Enhanced Fine Particle Collection by the Application of SMPS Energization

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Abstract: Over the past decade or so the health problems associated with the inhalation of submicron particles from industrial processes has taken prominence and has lead to the stricter legislation of emissions such as the US PM2.5 approach. Generally most forms of control equipment readily handle and collect particles greater than 1 micron diameter, however, those less than 1 micron diameter are very much more difficult to collect.

In the case of electrostatic precipitation, which involves both particle charging and migration under the influence of an electric field, the larger particles, generally greater than 1 micron are charged by collision with the ions and electrons present in the inter electrode area. It will be shown that the charge on these particles is proportional to the radius squared and its migration velocity proportional to the voltage squared, both reducing with particle size. The very small particles however, are charged by a diffusion processes and migrate under the influence of Brownian Motion which increases as the particle size decreases. The result of this is that a typical particle size/efficiency curve indicates a significant penetration window in the 0.8 to 0.2 micron diameter, which coincides with the change from collision to diffusion charging of the particles.

Because of this penetration window, should an existing precipitator operating under optimum electrical conditions, not comply with fine particle emission requirements, the conventional enhancement scenario would be to increase the precipitators plate area, a very expensive solution, since the charging and precipitation operating conditions have been already optimised. It will be shown, however, that the replacement of the conventional mains energization system by an SMPS approach in an existing ESP will enhance the collection efficiency of particles in the penetration window as a result of the increase in both operating field voltages and currents.

An application was applied to a 2 field ESP, dealing predominately with sub micron fume. This was initially assessed using PALCPE™ (Proactive Approach to Low Cost Precipitator Enhancement), which indicated a significant reduction in the fine particle emissions was achievable by operation under SMPS Operation. An SMPS unit was subsequently fitted to the outlet field of this precipitator and the operating data will be examined in detail. With the outlet field under a mains rectification energization system the overall emission was -25 mg/Nm^3, which after installation of the SMPS unit reduced to less than 15 mg/Nm^3.

Keywords: ESP fundamentals and applications Enhanced Collection of Sub-micron Sized Particles for Electrostatic Precipitators

1 INTRODUCTION

With increased industrialisation amongst the developing countries, the impact of increased pollution from particulates has lead to environmental concerns being raised and many countries have enacted more stringent emission legislation. In addition to reducing the general level of pollution, concerns have been addressed to the emission of heavy metals, particularly in the sub micron range, which are considered injurious to the health of man and other living organisms since they are readily absorbed into the food chain or in man during normal inhalation. On most pollution control approaches, whether it be ESP, bag filter or scrubber, they readily handle and collect particles greater than 1 micron diameter, however, it is those less than 1 micron diameter which are the most difficult to capture, however, by improving the overall collection efficiency of the device a higher proportion of the fines are collected.

Most existing pollution control installations, designed to meet earlier legislation, are now faced with improving their collection efficiency to comply with the more stringent emission levels being promulgated. Obviously with an existing installation any enhancement in collection efficiency can prove costly to the user, either in terms of requiring additional plant or in higher operating costs.

Many existing process plant, as part of their pollution control system, employ electrostatic precipitators, the operating principle of which is that the gas and particulates are passed through an electric field where the particles receive an electric charge and then as a charged particle are deflected across the field to be collected on the receiving electrodes. Although electrostatic precipitators have been used for almost a century in collecting particulates, it has only been in the past 20 years or so, following the development of high speed computers enabling solutions to Poisson equations, that precipitation theory can now been related to practice with confidence.

Because of the earlier difficulty of resolving Poisson equations, traditionally, the sizing of electrostatic precipitators has been based on the experience and expertise of the suppliers using operating data from similar applications. Initially this was based on the traditional Deutsch relationship and more recently using the modified Deutsch relationship, such as that proposed by Matts and Ohnfeldt [1].

$$\omega_k = \left(\ln 1/(1\text{-efficiency}) \right)^2 \times V/A \qquad (1)$$

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where: A is the total collector surface, V the gas volume and ω_k is the modified effective migration velocity of the particles.

Rearranging:

$$\text{Efficiency} = 1 - (e^{-\omega_k A/V})^{½} \qquad (2)$$

From this in order to increase the efficiency, the options are to increase A the collection plate area, reduce the gas volume being treated, which may not be possible without effecting the actual process, or to increase the value of ω_k.

2 THEORETICAL CONSIDERATIONS

(1) If one considers the physics of a charged particle in an electric field, the charge attained by a particle is given by:

$$Q^{\infty}_p = p\,E\,d_p^2 \qquad (3)$$

where p is a constant, which varies between 1 and 3 for non conductive particles and is 2 for conductive particles.

(2) Within a precipitation field a particle experiences the following forces acting upon it, a momentum force F_m, an electrical force F_e and a drag force F_d. Where F_m = - $m\,a$, $F_e = Q_p\,E$ and F_d = (Re) A Co Where $F_m + F_e + F_d$ = Zero (Steady state condition.)

Prior to solving this equation, the drag force F_d has to be calculated.

In the case of low Reynolds Numbers(Re), the drag coefficient is given by

$$\text{Co} = 24/\text{Re} \qquad (4)$$

As the particle size reduces and approaches the region where the fluid loses its' continuum (mean free path of molecules = λ) then Stokes Law needs to corrected by the Cunningham Correction Factor - Co.

where

$$\text{Co} = 1 + 1.246 \times 2\,\lambda/d_p \times 0.42 \times 2\,\lambda/d_p \times \exp -(0.87 \quad d_p/2 \quad \lambda) \qquad (5)$$

The drag force (or Stokes' Law) can be written as:

$$F_d = 3\,\pi\,\eta\,d_p\,\omega_{th} \;(6)\; 1/\text{Co} \qquad (6)$$

where: η is the gas viscosity,

d_p is the particle diameter

Co is the Cunningham Correction

ω_{th} is the particle migration velocity

Assuming the fluid has no component acting towards the passive electrode and all particles achieve their saturation charge, then the equation of motion of a charged spherical particle in an electric field is characterised by:

$$\frac{d\omega_{th}}{dt} + \frac{3\,\pi\,\eta\,d_p\omega_{th}}{m\,\text{Co}} = \frac{Q^{\infty}_p\,E}{m} \qquad (7)$$

Taking $\omega = 0$ at $t = 0$, the solution to the above equation can be readily found :

$$\omega_{th} = \frac{Q^{\infty}_p E}{3\,\pi\,\eta\,d_p\omega_{th}} \times \text{Co} \qquad (8)$$

Since $Q^{\infty}_p = pEd_p^2$

then $$\omega_{th} = \frac{E^2 d_p}{\eta} \times \text{Co} \qquad (9)$$

The significance of this relationship is:

(1) As the limiting charge on the particle is proportional to the radius squared, theoretically the migration velocity of the particle will increase with particle size.

(2) Since the electric field is proportional to the applied voltage, the theoretical migration velocity ω_{th} is proportional to the voltage squared.

Although the foregoing portrays the theoretical approach to the migration of charged particles through an electric field, the derived Fig. 1 of theoretical migration velocity ω_{th}, should not be confused with the "effective migration velocity", see equation (1) above, which is derived from plant efficiency measurements and the specific surface area of the precipitator (V/A).

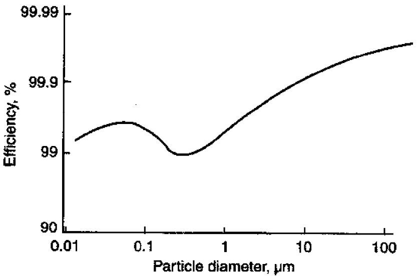

Fig. 1 ESP Fractionl Efficiency v Particle Size

The "effective migration velocity" derived from measured efficiencies and the specific collection area for the precipitator should more realistically be considered as a measure of precipitator performance rather than a measure of the average particle migration velocity.

Whichever approach is considered, the general trend of a much reduced migration velocity, based on a fractional efficiency, at around 0.5 micron is still apparent. The increase of efficiency for smaller particles being the result of Brownian Motion aiding in the charging and transfer of particles toward the collector plates.

3 PRECIPITATOR PERFORMANCE ENHANCEMENT BY CHANGING THE PARTICLE MIGRATION VELOCITY

To mitigate some of the expense of increasing the specific plate area of an existing precipitator, a novel computational methodology has been developed–the Proactive Approach to Low-Cost Precipitator Enhancements (PALCPE™)[2]. This approach combines many years of precipitator knowledge and expertise with advanced modelling to identify all performance upgrade options that are available.

The PALCPE™ programme includes the well recognised mathematical physics that describe the operation of the ESP and which are duplicated in the algorithms of the powerful ESPVI 4.0W model. The model, originally developed by the US EPA, when synchronized with the full-scale ESP, accurately duplicates its performance; for all-

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intents-and-purposes, the model is the precipitator and the precipitator is the model.

Particle collection in any precipitator is best described by the Deutsch Equation[3], which, in its scientifically rigorous form is applied to the model. The model's ability to duplicate space charge effects and the use of Deutsch are the keys to combining ESP experience and knowledge with expert modelling in order to perform the enhancement analysis. Fig. 2 indicates how a number of essential precipitation processes are duplicated within the model. The diffusion and field charging continuum is duplicated by dividing the size distribution within the model into 27 individual increments, for which each of the space charge contribution is computed. The continuing decrease in particle concentration, from inlet to outlet, is achieved by dividing the precipitator into individual length increments, upstream and downstream of each electrode element, where the incremental space charge is computed.

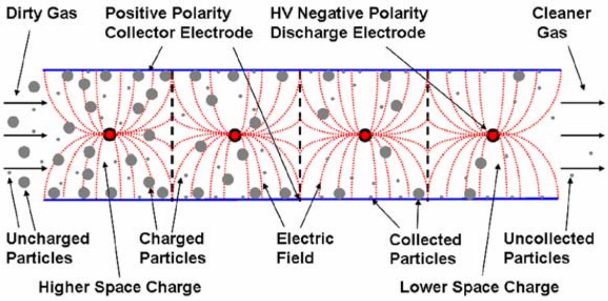

Fig. 2 Processes that occur within an ESP and the model

The model includes algorithms finding of solutions for Poisson's equation, which relates electric field and space charge. This allows the introduction of particle and ionic space charge, current and electrode geometry into the analysis. The model for given high-voltages, electrode configuration and particle characteristics, calculates a computed corona current for the performance prediction calculations, rather than the actual precipitator currents. By using different electrode element combinations or settings, virtually any electrode configuration in commercial use can be simulated. The modelled precipitator is divided into 2 length increments, one upstream and one downstream, for each electrode element. This allows space charge to be computed very rigorously, increment-by-increment and electrode-by-electrode. The rigorous computation of the space charge effect by the model allows it to actually match any corona current suppression, which causes the lower currents seen in the inlet sections of the precipitator.

Adjacent to the corona discharge electrodes the high electrical field ionizes the gas molecules, forming electrons and positive ions. The positive ions are immediately captured by the negatively charged electrodes, while the electrons start to migrate under the influence of the electric field into the inter electrode space. Within a relatively short time the electrons intercept gas molecules that are capable of forming negative ions. The majority of the negatively charged ions complete the journey to the collecting electrode, however, a small fraction of these negative ions transfer their charge to the particles in the gas stream.

The larger particles predominantly receive their charge by ion attachment (field charging), while the smaller particles receive theirs by collision with the ions (diffusion charging). Neither diffusion nor field charging dominates in the size range of approximately 0.2 μm to 0.8 μm; consequently the poor level of charge that they receive makes them more difficult to collect. The change in charging regime produces a collection penetration window in the particle size efficiency curve as shown in Fig. 1. The increase in efficiency for particles in the 0.1 micron range is the impact of Brownian Motion aiding the movement an collection of these size particles. The model computes the level of particle charge that each particle size acquires.

After the precipitator's physical size, gas flow and particle properties are entered into the model; the electrical characteristics of the discharge electrodes are determined by matching actual ESP generated air load VI curves to model generated ones. Air load data is primarily used to isolate the electrode's electrical characteristics from the particle space charge effects. Since the model's algorithms consider all discharge electrodes to be of a circular format, it is this matching of the site clean air curves, by changing the model's discharge electrode (DE) file, which enables, whatever actual format/profile is used on site, to be represented by a simple round wire or array.

The next operation is to determine the ash particle size and concentrations by carefully comparing the ESP's individual VI curves under actual operating conditions to ones generated by the model, using the now fixed DE data file. The identifying key is the change in space charge corona suppression, from inlet to outlet, for the full-scale to model generated curves for differing particle property settings. When the curves show reasonable agreement the model's particle settings represent those entering the precipitator.

At this stage it is now possible to calculate the performance of the precipitator under the plant's actual operating conditions of gas flow, temperature, particulate loading and electrical operation. Changes to the plant operating and physical conditions can then be applied in the model and the performance recalculated for each change. This approach then enables to most economic solution to enhancing the performance to be selected.

Although the traditional approach has been to increase the plate area, either as a series or parallel addition, this is expensive and can involve plant downtime for installation assuming adequate space is available; another approach has been to reduce particle resistivity, either by reducing the gas temperature, or injecting some form of conditioning agent.

As an alternative, however, considering equation (9), the theoretical evaluation of effective migration velocity, if the operating voltage can be increased, then since the value is proportional to the voltage squared the performance should be enhanced. Using the model, one can change the discharge electrode format to one having a less aggressive characteristic, that is, one having a lower emission characteristic, such that a higher voltage is required to achieve the same corona current, this, however, requires plant downtime to change the electrodes, or, as will be shown, to change the form of energization from a conventional rectified mains frequency unit to a high frequency DC, or SMPS, type of energization [4].

The development of SMPS type of energization goes back some twenty years and typically operate from a 3 phase supply using topology as indicated below (see Fig. 3).

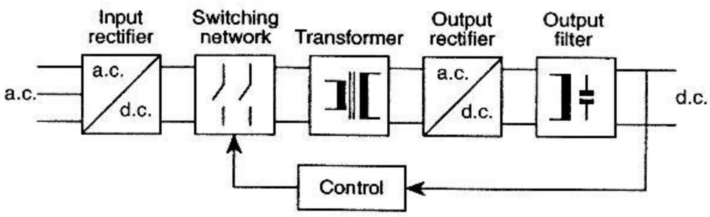

Fig. 3

In operation the DC from the input rectifier is switched to a high frequency to feed the transformer. The major advantage of this is that, for a normal 50 Hz supply the switching time is 100 milliseconds, whereas with say a 35 kHz supply the switching time is -140 microseconds, this enables a much closer control of flashover with an extremely fast spark recovery.

This results in the optimum field voltage being increased significantly, because of the small voltage ripple and minimum time loss in flashover recovery, thereby providing a significant improvement in ESP efficiency. This approach has been a hot topic over recent years; however, the practical experience with SMPS has unveiled some areas that have needed to be improved. The main concerns have been associated with operating reliability, cooling issues and the interaction between the ESP load and the SMPS Unit itself. Flexibility in power and voltage ratings has also been an issue with some existing designs.

The two first concerns from the market, i.e. reliability and cooling issues, are closely connected. At APP, cooling is recognised as one of the main challenges to provide longevity. Liquid cooling for the IGBT's, inductors and HV transformers has been incorporated in the design as this is considered the most robust and cost effective cooling method for power electronics and for SMPS usage.

To overcome flexibility in power and voltage ratings a modular design has been chosen. One module has one specific output power level and by connecting modules in parallel, all power needs can be served. Each module can be designed for different output voltage levels, so that almost any thinkable ESP configuration can be accommodated by the modular approach. The modular concept is also important when concerning reliability, since if one module fails, the remaining modules may still ensure uninterrupted ESP operation, albeit at a possible restricted current level.

In order to achieve this modular design, certain technical challenges must be handled. Parallel connection is required and the SMPS must not have any interaction with the load concerning its control or stability. It must also be stable and self-protective regardless of load. This was achieved by choosing a hard switching approach. The traditional disadvantage/supposition against hard switching is that switching speed is limited because of the high leakage reactance with the high voltage transformer. By hard and focused work over a number of years, APP has developed a patented fast transformer design that removes this limitation. The APP ModuPower runs efficiently at a switching frequency of 35 kHz.

The fast response of an SMPS is an inherent property set by the switching frequency. The challenge is to have a control system able to produce a fast and safe response to any disturbance. In each power module a powerful microcontroller is present which directly controls every switching transient of the IGBT's. The regulation speed can be controlled very accurately and response times can be trimmed towards the limits given by the switching frequency.

The design and operating characteristics of the following case study ESP were used as the model computer inlets and measurements of the cold air electrical characteristics were matched on the model using an equivalent discharge element diameter of 3.5 mm at 300 mm spacing. The curves produced from the model gave reasonable agreement with the site cold

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air figures, so one can proceed with determining the performance of the ESP under current operating conditions of temperature, particulate loading etc.

Under mains rectified energization, optimum performance occurs at the breakdown voltage of the precipitator, i.e. peak kV, however, since corona current is being drawn the voltage waveform exhibits a considerable ripple, which reduces the mean operating kV. With high frequency SMPS operation, which is very much like pure DC energization, there is minimum ripple on the waveform, while the flashover voltage condition remains the same, and hence the actual mean operating voltage is higher which results in an enhanced performance. Using the characteristics of the case study ESP applied as inputs to the model, the waveforms produced from conventional and SMPS energization is shown Fig. 4.

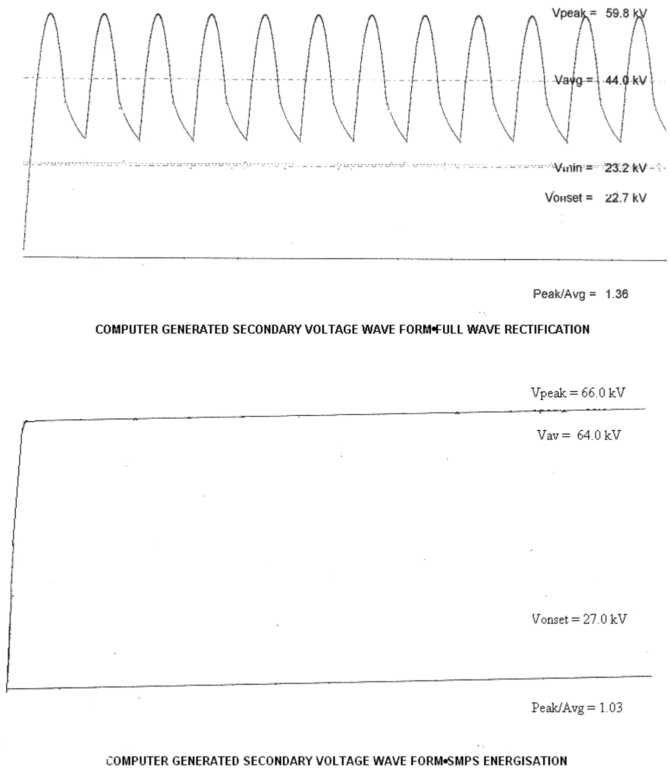

Fig. 4 Comparison of Outlet Field Voltages under Normal and SMPS Operation

Using the case study data as the model inputs, the relative emissions under the two energization approaches produces evaluated figures of 28 mg/Nm^3 for the AC rectification and 15 mg/Nm^3 with the outlet field energised by the SMPS Unit. The emission of 15 mg/Nm^3 is that obtained from the model operating at the same present average kV of 47.3 kV, whereas in practice, because of the current limiting and hence restricted kV situation with the present outlet field TR, then under SMPS operation the average voltage should be much higher, which will further enhance the collection efficiency.

Since the outlet field TR is operating below optimum, because of the current limiting situation, it was agreed that in the first instance only the outlet field TR be changed to SMPS operation. Running the model with the outlet field under DC operation at the same operating voltage gives waveforms as indicated in Fig. 2 above. This shows that under DC operation there is an increase in the average operating voltage of 7.7 kV, or an increase of -20%, which is reflected in a much enhanced collection efficiency, producing an emission figure of 15 mg/Nm^3 as against the original model evaluated figure of 28 mg/Nm^3.

Fig. 5, indicates the change in particle penetration for the above cases, of particular interest is the significant reduction in penetration efficiency for the smaller sized particles. Although the increase in operating voltages results in an increase in the collection efficiency of the larger particles, the change is small compared to the increase in the sub micron sized particulates.

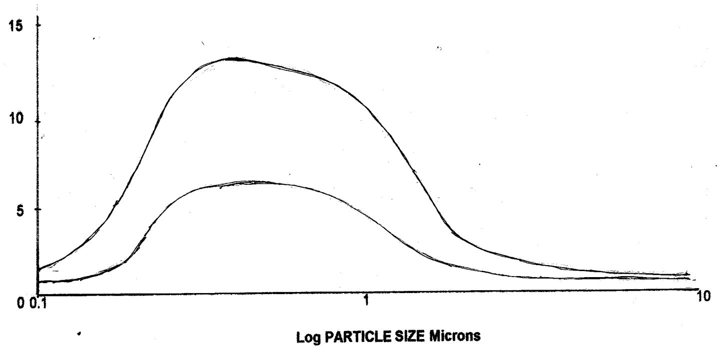

Fig. 5 Change in penetration (1-efficiency) resul ting from change in enerfization

4 CASE HISTOR

To validate the approach a plant was selected which has a sea water scrubber following the ESP and has a strict discharge limit of 1 tonne per annum of zinc in the discharge effluent which is returned to the fjord. The plant is anxious to recycle as much of its waste materials as possible, but as the level increases, so does the heavy metal carryover into the scrubber, which is in conflict with the plant needing to satisfy their discharge limit. The zinc arrives at the scrubber as sub micron zinc oxide particles and to increase the performance of the ESP fine particle collection it was agreed, based on the above evaluation, to replace the outlet field energization system with an SMPS Unit.

The actual process involved in the exercise is the production of Bentonite Pellets for subsequent use in an Electric Arc Furnace. The raw material is initially ground in a ball mill and then drum pelletized and screened to give pellets of ~ 10 mm diameter. These pellets then pass onto a 4 section sintering grate, where they are progressively heated with coal as a reducing agent to reach a temperature of around 1250 deg C before passing into a kiln for final hardening and cooling.

The off gases from the grate and kiln are collected and after passing through a cyclone, to remove the larger particles for recycling, then enter a two field precipitator to remove most of the particulates and are finally passed through a packed bed sea water scrubber to remove any sulphur dioxide before being discharged to atmosphere.

The ESP is of a conventional design having two series fields each containing 35 collector plates 4.5 m long x 9.6 m high with a collector spacing of 400 mm. The discharge electrode format is a conventional spiked tube having rather aggressive corona characteristics. The fields are currently energized by individual TRs rated at 110 kV pk at 1100 mA.
The design gas flow rate at 245 deg C is 106 am^3/s and the SCA is 56.8 m^2/m^3/s. For an inlet particulate loading of 2.43 g/Nm^3 the measured emission is 25 mg/Nm^3.

During operation, although the emission guarantee is generally satisfied, the outlet field TR operates at current limit, whereas the inlet field operates satisfactorily just below current limit with an acceptable rate of flashover. With the strict discharge limit on zinc in the scrubber effluent the Client is seeking a cost effective approach to enhance the collection efficiency, particularly of the finer particles primarily consisting of the heavy metals.

5 TEST RESULTS

With the Tinfos plant arrangement, there is no ideal test location on the outlet ducting of the ESP, since it goes directly into the ID Fan and then into the packed bed seawater scrubber, so the overall plant performance has to be based on stack emissions. As far as the Client is concerned, these results are pertinent to his operating permit. The stack emission measurements were carried out at a level some 30 metre above the ground, and were made using an Electrical Low Pressure Impactor (ELPI), the principle of which is that the gases entering the impactor are initially passed through a corona charging field before entering a low pressure impactor having a cascading series of electrically isolated low pressure stages. The electrical current, carried by the charged particles for each stage of the impactor, is then measured in real time by a sensitive multi-channel electrometer. The measured current signal is directly proportional to the particle number and size, while the aerodynamic particle diameters are determined by weighing catch on each stage of the impactor.

The results of the measurements taken on the 16th June, around midday, are shown in the attached figure. These measurements were carried out under normal mains energization of the ESP, with the inlet field operating at 59 kV and 800 mA and the outlet field at 46 kV and 1100 mA (TR current capacity). This curve shows a fairly normal particle size distribution following a precipitator where there is a penetration window around the 0.5 micron diameter, see Fig. 6 The higher levels in the sub 0.1 micron diameter are due to condensation following the scrubber.

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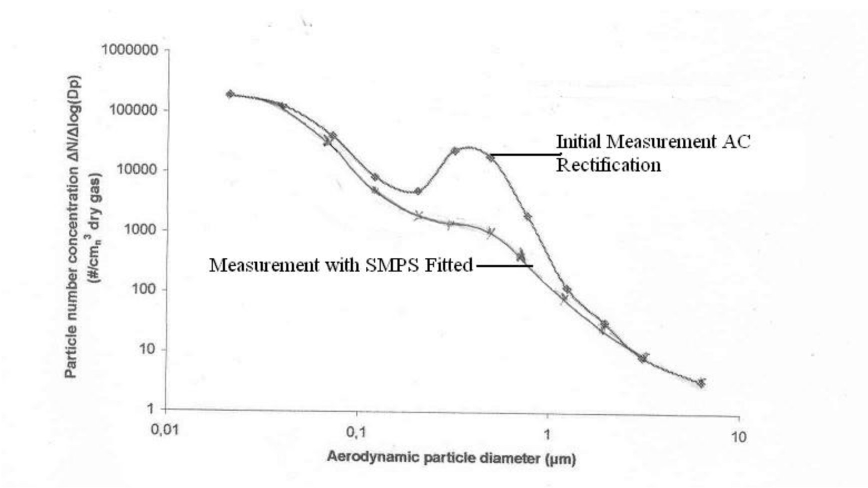

Fig. 6

A further set of measurements were taken after the outlet field TR had been replaced by an SMPS Unit, these for comparison are also included in the attached curve. From the results with SMPS Operation there is a notable shift in the sub micron range penetration as predicted from the modelling and confirm that the higher voltage and current improve the particle collection in the 0.8-0.2 particle size range.

6 CONCLUSIONS

The initial concept of using the PALCPE Programme to assess the various enhancement scenarios has resulted in a cost effective method of enhancing the performance of the existing precipitators, particularly in the sub micron range.

Although no actual precipitator outlet measurements were possible, because of an unavailable test location following the ESP, the results of the stack measurements indicate that there has been a significant reduction in the sub micron range of particles and confirm that the modelled emission of < 15 mg/Nm^3 has been satisfied.

While the SMPS measurements were carried out with the voltage held at the same level as the AC peak rectified voltage, the SMPS Unit has more capacity in hand and it is proposed to explore this at a later date.

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