

# The Development and Testing of a Small Scale Dry Electrostatic Precipitator for the Removal of Particulate Matter

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## NOMENCLATURE

**Abstract**—This paper presents a small tube/wire type electrostatic precipitator (ESP). In the ESPs present form, particle charging and collecting voltages and airflow rates were individually varied throughout 200 ambient temperature test runs ranging from 10 to 30 kV in increments on 5 kV and 0.5 m/s to 1.5 m/s, respectively. It was repeatedly observed that, at input air velocities of between 0.5 and 0.9 m/s and voltage settings of 20 kV to 30 kV, the collection efficiency remained above 95%. The outcomes of preliminary tests at combustion flue temperatures are, at present, inconclusive although indications are that there is little or no drop in comparable performance during ideal test conditions. A limited set of similar tests was carried out during which the collecting electrode was grounded, having been disconnected from the static generator. The collecting efficiency fell significantly, and for that reason, this approach was not pursued further. The collecting efficiencies during ambient temperature tests were determined by mass balance between incoming and outgoing dry PM. The efficiencies of combustion temperature runs are determined by analysing the difference in opacity of the flue gas at inlet and outlet compared to a reference light source. In addition, an array of Leit tabs (carbon coated, electrically conductive adhesive discs) was placed at inlet and outlet for a number of four-day continuous ambient temperature runs. Analysis of the discs' contamination was carried out using scanning electron microscopy and ImageJ computer software that confirmed collection efficiencies of over 99% which gave unequivocal support to all the previous tests. The average efficiency for these runs was 99.409%. Emissions collected from a woody biomass combustion unit, classified to a diameter of 100  $\mu\text{m}$ , were used in all ambient temperature trials test runs apart from two which collected airborne dust from within the laboratory. Sawdust and wood pellets were chosen for laboratory and field combustion trials. Video recordings were made of three ambient temperature test runs in which the smoke from a wood smoke generator was drawn through the precipitator. Although these runs were visual indicators only, with no objective other than to display, they provided a strong argument for the device's claimed efficiency, as no emissions were visible at exit when energised. The theoretical performance of ESPs, when applied to the geometry and configuration of the tested model, was compared to the actual performance and was shown to be in good agreement with it.

**Keywords**—Electrostatic precipitators, air quality, particulates emissions, electron microscopy, ImageJ.

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AAQ	Ambient Air Quality
$A_c$	Collecting electrode surface area ( $\text{m}^2$ )
$A_{in}$	ESP charging cylinder inlet area ( $\text{m}^2$ )
CAL	Clean Air London
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
$C_c$	Cunningham slip correction factor (dimensionless)
$C_u$	Cunningham correction factor
$d_p$	Particle diameter (m)
$E$	Electric field strength (V/m)
EN	European Standards
ESP	Electrostatic Precipitator
IEA	International Energy Agency
IAQ	Indoor Air Quality
HVAC	Heating, Ventilating & Air Conditioning
kVdc	kilo-Volts direct current
NTP	Normal temperature and pressure
PM	Particulate matter
$Q$	Gas flow rate ( $\text{m}^3/\text{s}$ )
SEM	Scanning Electron Microscope
$T$	Temperature (K)
$W_e$	Drift velocity (m/s)
$\epsilon_0$	Permittivity of free space ( $8.85 \times 10^{-12}$ ) (F/m)
$\mu_f$	fluid Viscosity (kg/ms)
$\eta_{esp}$	ESP collection efficiency (%)
$\lambda$	Mean free path between collisions (m)
$\rho_a$	Air density ( $\text{kg}/\text{m}^3$ )

## I. INTRODUCTION

FINE dusts of diameters less than/equal to 2.5  $\mu\text{m}$  have seriously harmful effects on our cardiovascular system when inhaled. These particles become embedded deep within the lungs thus reducing the available area for gaseous exchange. Ultra-fine particles can pass into the blood system, which carries them to the heart and around the body. Analyses have shown that traces of heavy metals and organic carcinogens form part of the total distribution of these particulates.

According to the report published in 2013 Clean Air London (CAL) [1], the quality of air in urban areas can be worse inside buildings, such as; hospitals, schools, offices and departmental stores, than outside. The most common forms of pollution at and above molecular level are fine and ultrafine particulate matter,  $\text{PM}_{2.5}$ , including particulates emitted from traffic exhausts, power stations, and bio-aerosols. Theodore [2] defines PM as *solid or liquid matter having an effective*

diameter larger than a molecule but smaller than 1000  $\mu\text{m}$ . In addition, tobacco smoke, asbestos, and silica dusts also contribute to the overall dispersal. Without filtration, 50% and above of air pollution found indoors comes from outside.

The World Health Organisation published a report in 2010 titled '*WHO guidelines for indoor air quality' (Selected Pollutants)* [3]. While Ambient Air Quality (AAQ) assessment typically focuses on particle mass concentrations and gases, there is increasing concern among scientists about the health impact of higher particle number concentrations and surface area among smaller particles.

British and European standard BS: EN 13779:2007 states that ambient air quality has a direct effect on indoor air quality, therefore different grades of particle filters are selected for the ventilation inlets of non-residential buildings, depending on location, to meet specific targets. In cases where ambient air exceeds the EU limit by 50%, two-stage particle filters are required to reduce ingress of 0.4  $\mu\text{m}$  diameter particles by at least 80% [4].

A study conducted by the EU air quality and emissions policy committee concluded that: as buildings become virtually 'airtight' in order to improve energy efficiency, it becomes increasingly important to install efficient air filtration devices as a minimum requirement and as part of their ventilation systems [5].

CAL found that only seven buildings in Transport for London's 'Head Office Portfolio' were due to comply fully with EN 13779 by April 2012 with eight others in 2012/2013 and many more having no expected compliance date [6]. There is, however, no mention of health and safety issues concerning air pollution in the portfolio section headed challenges [7]. The investigation should consider buildings with existing mechanical ventilation and others where standalone or ducted air filtration may be needed. There are tremendous opportunities for improving public health, and at the same time, saving energy in the running of these buildings providing the balance is right between the ethical and commercial interests. All this can be achieved by installing the most suitable systems which comply fully with EN 13779 and that they are regularly maintained.

From the foregoing discussion, it is reasonable to assume that there is much room for improvement in raising the standard of air quality throughout the non-residential buildings in our cities. Despite the fact that doing nothing is not an option there seems to be two common statements given out by some authorities and they are: "that's not my responsibility" or "we simply cannot afford it". In fact, it is everyone's responsibility to a greater or lesser extent. The financial costs could be outweighed by costs of sick days, chronic respiratory and cardiac illnesses and the increased burden these put on the Public Health System.

The dispersal rate of PM, under the influence of gravity and atmospheric conditions depends, to a great extent, on particle size. The larger particles settle at or close to source. Fine particles, 10  $\mu\text{m}$ , remain suspended for much longer and are carried further afield. Ultra-fine particles, 1.0  $\mu\text{m}$ , tend to remain suspended in air which is of greatest concern to

environmentalists and public health authorities. These particles are transported on winds way beyond source and in cities will be carried to the rooftops on up draughts.

Another possible contributory factor to overall pollution from solid and liquid particles is nucleation, according to Wurzler et al. [8], which is cyclical by nature. In effect, dusts can provide nucleation sites for water vapour in the atmosphere to form clouds. These dusts remain as the vapour condenses to form rain and stay within the droplets during precipitation. The assumption which can be drawn from this is that: once on the ground or other solid surfaces evaporation will eventually take place leaving settled, dry dust particles to be re-entrained by air movement. Settlement on water can lead to either re-entrainment during evaporation or pollution in the body of water.

A further disturbing reasonable assumption is that fine particles will be drawn into the air intakes of Heating, Ventilating, and Air Conditioning units, and if not captured as part of the air conditioning system, can be delivered throughout the building. Many multi-story buildings tend to have the air intakes of HVAC equipment housed on their roofs. Unfortunately, this may not be the ideal place if there is no, or an inadequate, PM control and captivation system in place.

A number of methods are employed to control and capture PM which includes separation by cyclonic centrifugal forces, impaction systems such as bag-houses and the use of electrostatic forces. These methods are predominantly designed to capture particles from enclosed sources such as power stations, manufacturing and metal processing facilities before they reach the open air. Even so, no system is 100% effective which implies that some pollutants do escape and add to natural and other manmade pollution extant in the atmosphere from outdoor activities. Clearly, there are no defined points of reference where outdoor pollution can be captured directly at source therefore the aim should be to capture it as close as possible to sources. Fine and ultrafine emissions generated in urban areas do reach rural areas and are found in soil samples from where they are taken up by plant life together with nutrients. This is an area of concern which emphasises the need for pollution control. Conversely, stray emissions from dust producing rural activities, such as cereal crop harvesting, do reach urban areas indicating that all communities have a role to play in reducing pollution.

The use of electrostatic forces to separate particulate matter from flue gases is not new [9] with the basic principles of ESP operating systems having remained unchanged. Efficiencies, however, have improved especially since the arrival of computers by which fully automated proactive control systems were introduced. In addition, Computational Fluid Dynamics (CFD) offers designers a more cost effective research and development method than was previously possible. Collection efficiencies, in some large industrial applications and power plants, are now higher than 99.9% [10]. Irrespective of ESP plant size and geometry they all rely on PM, en masse, being capable of receiving and holding an electrostatic charge long

enough for them to migrate to and be captured by a collecting surface.

## II. OPERATING PRINCIPLES OF ESPs

All ESPs operate basically in the same way. Incoming PM receives an electrostatic charge which causes it to migrate to one or multiples of oppositely charged or grounded collecting surfaces. The PM agglomerates and builds up on the collecting surface where it remains until systematically removed by mechanical means such as rapping. During removal, the 'caked' PM falls, en masse, into storage hoppers except for a significant amount which becomes re-entrained in the gas flow. In single section, ESPs re-entrained particles are carried through and into the atmosphere. In order to meet specified emission targets, some precipitators are built having two or more sections aligned in series. Each section reduces re-entrainment until the specification is met.

Fig. 1 shows a typical ESP arrangement used in power stations. For economic and restricted space reasons, this wire/plate configuration is not, generally, suitable for smaller scale combustion units as shown in the paper of Pettersson and Strand [11] or HVAC installations in small commercial buildings. The acceptable preference to date seems to be the tube/wire type ESP having a variety on geometries as discussed throughout the remainder of this paper which are equally suitable for collecting PM at ambient or combustion temperatures. The majority are, so called, single stage ESPs where particle charging and collection take place within the same space. Other models have a wire type PM charging electrode in a section preceding that of precipitation or a flat charging grid spanning the precipitator's inlet. These arrangements can work efficiently at capturing PM but none of them prevent re-entrainment to any significant extent. Rapping, which is the mechanical procedure for removing the build-up of particulates on the collection surfaces, is the main cause of re-entrainment. Anomalies such as PM rebounding off the collecting surfaces [12], back corona discharge and loss or reversal of charge on contact with the collector have also been observed by researchers resulting in a reduction of the overall efficiency of the system.

## III. DEVELOPMENT OF A TUBE/WIRE TYPE ESP

### A. Overview

In this study, a model is discussed which shows how the re-entrainment problem was significantly overcome. A particulate repelling function was applied to simple single and two-stage tubular precipitators. This is a novel feature comprising a stainless steel fine wire mesh tube positioned centrally and axially within the collecting cylinder with its open top sealed round the top plate outlet and the bottom blanked off. Fig. 2 illustrates the geometry of a two-stage laboratory demonstration unit. The mesh receives a constant negative charge which repels the negatively charged PM but allows uncharged gases to pass through. The principle is based on Jonassen's findings that 'gases do not charge' [14]. Throughout trial runs, gas permeation remained constant and

pressure between the precipitator's inlet and outlet remained the same. It was observed that some charged particles are rod shaped, bipolar and smaller in diameter than the 300  $\mu\text{m}$  mesh apertures. Early concerns were that these may not respond favourably to the repelling mechanism and could pass through the mesh, thus reducing the collecting efficiency. However, close inspection after shutdowns revealed that bipolarity is not a serious issue. Rods were found on the outside of the mesh wires protruding at right angles to them. No rods were found on the inside of the mesh (the clean side); they remained in place until removed by the cleaning process or until all electrostatic charges had dissipated.

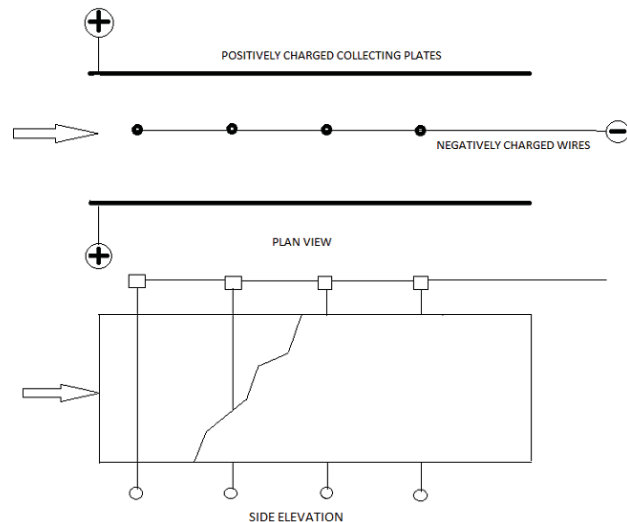


Fig. 1 Typical power station electrostatic precipitation arrangement [13]

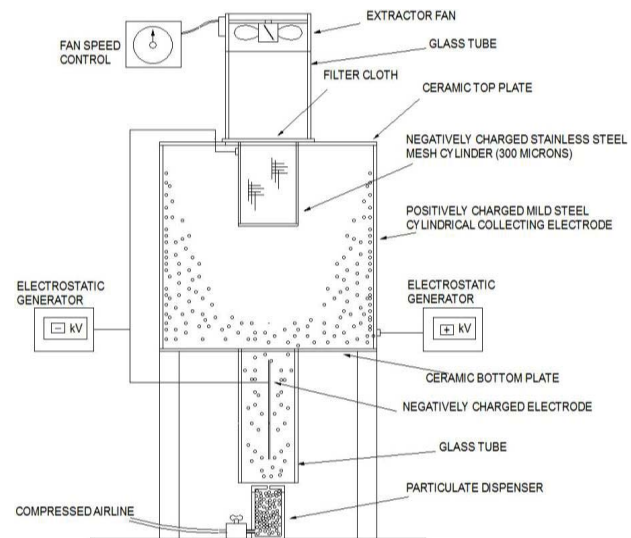


Fig. 2 Schematic of the test rig for dry PM

### B. Functional Aspects of the Design

A particulate reservoir/dispenser is connected to a regulated compressed air supply that is used to slightly pressurise it and

agitate the PM which discharges through a small aperture in the lid. On leaving the dispenser, PM together with ambient air, is drawn into the bottom glass tube containing a wire electrode to which a high voltage negative charge is applied. On entering the collecting cylinder, the PM migrates to the oppositely charged cylinder wall. The negatively charged mesh cylinder repels the PM and, at the same time, assists migration. The gases, having no charge, pass through the mesh cylinder unhindered. An additional contributory factor aiding PM migration to the collector and efficiency is the reduction in velocity due to the difference in cross sectional areas between the charging tube and the collecting cylinder. Large particles tend to be captured towards the bottom of the collector and the very finest at the top. This was verified by comparing the diameters of samples taken at five points along the collecting cylinder's length. This may be an indicator that the reduction in velocity mentioned earlier together with the repelling effect of the mesh could be significant contributing factors to the unit's efficiency, particularly in collecting the very fine particles. An optical microscope with a calibrated graticule was used for sizing the coarser PM and images from scanning electron microscopy for the finer ones.

### C. Variables Controlling the Performance of the ESP

#### 1. Power Input to the Electrostatic Generators

During 200 ambient temperature laboratory test runs, voltages on the charging electrode, collecting electrode and mesh cylinder are collectively varied between 10 kV DC and 30 kV DC in steps of 5 kV. Additional sets of tests were carried out with the same range of negative voltages applied to the charging electrode and mesh cylinder but with the collecting electrode grounded. There was a significant drop in efficiency during these test runs and, as a consequence, this option was not pursued further. Power consumption of the static generators varied slightly but did not exceed 38 W throughout 200 test runs.

#### 2. Gas Flow Rates

Gas velocities entering the particle charging section ranged from 0.5 m/s to 1.5 m/s, controlled by varying the extractor fan's rotational speed and verified by readings taken at inlet using a hand-held anemometer.

#### 3. Performance Analysis of the ESP

200 test runs were carried out under ambient conditions. Eight runs were completed at each air velocity and at the five set voltages. Fig. 3 shows the average efficiencies achieved at each of the five set voltages and range of inlet air velocities.

#### 4. PM Input Size Distribution as Verified by Scanning Electron Microscopy

The particulate dispenser holds PM classified from 100  $\mu\text{m}$  down, however, the main concern is with the precipitator's performance in capturing particles having maximum diameters of 20  $\mu\text{m}$  ( $\text{PM}_{20}$ ).

#### 5. Determining Collection Efficiency

Mass balance was used to calculate efficiencies. The PM reservoir and filter cloths were weighed prior to and again on completion of each test run.

In addition to the mass balance method, a small number of ambient temperature test runs were performed, with the filter cloth removed, using arrays of carbon coated adhesive tabs positioned at inlet and outlet. Comparisons of PM build up were made, using scanning electron microscope images and ImageJ software. A 0.06 mm<sup>2</sup> area of an inlet tab is shown in Fig. 4 and a typical particle count and size distribution at inlet and outlet shown in Table I. Both illustrations show a high proportion fine PM, (<10  $\mu\text{m}$ ) which are the most harmful to human health and the environment.

Collection efficiencies over the range 0.1  $\mu\text{m}$  to 20  $\mu\text{m}$  are shown in Fig. 5.

During 4-day continuous test runs inlet velocities were set at 0.8 m/s but fluctuated between 7 and 9 m/s due to varying external conditions. The electrostatic generator voltages were set at 20 kV negative and 20 kV positive.

Fig. 5 depicts the ESP's collection efficiency for the particle size range  $\text{PM}_{0.1}$  to  $\text{PM}_{20}$  after a typical 4-day continuous test run.

The average collection efficiency for this run was 99.409 %.

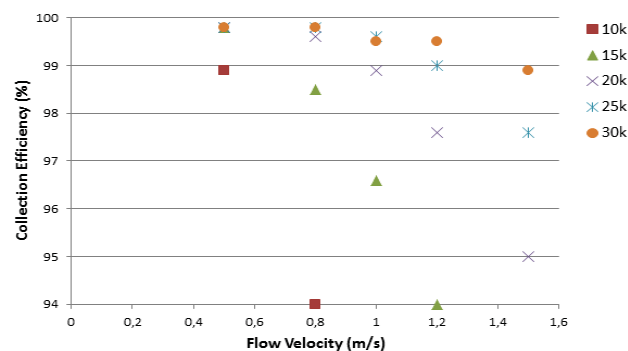


Fig. 3 Variation of collection efficiency with air velocity

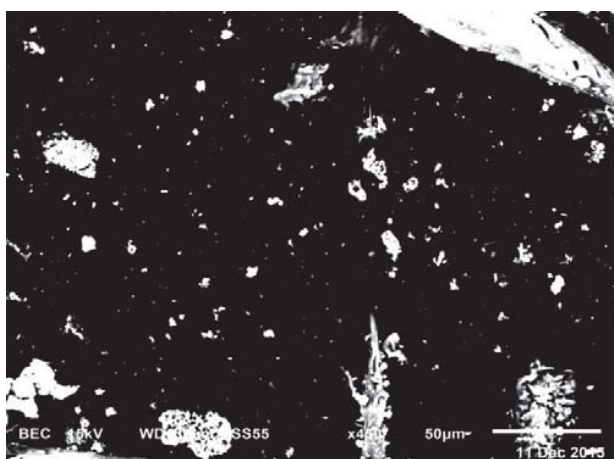
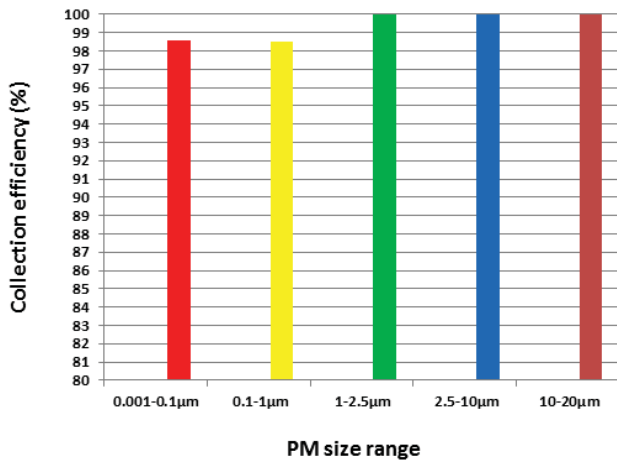


Fig. 4 Sample inlet image taken from SEM



Fig. 5 Collection efficiency for each size from PM<sub>0.1</sub> to PM<sub>20</sub>

#### IV. THEORY OF ESP

##### A. Theoretical Model

The theoretical model has the same geometry and is of comparable size to the tested model. It should be emphasised

that the theoretical model's exceptional performance is due to the ideal conditions under which data were presented.

Simulated applied voltages, air velocities, and particle size distribution matched those of the actual demonstration model which allowed comparisons to be made between theoretical and experimental test runs. Theoretical results were also based on an average particle diameter of 5 µm, which was the mean diameter of the particles in the actual test sample. See Table II.

##### B. Particle Migration

Due to the harmful nature of fine and ultrafine PM, the theoretical behaviour of those within that range is of particular interest. To this end the following assumptions and conditions apply in this analysis.

Operating temperature is 21°C±1. Particle size limit is 5µm (PM<sub>5</sub>). The particles are in random, Brownian, motion within the system and are charged by diffusion and bombardment (field charging). All particles are dry and have ideal resistivity. The electric field strength between the charging and collecting electrodes and charge saturation of the particles prevail throughout the precipitator.

TABLE I  
PM DISTRIBUTION ON INLET AND OUTLET TABS

Particle diameter (µm)	PM0.001-0.1	PM0.1-1	PM1-2.5	PM2.5-10	PM10-20
Inlet tab 1	44	92	69	47	12
Inlet tab 2	89	38	33	52	14
Inlet tab 3	6	2	6	4	1
Outlet tab 1	1	0	0	0	0
Outlet tab 2	0	0	0	0	1
Outlet tab 3	1	2	0	0	1
Inlet size distribution (%)	27	26	21	20	5

TABLE II  
INPUT DATA FOR THE THEORETICAL MODEL

Parameter description	symbol	value	units
Temperature	T	293	(K)
Dynamic viscosity	$\mu_f$	1.81E-05	(kg/ms)
Area of collector	$A_c$	0.5429	(m <sup>2</sup> )
Area of the ESP charging inlet	$A_m$	0.00502	(m <sup>2</sup> )
permittivity of free space	$\epsilon_0$	8.85E-12	(F/m)
Mean diameter of particle	$d_p$	5E-06	(m)
wire to plate distance (m)		0.14	(m)
Mean free path (air)	$\lambda$	6.8E-08	(m)
Cunningham correction factor	$C_c$	1.045	(Dimensionless)

The resultant particle velocity towards precipitation, i.e. particle migration or drift velocity ( $W_e$ ), is calculated using a modification to Stokes' Law which includes the parameter known as the Cunningham Slip Correction Factor ( $C_c$ ).

$$W_e = C_c E^2 \epsilon_0 \frac{d_p}{\mu_f} \quad (1)$$

where

$$C_c = 1 + \frac{\lambda}{d_p} \left[ 4 + 1.05 e^{\left( -0.39 \frac{d_p}{\lambda} \right)} \right] \quad (2)$$

The slip factor for the different flow behaviour of these particles regards the surrounding gas molecules as individuals rather than a continuum. The factor is dependent on pressure, temperature, particle size (m), and mean free path between collisions ( $\lambda$ ). According to [13], a typical value of ( $\lambda$ ) for air is 0.066 µm.

Fig. 6 graphically presents a range of correction factors as a function of particle diameters. The curve levels out for particles having diameters larger than 0.7 µm, but it shows the importance of  $C_c$  for finer PM.

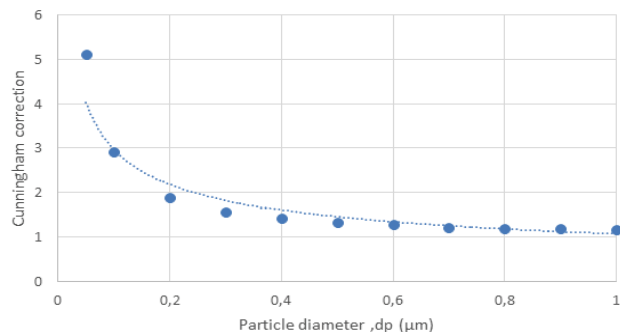


Fig. 6 Variation of Cunningham factor with particle diameter

### C. Collection Efficiency

The theoretical collection efficiency of electrostatic precipitation systems can be modelled by the Deutsch-Anderson equation.

$$\eta_{esp} = 1 - e^{-W_e \frac{A_c}{Q}} \quad (3)$$

where  $A_c$  is the collector's surface area ( $m^2$ ), and  $Q$  is the volumetric flow rate of the gas ( $m^3/s$ ).

### D. Theoretical Performance of a Small Tube/Wire ESP

The resulting theoretical collection efficiency as a function of flow velocity is shown in Fig. 7.

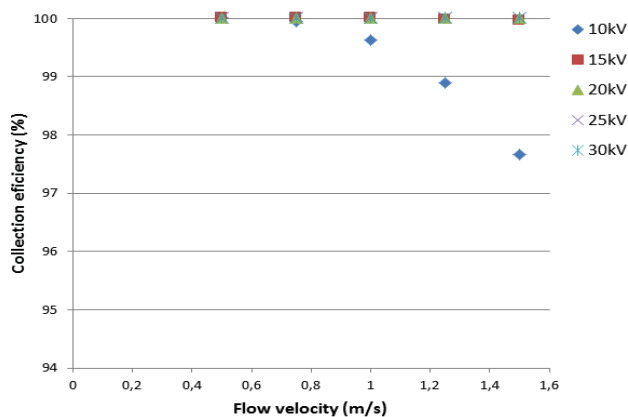


Fig. 7 Theoretical ESP efficiency

### E. Comparison of Actual Performance to Theoretical Results

The theoretical model was assumed to be working under ideal operating conditions including geometry, uncontaminated charging/collecting electrodes, and environmental conditions. The theoretical particulate matter was given ideal resistivity for the most efficient collection i.e.  $10^{10}$  to  $10^{11}$  Ohm.cm and was classed as spherical,  $\mu_f$  was air at ambient temperature and  $\rho_a$  remained constant.

Like-for-like comparison between the tested and theoretical model cannot be made due to introduction of the repelling mesh cylinder. No theoretical or other actual models have this feature.

Other dissimilarities between theory and practice include random ingress of surrounding particulate matter, inconsistent environmental conditions on test days and increasingly contaminated electrodes after the first test run of each set. On reflection, the difference in the overall efficiencies between the tested and theoretical models can be attributed to these varying conditions as would be expected. However, the mesh cylinder seems to be a major influence in significantly reducing the amount of re-entrained PM that would otherwise pass through to atmosphere; which is inherent in other models.

#### 1. Theoretical Model

The theoretical model shows that, given overall ideal conditions, it is possible for tube/wire precipitators to have

collecting efficiencies >99% for input voltages of 15 to 30 kV and input air flow velocities >0.5 m/s. Given input voltages  $\geq 20$  kV and air velocities of between 0.5 and 1.5 m/s the efficiency approaches 99.99%. At 10 kV, a rapid fall in collection efficiency is indicated with increasing air velocity.

#### 2. Actual Model

The test results confirm that efficiencies in excess of 99% are achievable at voltages of between 15 and 30kV over an air velocity range of 0.5 to 1.5 m/s, even when taking into consideration fouling and wide variations in PM population within the system. At lower voltages and air velocities in excess of 0.5m/s collection efficiencies decrease. However, collection efficiencies in excess of 95% are possible at 1.5 m/s with a 20-kV input voltage.

There are discrepancies between theoretical and actual performance, but these are less pronounced than would be expected in models not having the repelling mesh cylinder.

### V. COMMERCIAL BENCHMARK

In order to establish whether the new design is worthy of further research, development and possible commercialisation, its performance was briefly compared to other small scale ESPs.

Readers are referred to a survey coordinated and prepared by "Bios Bioenergiesysteme" GmbH in cooperation with Graz University of Technology in Austria [15]. The object of the survey was to test the performance of 12 small scale ESPs which were all of similar size and performance duties and to report on the findings. Three of the units, at the time of testing, were commercially available and four about to enter the market. Some of the remaining five, still in the development stage, were tested 'in house'. The results were submitted and included in the survey.

In the "Conclusions and Recommendations" section of the 100-page survey, it was strongly recommended that further development work in the field of small scale electrostatic precipitation was needed. It was also highlighted that standardised test procedures need to be put in place to a European Technical Specification. With the lack of such standards, it would not be expedient to compare the survey's findings directly with those in this paper. However, as an indication of comparability, it was stated that: 'general mean total dust precipitation efficiencies of 50 to 85% can be achieved'.

An assumption can be made with regard to the performance discrepancies between those in the above survey and the model discussed in this paper. It could be attributed to the contribution to efficiency made by the repelling action of the mesh cylinder.

### VI. CHEMICAL ANALYSIS OF PM AT THE SYSTEMS ENTRY AND EXIT POINTS

The chemical analysis of PM entering the precipitator during one 4-day continuous ambient test run in the laboratory is shown in Fig. 8 (a). Fig. 8 (b) highlights the composition of particulates present at the exit to the system.

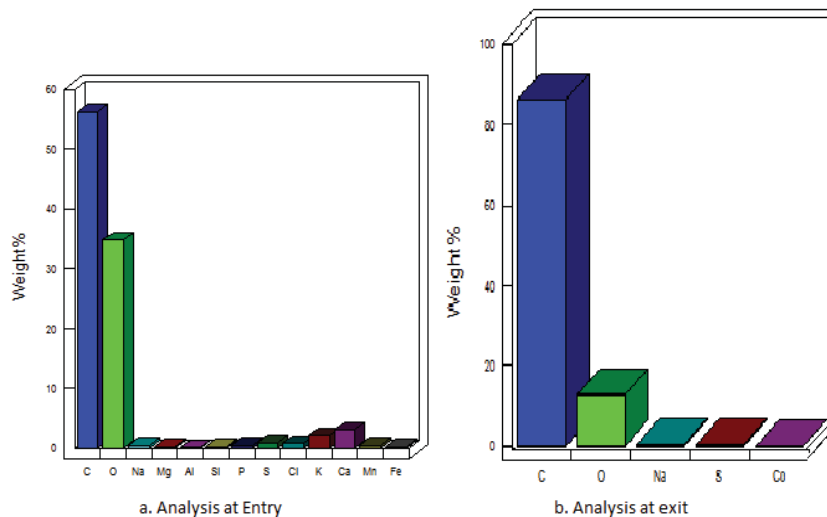


Fig. 8 Chemical analyses of particulates at entry (a) and exit (b) from the system

The high carbon content is due to a number of identified reasons.

- 1) The SEM is unable to discriminate between the carbon PM and the background adhesive carbon coating on the Leit tabs.
- 2) Running an electron beam over the samples causes carbon to be deposited on the tabs.
- 3) Carbon is found on the focusing window of the instrument. The high oxygen content is attributed to PM surface oxidation.

The trace of cobalt on the exit tab, not found on other tabs, is considered to be contamination from within the laboratory during preparation.

An SEM – JEOL JSM 6610V variable pressure scanning electron microscope with Oxford Mmax50 X-ray EDS system was used for this analysis.

## VII. CONCLUSIONS

### A. Outcome

In the present study, a small-scale tube/wire type ESP was designed, manufactured, and tested under ambient conditions. It has a novel feature set axially within the tube, namely, a fine stainless steel mesh cylinder through which the flue gases have to pass before reaching the precipitator's outlet. During tests the mesh was given a continuous negative electrostatic charge which repelled the negatively charged particulate matter within the precipitation tube but allowed the uncharged gases to pass through unhindered.

The results of the tests are encouraging in that there is a correlation between it and the theoretical model having the same geometry and characteristics apart from the repelling mesh cylinder. It should be noted that the theoretical model's 'performance' is based entirely on ideal particle resistivity and ideal operating conditions.

### B. Harmful Effects of PM on Human Health

With regard to public health there seems to be no safe level of exposure to fine dust particles of 10  $\mu\text{m}$  ( $\text{PM}_{2.5}$  to  $\text{PM}_{10}$ ). Even short term, intermittent exposure causes acute respiratory problems particularly in children and older members of the population with corresponding increases in hospital admissions. PM of 2.5  $\mu\text{m}$  diameter and less penetrate deeply into the respiratory system where they cause chronic life threatening pulmonary and cardiovascular illnesses. The fine particles remain embedded deep within the lungs thus reducing the available area for gaseous exchange and the ultra-fine particles can pass into the blood system which then carries them to the heart and around the body [16].

### C. Recommendations for Future Work

There are two strong assumptions as to why the system's collecting efficiency is so high.

- 1) The repelling action of the innovative mesh cylinder.
- 2) The pressure drop and subsequent reduction in flow velocity on entering the collecting cylinder.

The slower air flow reduces the scouring action on the cylinder wall which dislodges captured PM. These assumptions need to be confirmed by further experimentation but they do not detract the existing experimental evidence.

Trials in which the effects of applying different coatings to collecting surface areas are planned.

All of the above developments will include the mesh repelling cylinder.

Combustion temperature trials have started. A test rig has been retrofitted into the flue system of a 45  $\text{kW}_{\text{th}}$  wood pellet fueled central heating boiler. Preliminary results are very encouraging and indicate that there is no appreciable reduction in collecting efficiency when compared to that of ambient temperature experiments.

There is always room for improvement; therefore, work on achieving even higher collecting efficiencies is always to the fore. A laboratory bench ESP demonstration unit has been

built and fitted into a clear glass container. The intention is to help researchers in their understanding of electrostatic precipitation by witnessing PM movement within the system and by gaining hands on experience.

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