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Modeling the pulse mode energisation of electrostatic precipitators

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Elektrosztatikus porleválasztó berendezések impulzus üzemű táplálásának modellezése

PhD thesis

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1 Introduction

Nowadays the environment protection especially air pollution control is of great importance. The regulations for dust emissions became more strict worldwide over the years. PM_{10}, $PM_{2.5}$ regulations[1] are for limiting the emission of particles of 10 micrometer in diameter or smaller and 2.5 micrometer in diameter or smaller. These regulations and the observation of these are possibilities for controlling the air pollution of industrial processes.

One of the most efficient device for controlling the particle emission of processes is the electrostatic precipitator[2]. The installation costs for an electrostatic precipitator are rather high and there are also running expenses. Comparing to other flue gas cleaning devices the installation costs of an electrostatic precipitator are higher but the long time operational costs are lower. Comparing the flue gas cleaning efficiency to other devices, the electrostatic precipitators efficiency reaches or surpasses the efficiency of other devices. Unfortunately this statement is not true for the efficiency of fine and ultra-fine dust fractions. Since the ESPs are widely used upon the advantageous properties, therefore it is of great importance to enhance the existing technologies for better performance in the fine and ultra-fine particle fractions.

To meet the more and more strict regulations for the emissions the continuous development of the electrostatic precipitators were needed. One way of development is the modification of the ESPs supply mode. Modern ESPs work no more with DC voltages but with short voltage pulses.

A lot of electrostatic precipitators operated these days in the industry are equipped with the conventional DC energisation. To operate these ESPs with an efficiency which meets the strict regulations nowadays it is necessary to upgrade these devices. One of the possibilities for the upgrading is to dismount the old DC power supply and equip the electrostatic precipitatorwith a new pulse mode power supply. In the pulse mode power supply voltage pulses are used which parameters are chosen on practical experiences. If settings for the pulse parameters are correct then the particle charging efficiency is rising, the back corona occurrence is reducing therefore the precipitations efficiency is increasing and the used energy is decreasing.

During the upgrading process the use of a numerical model can be very useful (or in some cases it is essential). The use of a numerical model makes it possible to calculate the new parameters and properties of the upgraded electrostatic precipitator. It is essential to set the parameters of the pulse mode energisation correctly, since there are cases possible (upon the gas flow, dust properties and other physical parameters) when the incorrectly set pulse energisation creates a situation with dramatically decreased collection efficiency. With the help of a numerical model it is possible in the given situation to choose the best solution from the possible parameters of the pulse energisation.

There were numerous models developed by experts in the past years. Some of these takes into consideration the effects of the dust and ionic space charge but consider stationary ionic current between the corona electrodes and collecting plates. This calculation method is accurate for DC energisation but inappropriate for the modelling of the pulse mode energised ESP.

[1]PM: Particulate Matter, Fine particles – Regulations for *Fine Particle* emission
[2]Abbreviation for electrostatic precipitator: *ESP*

The colleagues of the Department of Electric Power Engineering Group of High Voltage Engineering and Equipment and the Department of Fluid Mechanics created a numerical model for the examination of electrostatic precipitators[Kiss, 2004], [Suda, 2007]. The created numerical model is able to model the DC mode energisation of the ESP among others taking into account the ionic and dust space charge, the uncertainties in the properties of the dust and it is able to handle polydisperse dust. The modular construction of the model makes the group of calculated phenomena easily expandable and the change of the calculation method respectively. This model is limited in following the changes in the ionic and dust space charge in the ESP channel created by the change in the supply voltage, so it was able to model pulse energised electrostatic precipitators just in cases when the voltage changes were slower than a few milliseconds. Nowadays it is common to use ESP devices with power supply having pulses in the μs range.

2 The development of the model

To model the processes in a modern electrostatic precipitator more accurate it was necessary to improve our existing numerical model. The improved model should be able to accurately follow the processes in a modern pulse energised ESP such as the μs range voltage changes and the back corona formation. Based on the modular structure of the model it is easy to modify the calculations or change some modules to achieve these goals.

To follow the fast parameter changes in a pulse energised ESP it was necessary to replace the module which calculated the ionic and dust space charge in steady state for a module which cab handle the fast changes in the space charges. For this the donor-cell method were used in the new module. Using the donor-cell method the model can calculate the ionic current with fast changes and so can calculate the ionic and dust space charges in case if there are μs range pulses in the supply voltages.

The other objective of the improvement was the more precise calculation of back corona and the time necessary to its formation. Before the modifications the model were able to take the back corona into account with a module which used a fuzzy methode to calculate the back corona. To have a more accurate modelling of this phenomena the fuzzy module had to be replaced with a module which calculates the back corona upon the dust properties and electric field intensity. With the new module the model calculates the efficiency reducing effect of the back corona more accurate. This module makes also possible to determine — knowing the dust properties and the parameters of the energisation — if in a given situation back corona appears or not. Upon these the parameters of the pulse energisation can be chosen to reduce or avoid the appearance of back corona, ensure higher collection efficiency in the modelled ESP.

This module tracks the collected dust layers thickness on the collecting electrodes for determining the presence of the conditions necessary for the back corona formation, and calculates the place and time of back corona. For this, the collected dust layers charge, specific resistivity, relative permittivity and the time for the collection of a given thickness are taken into account.

3 New scientific results

The goal was to create a model for modelling the pulse mode energisation of the electrostatic precipitatorand include an accurate model of the back corona in the electrostatic precipitations process.

The first step for the improvement was to change the model to be able to track the fast changes during the operation with pulse energisation. The modular structure of the model provides a possibility for these changes. The module which calculated the steady state dust and ionic space charges had to be replaced with a new module which can track the fast changes in the ionic and dust space charge during the operation with pulse energisation. The so created new model is capable for complex examination of the ESPs, taking jointly into account the electric and flow field, the pulsed supply voltages and polydisperse dust.

The other goal was the accurate calculation of back corona discharges. To achieve this a new module was necessary to calculate the back corona. One of the main factors of the appearance of back corona is the charge of the collected dust layer. To take the dust layers charge into account it is necessary to calculate the dust reaching the collecting electrode, tracking the thickness of the dust layers and calculating the charge in the layer. During the back corona dust and ions get into the gas flow which affects the dust amount leaving the electrostatic precipitator with the flew gas and so the collection efficiency. The novel use of the calculation method which can handle the changes during pulse mode energisation makes it possible to track the collected dust layers charge and the ions generated by the back corona which is taken into account by the calculation of the space charges.

Most of the published models are not able to calculate the effect of the pulse mode energization and the occurrence of back corona. The few models, which can model the pulse energization and back corona, are neglecting also rather important phenomena and can be used with limitations.

Of course the back corona formation depends not only on the amount and properties of the collected dust on the electrodes but also on the parameters of the energisation and the rapping frequency. In view of the parameters of the voltage pulses and dust properties the model can calculate if in the given situation back corona formation is possible or not and when it occurs if the formation is possible. If back corona formation is possible it can be determined with the model, which parameters should be set for the pulse energisation and rapping to avoid back corona during the precipitation process.

The developed numerical electrostatic precipitator model can model the processes in an electrostatic precipitatorwith greater accuracy than other models before, and so it can calculate the collection efficiency more precise.

The validation of the model were done by laboratory measurements, model experiments and the results were compared to results from the literature. The results were also compared to the results of the previous model version.

In the next chapter my new scientific results are described. The exact text of the thesis is emphasized with italic shape text. Each thesis is followed by the list of my publications relevant to the specific thesis.

4 Thesis

Thesis 1 *I created a new numerical electrostatic precipitator model which is able for complex analysis of the function of electrostatic precipitators. Beyond the handling of polydisperse dust and the inclusion of the electric and flow field the improved model is able to model*

- *with the more accurate handling of the interaction between electric and flow field*
- *with handling the fast changes in the supply voltage*
- *with handling dust fractions of extremely high specific resistivity*

the operation of a pulse mode energised electrostatic precipitator.
[Iváncsy & Berta, 2002b], [Iváncsy et al., 2007a], [Iváncsy et al., 2007b], [Iváncsy et al., 2009a], [Iváncsy et al., 2004], [Iváncsy et al., 2009c], [Iváncsy et al., 2009b], [Németh & Iváncsy, 2006], [Iváncsy et al., 2006b], [Iváncsy & Suda, 2005], [Suda et al., 2006] [Tamus et al., 2008]

The modular structure of the developed ESP model makes the improvement easy by replacing or changing the existing modules. The modules of the model communicate through an appropriate constructed data structure. The data structure contains all the relevant informations necessary for description of the modelled phenomena and the modelled electrostatic precipitator.

The first module in the model calculates the parameters of the flow field. This module takes into consideration the wake field of corona wires and effect of the ionic wind on the flow[Suda, 2007]. There are models which takes into account the effect of the ionic wind so thus they calculate electrohydrodynamic flow field but these neglect the effect of the electric field on the ionic wind speed (for example by Gallimberti [Gallimberti, 1998]). The other group of existing models are dealing with only one corona electrode therefore they can not correctly calculate the wake field of corona wires, the effect of the corona electrodes on the flow field (for example by Fujishima [Fujishima et al., 2004]).

The next step is the calculation of the electric field intensity generated by the applied voltage between the grounded collecting electrode and the corona electrodes. The results of the next steps can be calculated by iterations so these are constructed as a loop.

As the first step of the loop the ionic space charge and the dust space charge is calculated which are modifying the electric field strength in the ESP. The so generated electric field intensity will be included in the next flow field calculation and by the calculation of ionic wind. The calculation of the space charges also needs an iteration process, so it is a scond loop inside the first one.

To know the dust space charge on a given place it is necessary to model the charging of the particles. If the electric field and the charge of the particles to precipitate is known then the forces on the particles generated by the electric and flow field can be calculated. These forces determine the movement of the particle s inside the electrostatic precipitator. Upon the movement of the particles the change in the dust charge distribution and the amount of particles reaching the collection plate has to be calculated.

The already collected particles can re-enter the gas flow on some physical effects, these re-entering is calculated by the dust re-entrainment module. One reason for the re-entering of the dust is the gas flow itself which erodes the dust from the collection plates. This is calculated in the model on a statistical basis. One other reason can be the back corona formation, which blasts high amount of collected dust back to the gas flow. These effect is also taken into account in the calculations of the dust re-entrainment module.

At this point the results are given back to the first module — the flow field calculation module — which uses these results for the next step of flow field calculation. This means that the total simulation is calculated in loops, where the previous results are used by the next step in the loop.

On every loops end the collection efficiency can be calculated, that means the ratio of the dust entering and leaving the electrostatic precipitatorwith the gas flow. The amount of collected dust and the amount of dust leaving the ESP with tha ga sflow is also known. To get valuable results appropriate number of loops should run in the simulation.

By setting the time step in the outer loop the model can calculate any fast changes can be taken into account, but the time of the total simulation depends also on this time step. Choosing a smaller step results a longer simulation time.

Thesis 2 *I used in the new model the donor-cell method in such way, that beyond the tracking of fast space charge changes in the modern electrostatic precipitator the new model can track the charge of the collected particles on the collecting plates and the changes in the space charge caused by the back corona formation.*
[Iváncsy et al., 2009a], [Iváncsy et al., 2004], [Iváncsy et al., 2009b], [Iváncsy et al., 2006b], [Tamus et al., 2008]

For the calculation of dust space charge and ionic space charge such a method is necessary which is able to follow the fast changes in the field strength and space charges generated by the pulse mode energisation. For this challenge a possible adequate solution is the so called donor-cell method [Levin & Hoburg, 1990], [Meroth et al., 1999], [Meroth et al., 1996a], [Meroth et al., 1996b].

The donor-cell method calculates the electric filed on an irregular mesh (mesh with different cell sizes). This type of mesh could be advantageous because the cell sizes can be smaller close to high gradient changes in the fields and more accurate calculation is needed (close to the electrodes) and larger if the gradient is small (in the middle of the ESP channel) and the accuracy of the calculation is not so important. One other advantage is, that he same mesh can be used for the electric field and flow field calculations, because in both cases the high gradient places are close to the electrodes.

This method can handle the accumulation of charges in the mesh cells. This property of the method is important for the modelling of non stationary ionic current and non stationary charge distribution which is the case by the pulse energisation. Due to the voltage pulses the ionic current and the movement of the charged particles is not uniform, wich generates accumulation of charges in the ESP channel. The donor-cell method is able to handle these changes.

I used the donor-cell methods ability of handling accumulation of charges for taking into account of the collected dust layers electric charge. The charge of the collected dust layer influences the electric field of the ESP channel and highly affect the formation of back corona discharges. If back corona occurs then with the donor-cell method it is possible to calculate the effects of charges inserted from the back-corona back into the ESP channel. These charges are opposite charges to the charges generated by the corona discharges so these recharge the particles to the opposite charges, which has an influence on the efficiency of the precipitation because these oppositely charged particles has to recharge again to the correct charge.

In the model the particles reaching the collecting electrode are collected in the cells on the collecting electrodes of the irregular mesh needed for the calculation. The charges accumulated in these cells are leaving according to the specific resistivity of the dust to the ground, with the back corona discharge or with the dust falling down due to the rapping. This method permits of the calculation according these physical phenomena.

Since the ionic space charge and dust space charge are calculated in iterations so the donor-cell method is able to include the ionic current of the back corona discharges.

Thesis 3 *Depending on the parameters of the pulse mode energisation with the improved model it is possible to determine the time necessary for the back corona formation and the intensity of back corona, nevertheless with the use of the model the parameters of the supply voltage can be chosen in such way that no back corona occurs.*
[Iváncsy et al., 2009a], [Iváncsy et al., 2009c], [Iváncsy et al., 2009b]

In the process of electrostatic precipitation the back corona formation is a relevant phenomena. The occurance of the back corona discharges highly reduces the overall performance (the collection efficiency) of the ESP. During back corona high amount of particles re-enter to the gas flow from the collected particles.

The formation of back corona is dependent on the specific resistivity of the dust particles, the thickness of the collected dust layer and the frequency of rapping. The higher the specific resistivity of the dust the slower the transfer of the charges from the particle surfaces to the grounded collecting electrodes. So the thickening collected dust layer loses the accumulated charges very slowly. Because of the accumulated charges the electric field can be reach on different places the level necessary for a discharge through the dust layer. During this discharge high amount of the collected dust is blasted back to the gas flow, and on the channel discharges as electrodes corona discharges appears which emits charges to the EPS channel oppositely charged to the charges from the corona discharges on the corona electrodes.

The modelling of this process is essential for the calculation of the collection efficiency of the electrostatic precipitators. The modelling of back corona can be divided into two parts. One is during thickening of the dust layer on the collecting plates the calculation of time dependent electric field created by the accumulated charges in the collected dust layer. The other part is the determination and calculation of the ionic current generated by the back corona, and the effect of these current on the ionic and dust space charges.

By the calculation of electric field strength the dust layers thickening in time should be taken into account and the rush attenuation in case of rapping. In the calculations the model divides the collecting plate into sections where the thickness of the dust layer at a given time supposed to be even for each section, the speed of thickening supposed also uniform for a given section and the corona current distribution is also uniform. Using these assumptions the electric field strength can be calculated on the dust layer and collecting plate arrangement.

With the thickening of the dust layer the electric field strength reaches the breakdown limit after a time, when the back corona can form. Depending on the properties of the energisation and on the dust properties the time can be calculated taking into account the dust concentration distribution and the supply voltage when the dust layer thickness reaches on a section the necessary value for the formation of back corona.

The ionic current generated by the corona discharges on the corona electrodes reaches the grounded collecting electrodes through the collected dust layer. This current flowing through the dust layer generates a voltage which together with the charge of the dust layer forms the voltage leading to the back corona formation. The higher the specific resistivity of the dust the higher is this voltage component. If the supply voltage waveform is changed then the voltage generated by the ionic current also changes. The adequate change in the supply voltage waveform increases the time before back corona occurs. Only by thicker dust layer is the voltage enough for the formation of back corona discharges.

Thesis 4 *The new numerical electrostatic precipitator model using the physical properties of the dust and the parameters of energisation describes the processes in the pulse mode ESP more accurate and provides better possibilities for the planing and operation of modern electrostatic precipitator devices.*
[Iváncsy et al., 2009a], [Iváncsy et al., 2004], [Iváncsy et al., 2009c], [Iváncsy et al., 2009b], [Iváncsy et al., 2011a], [Iváncsy et al., 2011b], [Iváncsy et al., 2006b], [Iváncsy & Suda, 2005], [Suda et al., 2006], [Tamus et al., 2008], [Iváncsy et al., 2011a], [Iváncsy et al., 2011b]

In the numerical models of electrostatic precipitators is an important factor which components of the precipitation process and which parameters are taken into account in the calculations. Because of the process complexity some phenomena has to be neglected to hold the computation time below a reasonable limit. The extremely fast development in the computer technology allows the inclusion of more and more phenomena and parameters in the ESP models.

In a numerical ESP model the following effects play a role in the efficiency of precipitation:

– electric field modified by space charges (ionic space charge and dust space charge)
– ionization (the generated free charges on the corona electrode and the ionic wind)
– particle charging, saturation charge and charging process (diffusion, field and mixed)
– gas flow (turbulent and boundary flow)
– dust collection, dust layer expansion
– dust re entrainment, back corona

In the case of modern ESP devices these phenomena can only be modelled if the model not only calculates steady state but can follow the fast (small time constant) changes and the slow (high time constant) changes in the modelling. To model the pulse mode energisation the track of fast changes is necessary because the changes in the supply voltage are in the ms and μs range and the model should be able to follow the changes generated by the supply voltage. The track of the slow changes is essential when modelling long time operation of an electrostatic precipitator, so the thickening of dust layers on the electrodes[3]

[3] there is a dust deposition on the collecting plate and on the corona wires also, characteristically the thickening of the dust deposition on the corona wire is much slower

especially by changes in the dust properties (for example by fuel change in the power plants) has to be tracked. Upon these changes the properties of the dust collected and deposited on the electrodes are not uniform, which has to be taken into account by calculating the current flowing to the grounded collecting electrode and by the calculation of time and intensity of back corona. The easiest way to calculate with the dust deposit on the corona wire is the continuous slow increasing of the corona wire diameter, which influences the corona discharges and so the charging process.

The model I created is able to include the above mentioned processes in the calculation and so it is able to model the pulse energisation and track the fast and slow changes during a long time operation modelling. In the model I created a modified donor-cell method a modified corona model and changed the corona wire diameter slowly to make the model able to model the above processes.

5 Possibilities of Practical Applications

As a part of the more and more strict environmental protection regulations also the dust emission regulations are changing for less emission. Industrial companies has two possibilities to follow the regulations. The first one is building new electrostatic precipitator devices which are able to clean the flow gas having emissions below the limits. The other option is the upgrading of already existing ESP devices to improve the collection efficiency to meet the regulations. Through the relatively high costs of a new ESP it is beneficial to upgrade the existing EPS devices.

The new complex numerical electrostatic precipitator model allows the examination of the planned ESP devices or the planned upgrading measures. An accurate model can predict the different parameters of the ESP or rather it can predict how the ESP will perform with the planed parameters. The more phenomena and parameters are taken into account in the numerical model the better the calculation results are compared to the real situation, the closer is the calculated collection efficiency to the real one. Our new model takes more physical processes into consideration then other existing models so it produces more accurate results even in the case of modern pulse mode energised electrostatic precipitator. This model can be a good and cost effective tool for predicting the performance of planed ESPs or predicting the effects of the upgrading measures.

The newly created model can be used in such situations when the collection efficiency of an electrostatic precipitatorshould be examined by changes in the dust properties entering the ESP. In this case long term modelling is necessary with high accuracy which is possible using our new model.

The rash development of the computer technology, the extreme growth of the computational capacity permits of creating more precise numerical models without enormous growth in the calculation time. This makes further development of numerical ESP models possible which takes more and more effects and phenomena into account.

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