CFD modeling of the electrical phenomena and the particle precipitation process of wet ESP in coaxial wire-tube configuration

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1 Summary / Abstract:

Modeling the precipitation process in ESPs requires a strongly coupled system of the Maxwell-equations, describing the electrical conditions, and the Navier-Stokes-equations to determine the fluid flow. Another task is the implementation of the particle dynamics, i.e. the charging kinetic and the transformation of the Electric field distribution due to the resulting space charge. The purpose of the presented work is the development of a CFD-based designing tool to predict the ESPs precipitation efficiency as a function of important parameters, such as the geometric patterns, electric potential, particle size distribution and concentration.

2 Introduction (Heading 1)

The separation of dust- or aerosol-particles is mandatory in different kinds of industrial processes. Especially the sector of power generation requires efficient techniques for their removal, but applications of such techniques can also be found in other fields such as the production of cement and steel, in the fabrication of paper or in the petroleum industry. Under many operating conditions the electrostatic precipitation process can be used to achieve the required threshold for the emission of particles, while using a surprisingly low amount of energy. In modern power plants for example less than 0.1 % of the produced electrical power is necessary for the particle charging and precipitation. The efficiency of such devices is higher than 99 % [1].

Even though the first commercial use of this technology dates back to 1907 when F. Cottrell applied an Electrostatic Precipitator (ESP) to the collection of sulfuric acid mist and more than one hundred years of operational experience have gone by since then, the construction of ESP is still a difficult task for engineers based on a merely empirical approach [2].

The difficulties result from the fact, that the precipitation process is influenced by many different physical phenomena and therefore represents a very complex procedure. Since the fundamental relations to describe the process consists mainly of a set of partial differential equations, such as Navier-Stokes- and Maxwell-equations, the recent advances in modern numerical and computational techniques give rise to the opportunity of developing new concepts to properly design ESP against the background of the main physical principles.

Thus the objective of the authors work is the creation of a computational model based on commercial software to provide a helpful tool for the construction and optimization of industrial ESP. The software ANSYS CFX, which utilizes the numerical method known as “finite volumes”, is being employed to achieve this.

2.1 Modeling environment

In the present work the geometric arrangement to apply the numerical model to consists of a coaxial wire-to-tube configuration. This kind of setup is mainly used in case of wet electrostatic precipitation processes, where the treated medium is saturated with water vapour (i.e. it has a relative humidity of 100 %). The particles being contained in the medium are treated as aerosols with a diameter distribution between 0.1 microns to 10 microns. Under

these circumstances the precipitated particles at the collecting electrode are “washed of”, so they do not form a layer, which otherwise could significantly influence the distribution of the electric field, due to its higher electrical resistivity compared to the grounded electrode. Therefore it is possible to assume independency from time and thus utilize a steady state approach to describe the process. Furthermore the examination of liquid droplets (i.e. aerosols) justifies the assumption that particles, once they have reached the collecting electrode, are separated from the system and will not re-enter the fluid flow by any means.
It is generally believed that the resulting electrohydrodynamic-flow-field depends on the conditions at the inlet and outlet of the precipitation area [3]. Therefore it is necessary to consider two additional domains up- and downstream of the main volume which do not contain a corona wire and possess electrically isolated walls.
The calculations are performed in a multiphase approach. The fluid-phase and the ionic space charge are considered continuous and thus can be described with a eulerian approach, while the discrete phase is characterized using particle tracking (Lagrange method).

2.2 Numerical modeling

The description of the electrohydrodynamic flow field is governed by a coupled system of Navier-Stokes-equations and Maxwell-equations. The connection between the two phenomena, the fluid flow on the one hand and the electrostatics on the other hand, is the charge density, because it contributes to the Poisson equation and the current continuity equation as well as to the momentum balance for the fluid flow. The space charge density itself is a source of electric potential and for this reason it is part of the Poisson equation and thus also determines the electric field distribution represented by the negative gradient of the potential.

$$\nabla^2\Phi = -\frac{\rho}{\varepsilon_0} \qquad (1)$$

$$\vec{E} = -\nabla\Phi \qquad (2)$$

Where Φ is the electric potential, ρ the space charge density, ε_0 the dielectric permittivity of free space and $\vec{E}$ the electric field.
According to many different authors the effect of the electric forces on the flow field, i.e. the electric wind can be modeled by including an additional source term $\vec{S}$ in the momentum balance which only depends on the space charge density and the strength of the electric field [4].

$$\vec{S} = \vec{E}\cdot\rho \qquad (3)$$

The distribution of the space charge arises from the superposition of the proportions of the ionic space charge and the particle space charge, i.e. the free ions and the ones bounded to particles.
To calculate the ionic space charge distribution ρ_{ion} it is assumed that a certain amount of ions is generated in the active zone around the corona wire and than gets transported towards the collecting electrode where the ions leave the system. The amount of ions generated can be calculated under the assumption that the electric field strength at the surface of the corona corresponds to the breakdown electric field strength according to Peek´s formula [5] as stated by different authors [6, 7, 8]. The ionic motion in the drifting zone is clearly dominated by the influence of the electric field and therefore can be described by applying a slip velocity $\vec{v}_{ion}$ between the ionic component and the uncharged component of the fluid.

$$\overrightarrow{v_{ion}} = b_{ion}\cdot\vec{E} \qquad (4)$$

Where $\vec{E}$ is the electric field and b_{ion} is the mobility of ions which is a material property. That way the velocity field, derived from the Navier-Stokes-equation, as well as the electric forces are taken into account. Therefore it is possible to study the influence of the boundary conditions on the ionic space charge distribution of both aspects, the hydrodynamic, such as the inlet velocity and the turbulent dispersion on one hand and the electrical conditions, such as the applied voltage to the corona wire on the other hand.
In case of absence of particle space charge, the current density $\vec{j}$ can than be calculated directly from the ionic space charge distribution since it is proportional to the concentration of ions.

$$\vec{j} = b_{ion}\cdot\rho_{ion}\cdot\vec{E} \qquad (5)$$

Furthermore the current continuity condition is valid.

$$\nabla\vec{j} = 0 \qquad (6)$$

So far the presented model (of the eulerian phase) is straightforward and corresponds to those of other authors [4, 7, 8], though they mostly don't use commercial software to solve the problem. Differences arise if the phenomena caused by particle space charge are to be taken into account. To study the particle behavior and the precipitation efficiency as well as effects caused by the particle space charge, the particle dynamics, including the charging process and their motion, have to be modeled.

2.3 Particle dynamics

As already stated, particles are modeled using a lagrangian approach. To describe the charging process it has to be taken into account that the process depends on two different mechanisms, according to the particle size. Particles of a size lower than 1µm are mainly charged due to the diffusion charging mechanism, while in case of larger particles the field charging mechanism is dominant. As a modeling approach the field modified diffusion model derived by Lawless et al [9] is adopted. The implementation is carried out in terms of an adsorption process, such as ions are removed from the eulerian phase and added to the lagrangian phase. The particle motion caused by the electric field force $\vec{F}_{elec}$ in that case only depends on the amount of charge accumulated on the particle q_{ion} and the local electric field in the surrounding of the particle $\vec{E}_p$.

$$\vec{F}_{elec} = q_{ion} \cdot \vec{E}_p \tag{7}$$

This term is added to the momentum balance for each particle. The mutual interaction between the particle phase and the fluid flow is based on drag forces, which can be calculated by the Schiller-Naumann correlation.

Particles which collide with the grounded electrode, i.e. the inner wall of the outer tube are considered to be trapped, thus the precipitation efficiency can be determined by counting the trapped particles and than comparing the result with the particle size distribution at the inlet.

The consideration of the influence the particle space charge has on the electric field distribution, respectively on the distribution of the electric potential, is realized by extracting the accumulated particle charge at each position and applying it to the corresponding volume of finite volume as an additional source term in the Poisson equation.

2.4 Results of the numerical simulations

For validation purpose it is desirable to compare the simulation results with data from the literature. Despite the fact that many authors have published their experimental and theoretical results regarding the present research topic it is difficult to find appropriate data. This is because a complete set of data is necessary to generate a valid CFD simulation, involving exact information about the geometry as well as extensive knowledge about the flow patterns, the electrical conditions and the properties of the deployed substances. In addition the majority of the published literature deals with wire to plate configurations. However some simulations are carried out with a setup presented by O. Blejan et al at the 42nd industry applications conference [10] to verify the functionality of the model. The comparison between the computed and measured current-voltage characteristics for the experimental ESP consisting of a tube with a length of 198 mm and an inner diameter of 40 mm is shown in figure 2-1. The diameter of the used corona wire is 0.18 mm and the ESP is operated under conditions in which no effects caused by particle space charge are expected. As can be seen in the figure, the results obtained from the CFD model are in a very good agreement with the measurements.

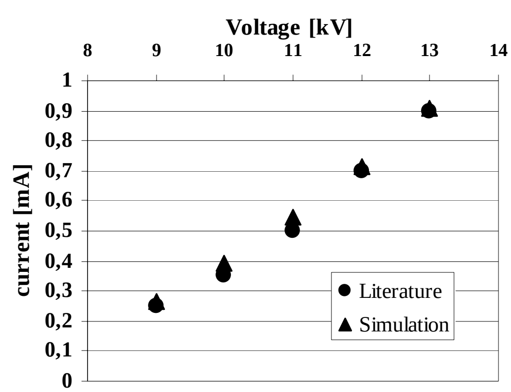

Fig. 2-1: Comparison of computed current-voltage-characteristic with data found in the literature [10].

To indicate the functionality of the implemented charging mechanism the accumulation of particle charge with increasing particle traveling time, i.e. the charge accumulation along a particle trajectory, is shown in figure 2-2. As an example the charging kinetic of a particle of the size of 1 µm is shown. In addition the dashed line in the diagram represents the corresponding saturation charge. The saturation charge indicates the threshold of the field charging mechanism and is highly dependent of the local Electric field strength in the surrounding of the particle. Since the electric field in the drifting zone of the ESP is inhomogeneous, the saturation charge of a particle moving through this zone is also a function of the position of the particle and thus varies with the traveling time. As can be seen, the accumulated particle charge exceeds the saturation charge very quickly. This indicates the dominance of the diffusion charging mechanism for particles of the given size.

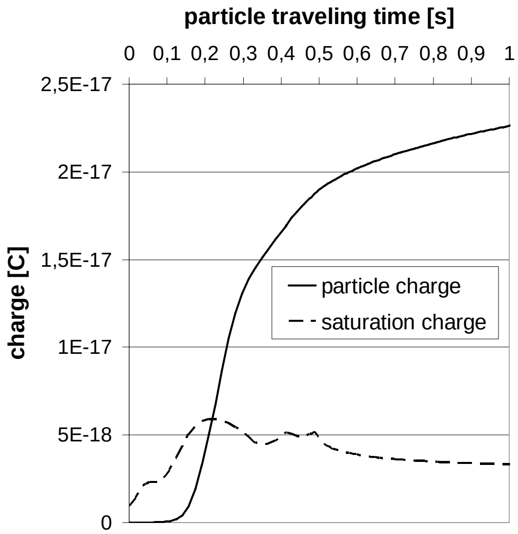

Fig. 2-2: particle charge accumulation with time for a particle of the size of 1 µm. For comparison purpose the particle saturation charge is also illustrated.

Due to the accumulated charge the particles experience an electrostatic deflection towards the inner wall of the tube where the precipitation takes place. By counting the particles of different size fractions arriving at the wall it is possible to determine the efficiency of the process. As an example the collection efficiency with respect to the particle size for two different applied voltages is shown in figure 2-3. The indicated curves represent the results of simulations in a testing geometry with a length of 1 m (excluding the inlet and outlet areas as stated in chapter 2.1) and a diameter of 0.25 m. The corona electrode has a diameter of 1 mm and the inlet flow velocity is 2 m/s. The particle collective defined at the inlet involves particles in the size range from 0.1 µm to 100 µm with a distribution equal in number per size fraction. Though this kind of distribution is of no significance in a nonacademic context it provides access to a facile comparison of the particle behavior for studying purposes.

As expected, the collection efficiency increases with the particle diameter. Moreover it is not surprising that the curve representing the progression at the higher applied voltage, i.e. 35 kV, exhibits a shift towards higher values. Figure 2-3 indicates that the general performance of ESPs is reflected well by the presented model.

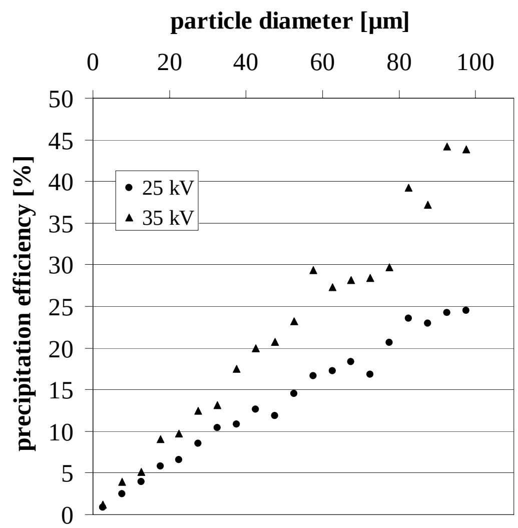

Fig. 2-3: Comparison of the computed precipitation efficiency for two different applied voltages.

To investigate the influence of the particle space charge, simulations with the same testing geometry and flow patterns as stated before are performed. A voltage of 25 kV is applied. The particle collective defined at the inlet consists of particles with a size range between 0.1 µm and 10 µm and again the distribution is equal in number per size fraction. The injected amount of particles is calculated in a manner that the overall particle load of the fluid totals to a value of 3 mg per m^3. In figure 2-4 the progression of the electric field is plotted against the radial distance from the corona wire at three different points along the middle axis of the tube with a logarithmic scale regarding the ordinate. Position 1 is located near the inlet to the precipitation zone, position 2 is displaced towards the middle of the tube and position 3 represents a location further upstream. The figure shows that the electric field is strongly altered by the particle space charge. As expected, the shape of the radial electric field near the inlet, where the particle space charge is not yet significant, remains almost unaffected. In contrast it can be seen that the field strength at position 2 is raised near the collecting electrode. This effect comes along with a drop of the electric field strength near the wire, respectively at the surface of the corona, though the influence is still marginal. The weakening effect on the field strength near the wire becomes more noticeable at position 3 but it is still not comparable with the impact near the collecting electrode. Here the particles have accumulated a significant amount of charge and have drifted towards the collecting electrode. Because the electric field strength in the inner region of the drifting zone is much higher then in the outer regions and the particle drift velocity has the same general dependency, the particles tend to assemble near the tube wall (the radial expansion of the assembling zone decreases and gets closer to the wall along the tube). Therefore it is obvious that the particle space charge effect becomes more noticeable in this area.

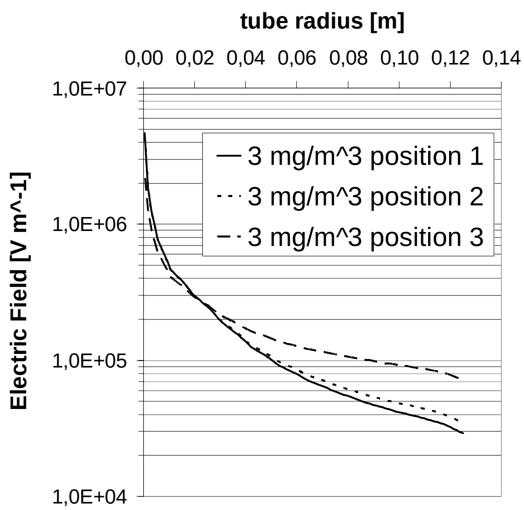

Fig. 2-4: Effect of particle space charge on the radial electric field at three different positions along the tube axis.

Figure 2-5 shows a comparison between the electric field progressions at position 2 for two simulations with different particle loads. All other parameters are held constant and have the values stated before. In one case the particle load has a value of 10 mg per m^3 and the other case represents the one already mentioned before with a particle load of 3 mg per m^3.

It is clear that the amount of particle space charge increases with the amount of particles and hence the difference between the two cases is apparent. The influence of the particle space charge is much higher in the outer region of the drifting zone as well as in the inner region near the wire for the case with a particle load of 10 mg per m^3. In the latter case the electric field strength at the surface of the corona is weakened significantly. Consequently it is assumed that under the given circumstances the effect known as corona quenching [11] would take place, resulting in a lower production rate of ions in the corona zone, but this dependency is not yet included in the model.

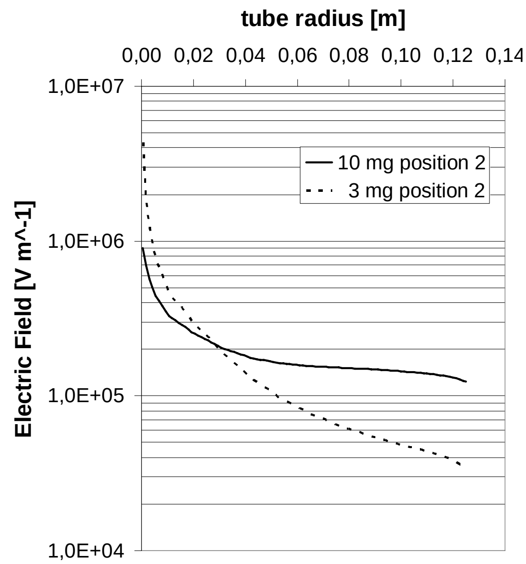

Fig. 2-5: Comparison between the effects of particle space charge on the radial electric field at two different particle loads in the middle of the tube.

2.5 Conclusions

The simulation results of the presented CFD model are in good agreement with the measurements and the considerations of other authors dealing with the given research topic.

It is shown that a coupling of the electrical portions of the Maxwell-equations and the Navier-Stokes-equation can be achieved with the used software package.

The calculation of the particle space charge distribution according to the computed particle behaviour represents the basement for the future modelling of the corona quenching effect. For this purpose further work has to be done to extend the corona model.

Due to the implementation of the model in commercially available software easy access for engineers to a useful tool for the design of wet ESP´s could be provided in the future.

3 Literature

[1] Theodore, L., Buonicore, A.J.; Air pollution control equipment; CRC Press Inc.;Boca Raton; 1988

[2] White,H.J.; Entstaubung industrieller Gase mit Elektrofiltern; VEB Deutscher Verlag für Grundstoffindustrie; Leipzig; 1969

[3] Schmid, H.-J.; Zum Partikeltransport in elektrischen Abscheidern; Dissertation; Universität Karlsruhe; 1998

[4] Lind, Leif; Nielsen, Niels F.; Simulation of particle transport in electrostatic precipitators; International Conference on Electrostatic Precipitation;Kruger Gate,South Africa;2004

[5] Peek, F.W.; Dielectric Phenomena in High Voltage Engineering; McGraw Hill Book Co.;New York; 1929

[6] Krichtafovitch, I.A. et al; Electrostatic Fluid Accelerator and Air Purifier – The Second Wind; Kronos Air Technologies;Seattle

[7] Nikas, K.S.P. et al; Numerical simulation of the flow and the collection mechanism inside a laboratory scale electrostatic precipitator; Journal of Electrostatics 63;2005; p.423-443

[8] Anagnostopoulos, J. Bergeles, G.C., Corona discharge simulation in wire-duct electrostatic precipitator; Journal of Electrostatics 54;2002,p.129-147.

[9] Lawless, P.A.; Modelling particulate charging in ESPs; IEEE Trans. Industry Applications;1988

[10] Blejan, O. et al; Experimental Study of the Corona Discharge in a Modified Coaxial Wire-Cylinder Electrostatic Precipitator; 42nd Industry Applications Conference;New Orleans;2007.10