Advanced computational tools for electrostatic precipitators

An advanced numerical model has been developed by ABB Corporate Research which, by deepening understanding of the processes taking place in electrostatic precipitators (ESPs), allows the efficiency of this mature technology to be further improved. The model links, for the first time, the actual ESP geometry (corona electrodes, collecting plates) and operating parameters (main flow velocity, gas data and electrical energization) to the performance of the precipitation process. Advanced visualization and animation tools are used to display the results. Numerical simulation can be expected to reduce expensive pilot and field testing in the future.

The separation of suspended fine dust particles or droplets from exhaust streams is mandatory for many industrial processes [1]. Among the areas in which efficient dust collection is required are power generation, steel and cement production, and the processing of paper and non-ferrous metals. In the chemical industry, precipitation is used, for example, in phosphate processing and petroleum refining as well as in sulfuric acid production.

By far the most important application of electrostatic precipitation is in the separation of fly ash particles from the hot flue-gas stream of coal-fired power plants **1**. A large power plant generating 500 MW of electrical power typically burns 200 tonnes of coal per hour. The ash content may be 10 to 40 %, depending on the quality of the coal. Most of this ash follows the flue-gas stream as fine particulates ranging in size from 0.1 to 100 µm. Several tonnes of fly ash have to be removed after separation from the flue-gas stream, which can have a volume flow of about 2.5 million cubic meters per hour. This is achieved with a collection efficiency approaching 99.9 % in large electrostatic precipitators. In an ESP, electrical gas discharges are used to charge the ash particles and electrical fields are used to exert forces on the charged particles and extract them from the gas flow. The dust particles are then deposited on large collecting plates, from where they can be transferred to hoppers and subsequently to the ash-handling system. The whole process requires surprisingly little energy. In modern power plants less than 0.1 % of the generated electricity is used for dust charging and collection in the precipitator.

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ABB is a leading supplier of air pollution control equipment and has experience in dust collection that goes back more than 60 years. To date, over 3,500 large ESPs have been delivered by the company.

Basic ESP configuration

At the entrance to the precipitator the flue-gas stream is decelerated and channelled into multiple parallel ducts which can be up

Electrostatic precipitators for environmental protection

Electrostatic precipitators (ESPs) are used in industry to clean flue and blast-furnace gases. They do this by collecting the dust particles that would otherwise escape with the gas to the atmosphere. The primary purpose of ESPs is therefore to protect the environment by removing most of the pollutant emissions. They are also used widely to recover valuable chemicals or metals from exhaust gases.

Inside an ESP are large plate-type electrodes at ground potential. Stretched between them are thin wires, called corona electrodes, at a negative DC voltage of 50–110 kV.

A corona discharge occurring close to the wire forms electrons which immediately become negative ions in the flue-gas environment. These travel towards the plate electrodes, attaching themselves to suspended dust particles on the way. As a result, the particles are negatively charged and pass, under the action of the electrical field, to the plate electrodes, to which they adhere.

Field experience and research programmes have raised ESP technology to a very high level. Ongoing development, with help from advanced simulations, is further reducing the residual dust in the flue-gas stream. By optimizing the electrode geometry and power supply, the movement of the particles can be systematically influenced in terms of their size, thereby improving the collection of what was formerly considered ‘problem dust’.

Fayette power plant of the Lower Colorado River Authority, in La Grange, Texas. The coal-fired plant has 3 boilers with nominal ratings of 600/600/450 MW. All three are equipped with ABB electrostatic precipitators. **1**

to 15 m high and are typically 0.3 to 0.4 m wide **2**. The walls are usually made of mild steel. High-voltage corona electrodes are mounted in the center plane of each duct. A negative high voltage is applied to initiate a corona discharge between the electrodes and the grounded collecting plates. Ash particles are charged in the corona discharge and travel under the influence of the strong electric fields to the duct walls, which serve as collecting plates. Accumulated particles form a dust cake, which can be made to slide down by periodic rapping of the plates. To ensure high collection efficiency, the flue gas passes up to eight segments, also referred to as fields. Each field has a maximum length of 5 m. The width of the precipitator is determined by the number of ducts required to achieve the desired flow velocity of about 1 m/s. For a large precipitator the total width can extend to 45 m, being typically sectionalized into 3 × 15 m.

Fundamental processes involved in electrostatic precipitation

The process of electrostatic precipitation is rather complex, and its optimization requires expertise in different fields. The quantitative description of the corona discharge calls for a solid background in plasma physics, while the treatment of the gas flow lies in the realm of fluid mechanics. Pronounced secondary flow patterns are generated by the interaction between the ion motion and the main flow. The charging of particles falls under the subject of electrostatics and the optimization of the high-voltage supply specified by the ESP designers is a task for electrical engineers. At ABB, international research teams with different professional backgrounds therefore work closely together with engineers in the company's technology centers to solve the problems involved. Such collaboration unites ABB's research resources with the practical experience gained from large numbers of field, pilot and laboratory tests.

ABB Corporate Research, Switzerland, teamed up with the newly founded Swiss Center for Scientific Computing at Manno in southern Switzerland to develop advanced computational tools for the precipitation process as a whole. The latter institution, which is devoted to high-performance computing, is an annexe of the Swiss Federal Institute of Technology at Zurich. Besides additional numerical skills, it brought to the project an NEC SX4 supercomputer that is among the fastest in the world. The goal of the project was to predict the fate of incoming dust particles by following their trajectories through the different corona sections until they hit the collecting plate or exit the precipitator. It was envisaged that such a computational tool could subsequently be used to optimize electrode geometries and operating parameters for any given application.

The multi-disciplinary nature of the problem requires advanced database concepts able to handle and interlink different program packages and connect different workstations to the NEC SX4 at Manno. The modular concept that was used allows program packages to be developed independently. 3 shows the database structure that was used. The main advantages of such an open structure are that the individual program packages can be exchanged for more advanced ones at any time, data can be readily transferred between different computers, and advanced visualization tools and computer animations can be used to display the results. The numerical treatment of such complicated problems generates huge data files. However, modern visualization tools allow these results to be presented in a way that supports the intuition of the design engineer and allows comparison with measured data. Different colour-coded sectional and perspective views are used for illustration, in addition to computer animations of the major physical processes in the form of videos.

The computational model treats the major physical aspects theoretically. At present, the model describes the physical phenomena in a 'clean' precipitator. In reality, additional problems are posed by the presence of a precipitated ash layer, its resistive properties, particle re-entrainment and agglomeration, and operating conditions which are close to the sparking limit. These more practical issues, typically handled by ESP design engineers, also have an important influence on ESP performance.

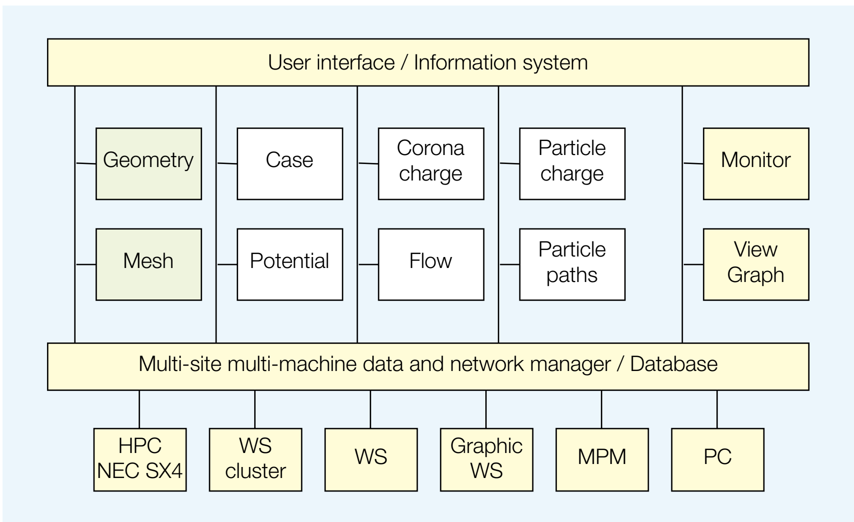
The corona model

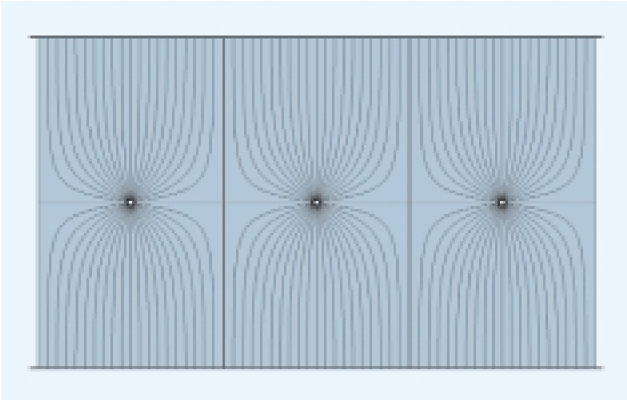
An essential step forward was the development of a corona model capable of de-

Structural design of an ABB electrostatic precipitator, type FAA. On entering the ESP, the flue-gas stream is decelerated and channelled into ducts up to 15 m high. 2

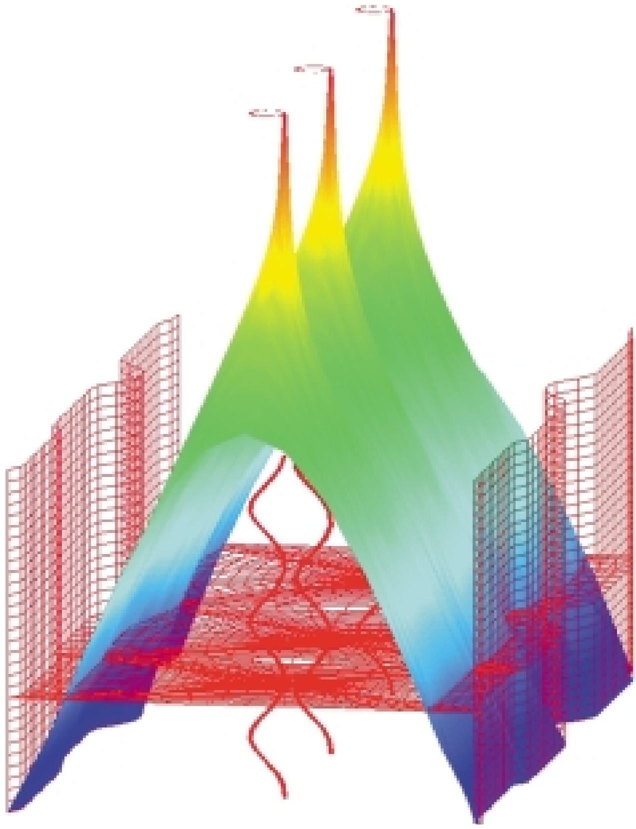
Advanced database concept for linking program packages and computers at different locations 3

HPC *High-performance computer*
WS *Workstation*
MPM *Massive parallel machine*
PC *Personal computer*





Electric field lines of cylindrical corona electrodes in a duct with planar walls **4**



Electrical potential of helical corona electrodes between specially formed collecting plates (g-plates) **5**

scribing the distribution of the current density, electric fields and ion densities in a complicated technical precipitator geometry [2, 3]. Many modern ABB precipitators use helical corona electrodes that require three-dimensional treatment. When the voltage is raised above corona onset, a corona discharge is initiated in which current flows from the high-voltage electrode to the grounded collecting plates. A very thin active plasma layer adjacent to the high-voltage electrodes generates electrons as well as positive and negative ions. Since negative polarity is used, the positive ions travel only a short distance to the corona electrode, while the electrons and negative ions start their journey towards the grounded collecting plates. In air or flue gas, free electrons are rapidly converted to negative ions by a process called attachment. As a consequence, most of the duct volume is filled by negative ions which connect the active plasma regions to ground potential at the collecting plates. Since the active plasma region occupies only a minute part of the available duct volume the corona action can be adequately described by the equations governing a unipolar ion drift region:

$$\boldsymbol{E} = -\nabla\Phi = -\mathrm{grad}\ \Phi \quad (1)$$

$$\nabla^2\Phi = \mathrm{div\ grad}\ \Phi = -\rho/\varepsilon_0 \quad (2)$$

$$\boldsymbol{j} = \rho\boldsymbol{v} = \rho\mu\boldsymbol{E} \quad (3)$$

$$\nabla\cdot\boldsymbol{j} = \mathrm{div}\ \boldsymbol{j} = 0 \quad (4)$$

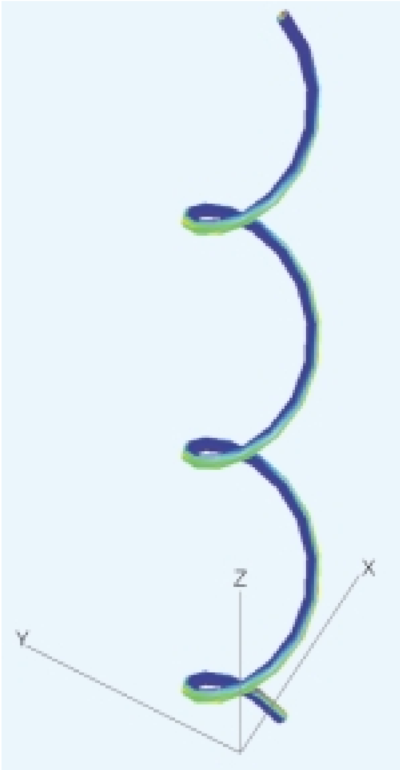
In these equations $\boldsymbol{E}$ is the electric field, Φ the potential, ρ the charge density, $\boldsymbol{j}$ the current density, $\boldsymbol{v}$ the ion velocity, μ the ion mobility, and ε_0 the vacuum permittivity. The charge density ρ includes the ionic charge and the charges accumulated on solid particles. These equations enforce strong coupling between the current $\boldsymbol{j}$, space charge ρ and electric field $\boldsymbol{E}$. The properties of the active plasma layer covering the corona electrode enter the equations as a boundary condition. In the corona model considered, the location and lateral extension of the active plasma regions are computed simultaneously with the properties of the ion drift region. The plasma region is adequately described by introducing ionization and attachment coefficients that are characteristic properties of the gas used, eg air or flue gas.

The computational challenge was to find a solution for this set of differential equations with sufficient accuracy throughout the duct volume. Special adaptive computational meshes were generated to cope with the steep gradients close to the corona electrodes and to handle the complicated shape of the latter.

4 shows a horizontal cut through a duct with straight wire electrodes and planar collecting plates. The curved lines represent the electric field lines, which practically coincide with the paths of negative ions travelling from the corona electrodes to the duct walls. Three-dimensional computations with helical electrodes and specially shaped collecting plates show more complicated phenomena. The electrical potential plotted in 5 reveals a drastic drop in the potential between adjacent electrodes in the center-plane of the duct. The helical shape of the corona electrodes has important advantages in that it enforces a well-defined current density distribution in the duct and at the collecting plate. The electrodes are like springs mounted under tension in metal frames. The tension provides a self-centering action. Also, helical electrodes are much less sensitive to misalignment than thin wires or planar strip electrodes. In addition, rapping of the metal frame causes the electrodes to start vibrating, thus efficiently cleaning them of deposited fly ash. Free parameters that can be optimized are the diameter of the wire and the pitch and diameter of the helix. The shape of the collecting plates, so-called ‘g-plates’, is influenced by mechanical considerations that ensure rigidity and mechanical strength in addition to electrical and fluid dynamic considerations.

Ion distribution and current density

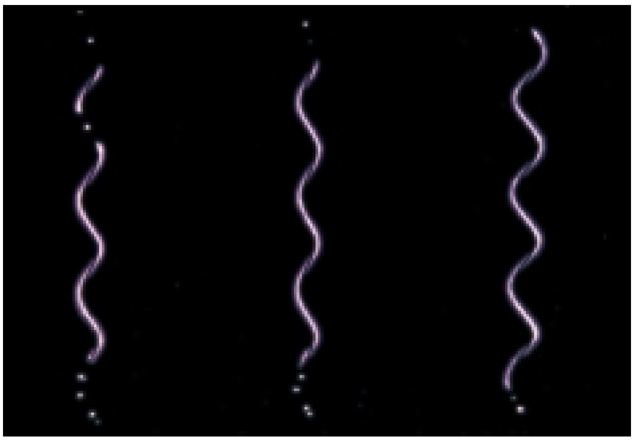
Ions leaving the active plasma regions at the corona electrodes follow the electric field lines to the collecting plate. The corona model determines the position and lateral extension of these active plasma regions along the helical electrode. 6 shows an enlarged view of a helix segment. Active regions are located mainly on the outside of the helix as the electric field is much reduced towards the inside due to the shielding action of neighbouring parts of the helix. This effect is also shown in photographs of the corona discharge on the helix electrodes 7. A faint dark line on the inner side of the spiral is an indication of much reduced corona activity. This result has severe implications for the distribution of the ion density in the duct 8. The red colour indicates the highest ion charge density. These regions are located close to the helix wire and point in a direction that is determined by the shape of the collecting plate and the spacing of the corona electrodes. The computations provide evidence of large blue zones of negligible ion density. The spacing of the corona electrodes clearly has to be optimized in connection with the shape of the collecting plates. Over the years, ESP performance has been tuned with the help of current distributions measured in the laboratory.



Computed ion charge distribution on a segment of the helical corona electrode. Active regions are located mainly on the outside of the helix as the electric field is much reduced towards the inside by the shielding effect of adjacent parts of the helix. 6

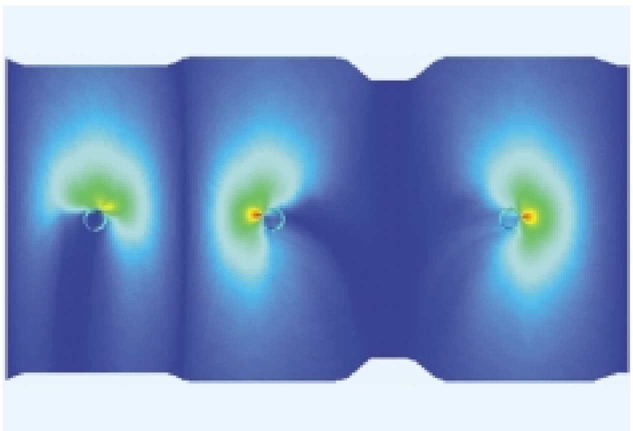
Colour scale: $0<\rho<1.5 \cdot 10^{-5}$ As/m³

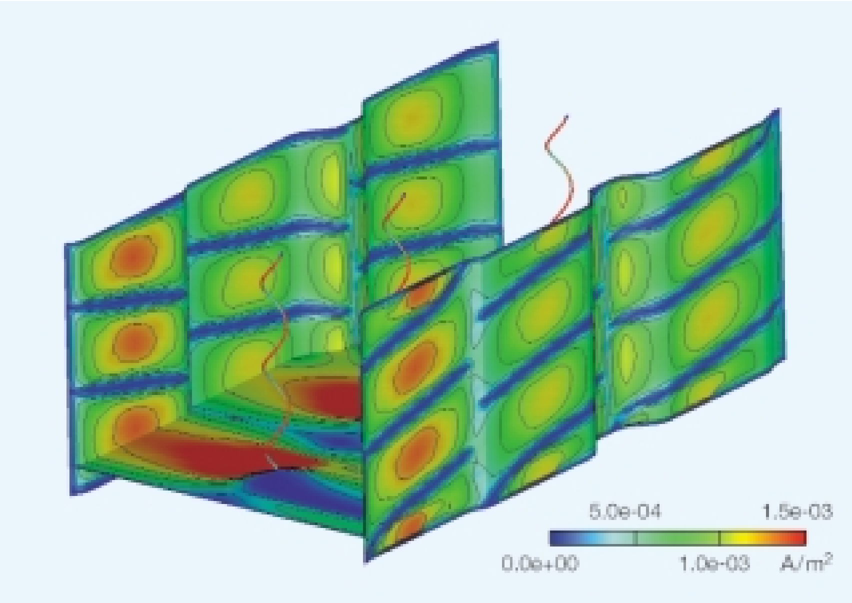
Photograph of corona discharge on helical high voltage electrodes. The faint dark line on the inner side of the spiral indicates strongly reduced corona activity. 7



Computed ion charge density in a duct with helical corona electrodes, presented in three different horizontal cuts 8

Colour scale: $0<\rho<10^{-4}$ As/m³





Current density in a duct with helical corona electrodes and g-plates. The patterns are related to the pitch and spacing of the helix electrodes. **9**

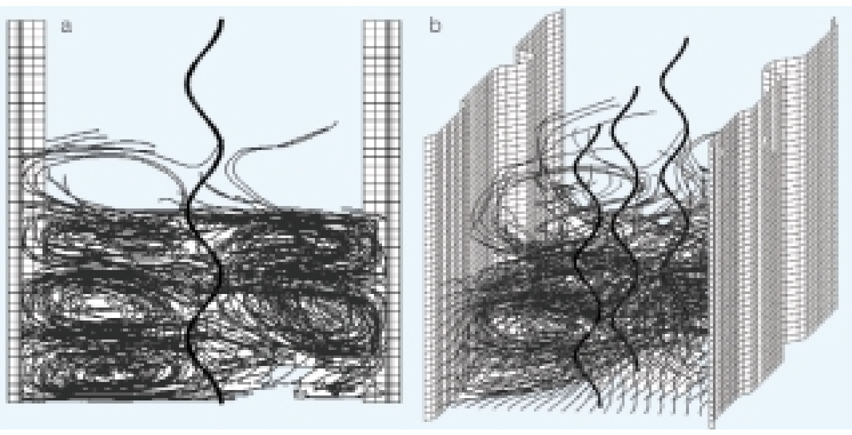
Current density computations **9** show the distribution in the duct volume and at the collecting plates. Similar patterns can also be observed in the dust deposited on the collecting plate. These are clearly related to the pitch and spacing of the helix electrodes.

Current measurements with a segmented collecting plate performed at the ABB Technology Center for air pollution control at Växjö, showed not only the same current density patterns but also yielded almost quantitative agreement with these model computations. Both the experiments and computations also showed zones of practically zero current density at the collecting plates [4]. The helical shape of the corona electrodes ensures a very stable distribution of the corona current, making it superior to other electrode shapes.

The electric wind

The ions travelling through the gas at speeds of about 100 meters per second generate an 'electric wind', sometimes also referred to as 'ionic wind' or 'corona wind'. The electric volume force, ρE, acting transverse to the main flow induces strong secondary flows that completely change the originally turbulent channel flow exhibiting flow separation and turbulence generation at the plate stiffeners and discharge electrodes. Since ions have approximately the same mass as neutral gas molecules, an efficient momentum transfer takes place between the accelerated ions and the background gas. By combining a flow solver package with the corona model, it was possible to calculate the resulting streamlines **10**. Pronounced three-dimensional vortex structures are the result. Fortunately for the computations, an extensive database exists within ABB for validation. This contains both qualitative information from laser light sheet visualization as well as quantitative data from laser Doppler velocimetry measurements [5]. It is interesting to note that the original flow is already substantially altered after passing just a few corona electrodes. **11** shows a vertical cut between the second and third helix electrode after the entrance to a precipitator. The higher the corona voltages are, the stronger the cross-flow velocity components are that are obtained in alternating directions at speeds comparable with the main flow velocity.

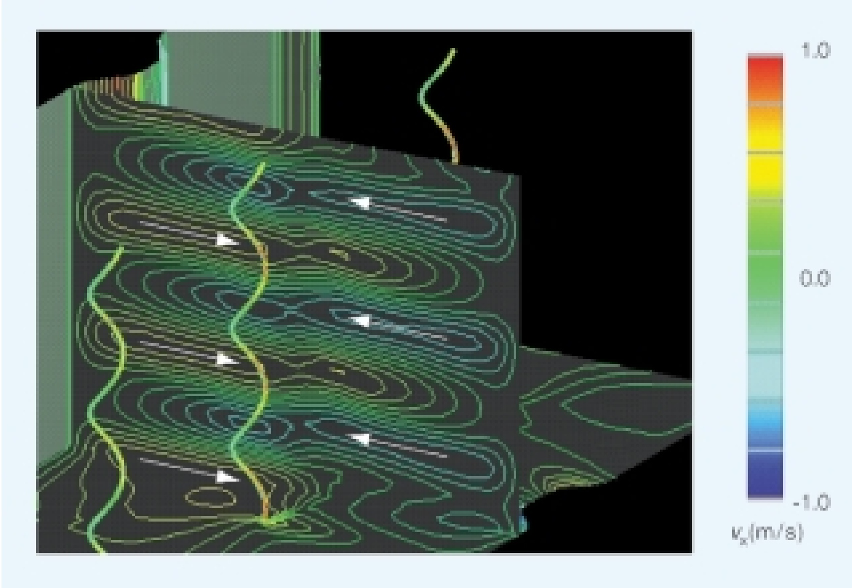
Front view (a) and perspective (b) of some flow streamlines in a duct with helical corona electrodes and g-plates **10**



Particle charging

Fly-ash particles entering the precipitator pass many corona sections on their way through the duct. They are subjected to collisions with negative ions whose concentration and velocities vary. Also, the local electric field strength changes along the trajectory. Two basic physical mechanisms are responsible for the charge accumulation on the dust particles. A process called *field charging* drives ions to the particle surface until a saturation charge is reached (this depends on the size of the dust particle and the value of the electric field strength). The initial speed of the process depends on the ion concentrations the particle sees during its passage through the corona regions. As the dust particles accumulate charge via ion attachment, further ions begin to be repelled by the particle, thus reducing the rate of charging. Once the saturation charge is reached a state of equilibrium is reached in which all further ions are repelled, thus reducing the charging rate to zero. Field charging is the main charging mechanism for particle sizes above 1 µm radius.

For smaller particles a different physical mechanism called *diffusion charging* is more efficient. This process depends on the random thermal motion of ions and the resulting collisions with dust particles. Strictly speaking, field and diffusion charging occur simultaneously once a particle enters an ESP. Consequently, the differential equations describing the charging mechanisms have to be solved at the same time as those determining the particle trajectory [6]. The computations show that a 5-µm particle in a large precipitator may accumulate several thousand elementary charges while a 0.3-µm particle rarely collects one hundred elementary charges. Particles passing close to the corona electrodes can reach fairly high charging levels already after a short distance. In 12 a colour code is used to indicate the charging level of individual particles along their trajectories. Red indicates a high

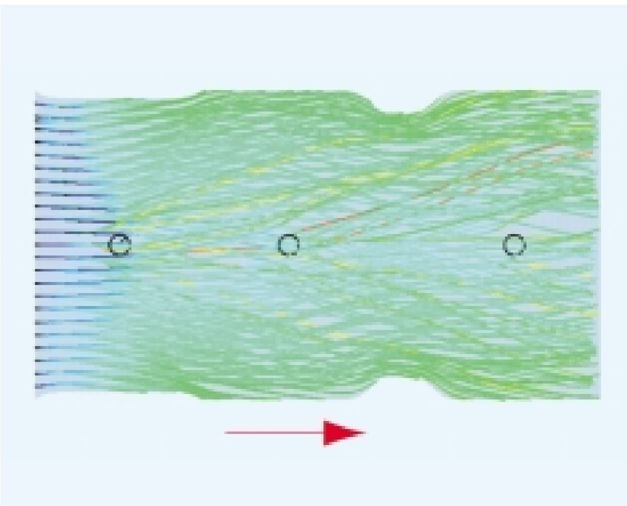


Cross-flow patterns in a vertical plane perpendicular to the main flow between the second and third corona electrode 11

v_x *Flow component perpendicular to main flow direction*

Trajectories of 2-µm particles, viewed from above. The colours indicate the elementary charges (0–975) collected on a fly ash particle. 12

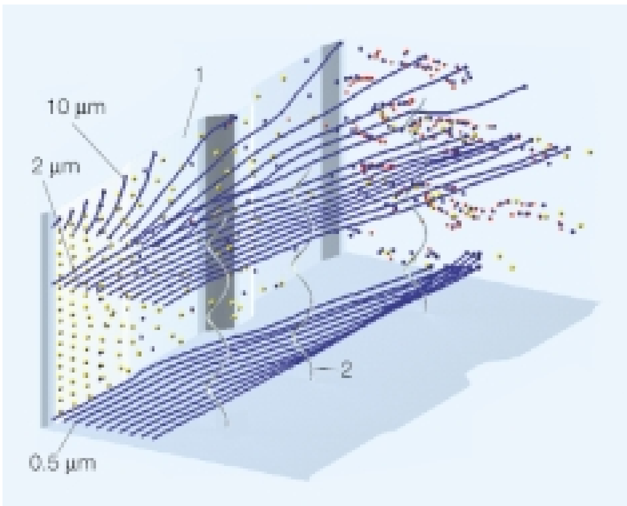
Red arrow *Direction of gas flow*



Perspective view of particle trajectories 13

Top level: *10-µm particles*
Medium plane: *2-µm particles*
Bottom: *0.5-µm particles*

1 *Collecting plate* 2 *Corona electrode*



accumulated charge, blue zero charge and green and yellow intermediate values.

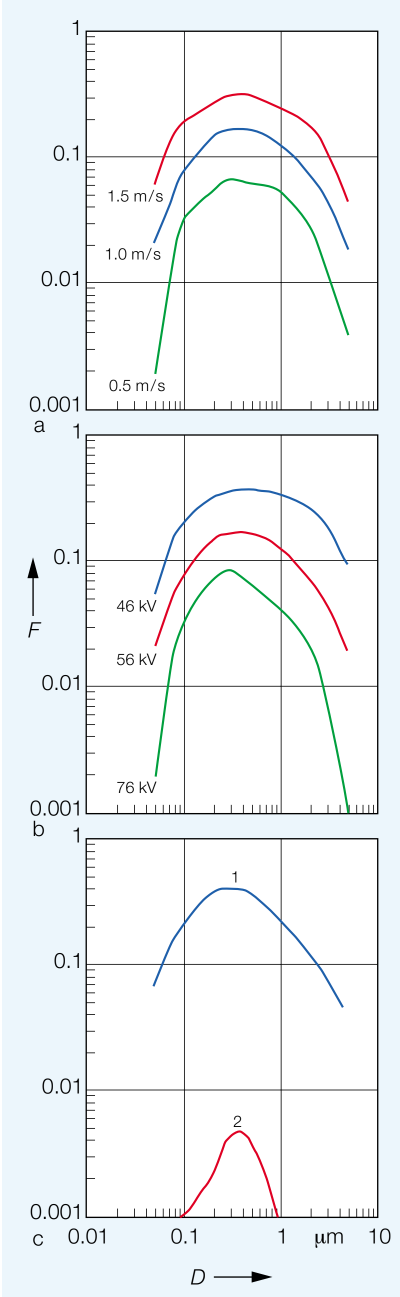
Particle trajectories

Once the flow field, the corona properties and the charges on the particles, q_p, have been determined, the total forces on individual particles resulting from electrical forces q_pE plus the inertial and frictional forces in the fluid can be computed. A special *particle pusher package* is used which was originally developed to trace individual particles in nuclear fusion experiments. At this stage all the different program packages interact to solve the equation of motion for individual fly ash particles. From 13, which shows a perspective view of particle trajectories, it becomes apparent that particle motion is heavily influenced by the corona and by the secondary flows in addition to the main conveying flow. Three different particle sizes with diameters of 10 µm, 2 µm and 0.5 µm enter the precipitator at different horizontal planes. Many of the large particles acquire enough charge to be driven to the wall by electric forces already after a short distance. Some of the medium-size particles and even more of the small particles are caught in a swirl that initially carries them to the center of the duct away from the collecting plates. 12 shows a large number of 2-µm particles in different planes, viewed from above. Most particles accumulate a moderate charge (green) very soon after entering. Some acquire more charges (yellow, red) and are strongly deflected towards the collecting plate by electric forces. Already after three electrodes, a considerable reduction in the particle concentration is observed. In the example shown, 22 % of the particles reached the collecting plates after passing three corona electrodes.

Penetration curves

The powerful computational tools described can be used to investigate the influence of different parameters on the performance of an ESP. For this purpose the trajectories of 2000 particles of each size class were computed for a large precipitator 12 m in length. The flow passes 45 helical corona electrodes.

The results can be summarized in the form of fractional penetration curves 14, in which the fraction of particles leaving the precipitator is plotted for each particle size. These curves exhibit a maximum for particles having a diameter of about 0.5 µm. This result is in qualitative agreement with measurements performed downstream of full-size ESPs used with modern pulverized-coal-fired power stations. 14a shows the influence of the inflow velocity. For a 4-µm particle the penetration is reduced by a factor of 10 if the flow velocity is reduced by a factor of 3. 14b shows the strong influence of the applied voltage. Due to this influence, precipitators are operated when possible close to the maximum voltage – given by the spark breakdown resulting in a voltage collapse. Modern ESPs have electronic controls that cut in at the sparking limit but allow a certain number of spark breakdowns to occur (typically 10 per minute, in certain applications up to 150 per minute). The most surprising result can be seen in 14c, which shows the influence of the electric wind. This diagram also demonstrates the power of advanced numerical simulations. In the computation it is possible to switch off the electric wind by eliminating the coupling between the corona discharge and the fluid flow. In reality, of course, this is not possible. The trick, however, helped to answer a question which had been debated for decades, namely how great is the influence of the electric wind in electrostatic precipitation? Is it helping or hindering particle collection, or can its influence be neglected? The model computations demonstrate that the influence of the electric wind on precipitation is



Penetration curves demonstrating the influence of different geometrical and operating parameters on particle collection 14

a *Influence of flow velocity (plane plates, 40-cm gap, length 12 m, 45 electrodes)*
b *Influence of applied voltage (plane plates, 40-cm gap)*
c *With (1) and without (2) 'electric wind' (56 kV, g-plates)*

D *Particle diameter*
F *Fractional penetration*

adverse and overwhelming. A comparison of the two curves in 14c reveals that the dust collection could be improved by about two orders of magnitude if the electric wind were eliminated. Consequently, it is worthwhile thinking about geometries and operating conditions that would reduce the influence of the electric wind.

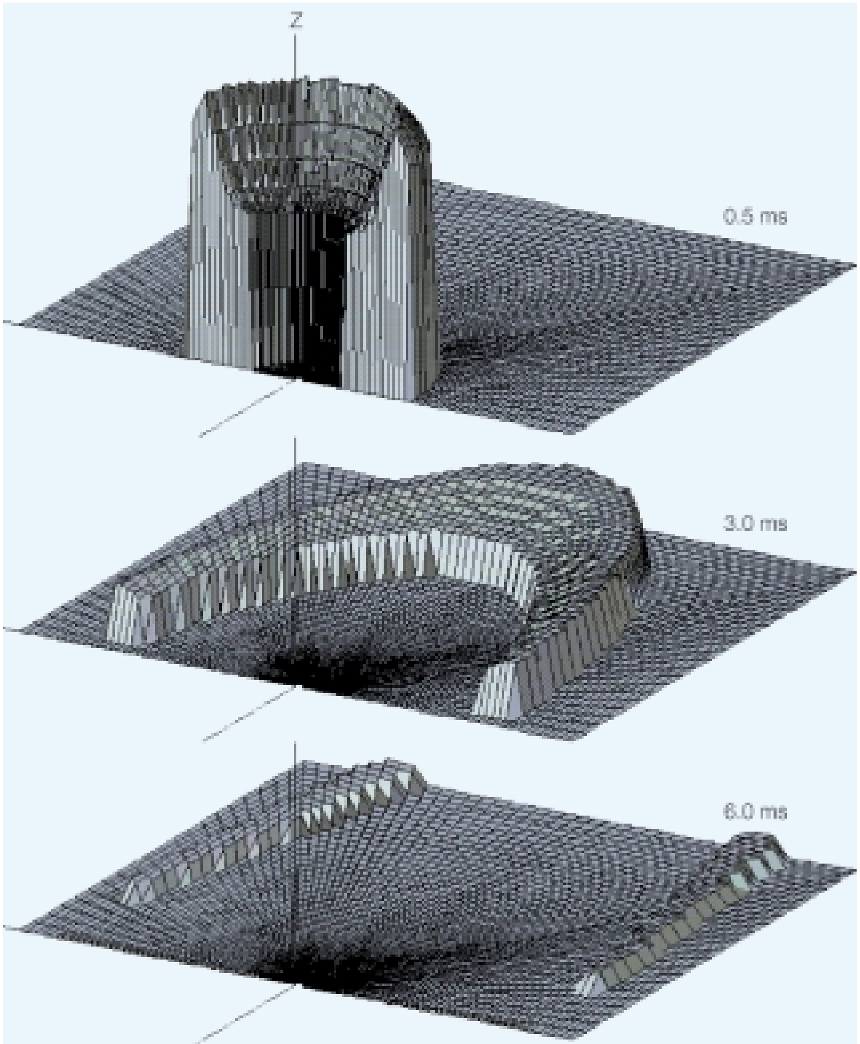
From the shape of the penetration curves it follows that particles in the diameter range of 0.1 μm to 1 μm are the most difficult to collect. Larger particles accumulate many elementary charges with resulting strong electrical forces. The somewhat surprising result that very small dust particles also are efficiently collected is due to a reduction in the aerodynamic drag (Cunningham slip) for particles in this size range.

Intermittent and pulsed energization

The results discussed so far refer to the steady state in which a constant high voltage is applied to the corona electrodes. In reality, the high voltage supplied by conventional line frequency transformer/rectifier sets fluctuates at twice the line frequency. In more advanced high-frequency rectifiers the voltage is close to a pure DC voltage [7]. In many applications intermittent energization is used. Pauses in the charging current can be introduced by suppressing a certain number of half-waves in the rectifier circuit, resulting in a more highly fluctuating high voltage with millisecond-long pulses. Much shorter high-voltage pulses can be obtained with special pulse-forming networks. *Pulse energization* consists of short-duration high-voltage pulses superimposed on a DC base voltage. These methods were mainly developed to improve the collection of high-resistivity dusts. As a side effect, the power consumption was further reduced.

The physical reasoning for abandoning DC energization in certain applications is given as follows. In the steady state of a corona discharge, current and voltage are rigidly coupled by the current/voltage characteristic, which is essentially determined by the electrode arrangement and the gas properties. The use of transient voltage forms introduces an additional degree of freedom for optimizing dust collection. Intermittent and pulse energization make it possible to reduce the time-average current and still retain good current distribution, which depends on the intensity of the corona formation (high-voltage peaks). Special effects can be expected when the pulse duration is shorter than the ion transit time, ie the time ions need to travel from the corona electrode to the collecting plate. In a typical ESP configuration this takes several milliseconds. Also, such effects can be investigated with the corona model [8, 9]. 15 shows the shape of the travelling ion cloud produced by a high-voltage pulse with a duration of 300 μs at three different times during transit. The ion cloud has well-defined front and rear edges and a shape that is mainly determined by the electrode and duct geometry as well as, of course, the pulse duration. The main gas flow with the suspended dust particles moves only a few millimeters during this ion transit time. Using short pulses it is possible to add charges to the

Shape of a travelling ion cloud produced by a high-voltage pulse of 300 μs duration. Z shows the position of the straight wire corona electrode. **15**



dust particles without adding much transverse momentum to the flow, and arrive at a more homogeneous current distribution at the collecting plates. This results in higher collection efficiencies, especially for high-resistivity fly ash [10].

Conclusions

Attempts at modelling and predicting the performance of electrostatic precipitators have a long history. Early investigations resulted in the famous equation of Walther Deutsch (1925) relating the collection efficiency of an ESP to the specific collection area and to a fictitious migration velocity towards the collecting plate. This relation was later refined and has been used extensively for precipitator sizing. In such integral models previous experience and pilot testing are used to predict the migration velocity for a new application.

The computer model which has now been developed is based instead on the basic physical processes involved in precipitation. It aims at predicting unknown situations and clarifying and quantifying different geometrical influences. It is used to investigate the influence of different electrical parameters, the gas composition, the temperature and the flow velocity. At present, the model assumes ESP operating conditions which do not lead to back-corona phenomena.

Such an approach has become feasible only recently due to advances in plasma physics, computational fluid dynamics and high-performance computing. It now appears possible to treat the full electro-hydrodynamics of a corona discharge in a transverse gas flow together with the equations for particle charging and particle motion. It is obvious that such complicated program packages have to be validated against experimental evidence. The results of checks performed so far by comparing measured *I/V* characteristics, measured current density distributions and measured penetration curves are very favourable.

The examples given demonstrate that it is now feasible to perform numerical experiments in order to optimize ESP performance and quantify the influence of different parameters. It is anticipated that numerical simulation will allow a reduction in expensive pilot and field testing. It is already apparent that such computer models will be used by design engineers as complementary tools for checking new ideas about advanced precipitation processes. Since some additional practical effects have not yet been treated in the computational model, practical experience and pilot testing will continue to be important assets during future ESP design work.

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