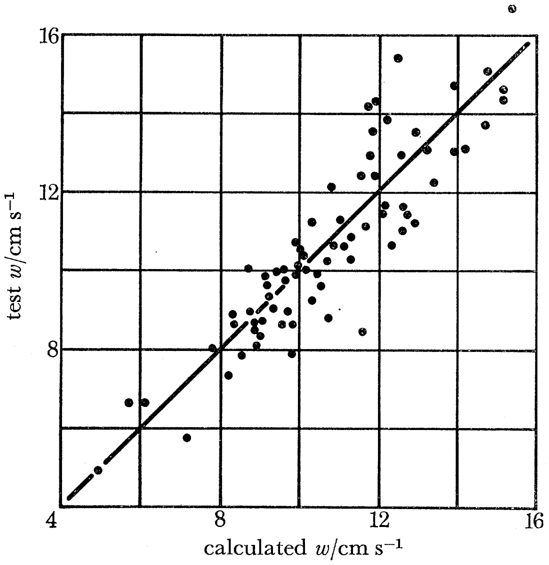

FIGURE 1. Comparison of Barrett correlation with test data.

4. PLANT DEVELOPMENTS

The following significant developments in the design of power station precipitators have taken place over the past few years:

4.1. The practice of preceding the precipitator with cyclone collectors has been discontinued. Both types extract the coarse particles more readily than the fine and, hence, are not complementary; moreover, removal of coarse particles by the precollector leaves the precipitator to handle a very fine dust which clings tenaciously to the electrodes and often causes adverse electrical effects (see § 5.1).

4.2. The relatively complicated, 'catch-pocket' types of collecting electrode, designed to prevent re-entrainment of coarse particles (particularly if they are electrically conducting), have been superceded by virtually flat plates—slight deformations being used merely to provide stiffness. This is an entirely logical development since the drive for high combustion efficiency has resulted in finer grinding of the coal and, hence, a finer fly ash which contains extremely few coarse carbon particles; also, pilot scale experiments have demonstrated that flat electrodes are equally effective and, of course, they are both cheaper and make better use of space (Dalmon & Lowe 1961).

4.3. Pilot scale evidence (Dalmon & Lowe 1961)—not confirmed by the Barrett correlation—that migration velocity showed a very flat optimum in the region of 1.8 to 2.1 m s^{-1} (6 to 7 ft s^{-1}), has allowed a modest increase of gas velocity in the treatment zone from about 1.5 to 1.8 m s^{-1}

(5 to 6 ft s^{-1}); this has eased the problem of accommodating the precipitators, the space available having tended to become more restricted as boiler size increased.

4.4. On the electrical side, solid-state rectifiers have superceded the rotary type and automatic control of the high voltage electrical supply is now standard practice.

5. CURRENT INVESTIGATIONS

5.1 *Dust resistivity and conditioning*

The influence of dust resistivity has been extensively studied and high resistivity has often been blamed for poor plant performance, particularly when this was accompanied by abnormal electrical behaviour.

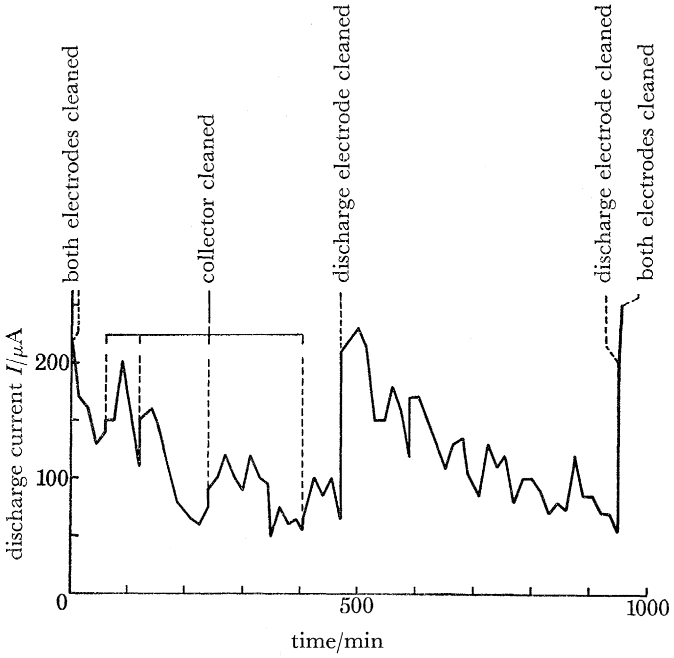

FIGURE 2. Variation of discharge current with time for experimental precipitator operating on the flue gas. High voltage = 20 kV; gas velocity = 2.1 m s^{-1}; gas temperature = 135 °C; rapping of discharge and collector electrodes every 5 min.

The most usual explanation is that the high potential difference across a resistive dust layer on the collecting electrode causes breakdown at localized points and, hence, emission of positive ions which counterbalance the normal negative ion charging process. The effect is known as 'back-ionization' and is readily demonstrated in the laboratory (Heinrich & Anderson 1957).

Back-ionization has occasionally been observed in commercial precipitators, but it is certainly very rare in British power stations and there is growing recognition that it does not adequately explain the type of abnormal electrical behaviour usually experienced. This takes the form of low, unstable discharge current whereas back-ionization is characterized by a high, stable discharge.

It has, incidentally, been shown that even extremely high levels of back-ionization have a remarkably small effect on precipitation efficiency, provided the voltage is maintained constant (Forrest & Lowe 1957). Admittedly, the power supplies in commercial installations will usually be unable to meet the latter requirement so that the occurrence of back-ionization will usually be accompanied by poor performance; this will result from the reduced electric field rather than from reverse particle charging.

A more plausible explanation for low, unstable discharge is to be found in the observations of Lowe, Dalmon & Hignett (1965) that highly resistive dust on the discharge electrodes, even in thin films, will strongly suppress the corona. The effect is very much more marked than that caused by field reduction due to the potential across a similar layer on the collecting electrode. It is well illustrated in figure 2. The level of electrode rapping in this experimental precipitator, which was connected to a pulverized fuel boiler, was high by commercial standards; none the less, there was a gradual decrease in the discharge current which was only partially restored when the collecting electrodes were brushed clean, but almost completely restored when the discharge electrodes were brushed.

There has been increasing evidence of abnormal electrical behaviour which could be attributed to high dust resistivity in British power stations in recent years. It is believed to be associated with a general reduction in the sulphur in relation to the ash content of our coal.

Fly ash at precipitator temperatures consists mainly of electrically insulating particles; conductivity is imparted by an adsorbed layer of water, salts and sulphur trioxide. The average ash content of our coal has climbed from about 15 to 25 %, mainly by the addition of floor and roof shale of low sulphur content; finer grinding of the coal, and with it the ash, to obtain more complete combustion has resulted in a far greater surface area of ash and one can readily imagine the situation where there is no longer sufficient SO_3 formed during combustion to coat the particles adequately with a conducting film of sulphuric acid.

It will be recalled that Barrett's analysis shows a correlation between precipitator performance and sulphur content of the coal. Closer examination shows that the effect is appreciable if the sulphur content falls far below 1.3 %. It is noteworthy that about 28 % of the coal currently supplied to the C.E.G.B. has less than this.

There is, therefore, a very strong incentive to find a simple and economic technique for overcoming the problems set by highly resistive dust from low sulphur coals. Since the practicability of maintaining the discharge electrodes sufficiently clean to eliminate the effect is doubtful, and such a solution is unlikely to be applicable to existing installations, it seems that the objective must be to coat the particles with a conducting film without, of course, giving rise to any significant, noxious emission from the stack. At first sight, this would appear to be a formidable limitation since the most obvious additives are the strong acids and bases, which provide high conductivity through the hydrogen and hydroxyl ions. On reflexion, however, it is evident that a very high proportion of the conditioning agent must be adsorbed on the particles' surface for it to be effective, and will therefore be almost entirely retained by the precipitator. None the less, all investigations carried out by the C.E.G.B. have been strictly supervized to provide the necessary safeguards.

If the hypothesis that the cause of high resistivity is a deficiency of SO_3 is correct, then the most obvious conditioning agent is SO_3 itself. Early reports by Trevor Busby & Darby (1963) indicated that it could be extremely effective, the injection of 15 parts/10^6 (by volume) to the flue gas producing an eightfold reduction in emission. This dramatic improvement has never been reproduced in the C.E.G.B. investigations. Indeed, the results have been very variable and have included a number of cases where there was no significant improvement at all; such cases are almost certainly due to either the plant having other major defects or to the SO_3 being injected in such a manner that it was insufficiently dispersed for adequate adsorption on the dust surface. The general indication of the C.E.G.B. investigations is that, where high dust resistivity is the genuine cause of poor performance, injection of SO_3 at the rate of 15 parts $/10^6$ is likely to reduce emission by a factor of about two. Higher rates of injection do not produce further significant improvement.

Sulphur trioxide, is, however, fairly expensive, difficult to handle and is a corrosion risk. These difficulties can doubtless be overcome but, since calculation shows that SO_3 molecules are 150 times more likely to combine first with H_2O in the flue gas than to meet an ash particle, it would seem that over 99 % reaches the ash particles as H_2SO_4. H_2SO_4 itself can, therefore be considered as a conditioning agent and laboratory pilot-scale experiments have shown it to be equally effective as SO_3, on a molar basis. It is cheaper than SO_3, easier to handle but still presents some risk of corrosion.

The search for alternative materials then led to sulphamic acid (NH_2SO_3H) in the belief that this dissociated into SO_3 and NH_3. Sulphamic acid is a fairly dry crystalline solid, easily handled and reasonably easily injected into the flue in solid form. Again, it proved to be about as effective as SO_3, on a molar basis, which was surprising in the light of subsequent laboratory experiments which indicated that only one sulphur atom in four goes to SO_3, the others to ammonium bisulphate, and thence to SO_2 at temperatures above 360 °C.

This poses the obvious question—is ammonium bisulphate an effective conditioning agent? It is hygroscopic and melts at 157 °C, so that it could be effective if the droplets were co-precipitated with the dust. Laboratory pilot-scale experiments showed that it is.

This, in turn, led to the consideration of ammonium sulphate whose complex thermal decomposition is believed to yield the bisulphate, probably via the pyrosulphate. Again, when injected at 400 to 450 °C into laboratory pilot scale precipitators, it has been found to be equally effective.

Thus, ammonium sulphate promises to be an acceptable conditioning agent; it is cheap, easily handled and unlikely to create a corrosion problem. Its effectiveness on commercial installations has still to be demonstrated, and the optimum technique for its injection has yet to be developed.

5.2. *Electrode rapping*

In view of the adverse effects of resistive dust on the electrodes, it is obviously important to provide effective means of dislodging the dust from them. This is usually achieved by periodically 'rapping' the electrodes with a hammer.

The discharge electrode is, for the reason given in §5.1, the more important; the rapping mechanism is operated continuously so that the electrodes receive an impulse at about 30 s intervals. On the other hand, a compromise has to be made between the loss of performance due to dust accumulation and the amount of dust re-entrained into the gas stream each time the collecting electrode is rapped. Thus, the heavily laden inlet zones are rapped more frequently than the outlet, typical intervals being 10 min and 1 h respectively (Dransfield & Lowe 1964).

The force required to dislodge a particle from a surface is highly dependent on particle size and surface properties. Laboratory experiments with a typical fly ash have shown that acceleration in the plane of the surface, i.e. shearing the dust layer, is about three times more effective than acceleration normal to it; also, that about twice the acceleration is required when the assembly is electrically energized to simulate precipitator conditions. These experiments indicate that a shearing acceleration of the order 25 g will dislodge most of the dust (energized), but the finest particles will still adhere even when subjected to acceleration of several hundred g.

A limited number of surveys on power station precipitators has indicated a very large variation in the rapping impulse over the surface of individual collecting electrodes and equally large variations from one installation to another; this is not surprising in view of the size and relatively flimsy nature of the electrodes. The investigation has not yet reached the stage of identifying a correlation between the local impulse and thickness of dust adhering to the plates but there is clearly scope for the development of electrodes and rapping mechanisms which will provide an adequate impulse over their whole surface without risking fatigue failure at the most heavily loaded points.

6. Conclusions

Recent years have seen no radical changes in commercial precipitator practice. There have been some significant advances tin basic precipitator theory but attention has been mainly devoted to the details of the physical processes and this has enabled installations to be built which, under normal circumstances, entirely meet the very exacting standards to which British industry is now required to conform.

Local conditions do, however, arise from time to time which depress performance; a particular example is that due to high resistivity dust which has tended to become more troublesome in British power stations, especially with low sulphur coals. Practical solutions to such problems are being vigourously sought.

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