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Modelling of Complex Physical Processes in Electrostatic Precipitators

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Modelling of Complex Physical Processes in Electrostatic Precipitators

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Abstract. Electrostatic precipitator (ESP) models have improved significantly in the past years. The dramatic development of the capacity of computers made it possible to increase the complexity of ESP models. Recently the different interactions between the gas, the electric field with ion space charge and the charged particles to be precipitated can be described more accurately by the newly developed complex approach. However even some of the newest computer models are limited; they are not able to follow the interactions of the complicated physical phenomena properly. For example pulse energisation of short time impulses cannot be described correctly with models assuming continuous corona current. There is another important problem, namely the examined duration of operation. Some of the models determine the trajectories of dust particles assuming that they are unchanged during the operation of an ESP. The validity of this assumption is very limited in such cases, where the development of certain phenomena is time dependent (e.g. back corona formation). In this paper the authors focus on the "long term" models, analysing such situations in which it is vital to investigate a longer period of operation of ESP-s. Using the newly developed model the effect of back corona, rapping, etc. can be analysed with higher reliability than it has been performed in previous ESP models.

1. Introduction

Numerical models are useful tools for predicting the performance of an electrostatic precipitator. There were numerous models developed by experts to predict the collection efficiency of ESP's. The difficulty in the modelling of ESP's is the large number of processes and phenomena which have influences on each other. In the modelling some of the effects are neglected because of the limited computational capacity or their minor influence on the modelled phenomena.

In the majority of the models 2D modelling is used. Both the electric and flow field can be treated as 2D, and the effect of gravity is neglected. This method provides a simple and good approximation of the processes in the electrostatic precipitator. The use of a 2D model reduces the amount of computation therefore longer sections – a whole ESP channel – and more complex processes can be modelled. 3D models also exists, but because of the high computational needs, these are just for short ESP sections (e.g. Chang[1], Adamiak[2]).

2. The modelled phenomena

In a numerical model it is necessary to include the parameters of the precipitated particles, the parameters of the energization and the gas flow. It is essential to know the *electric field* created inside the ESP channel since this is relevant for *particle charging* and the charged particles transferred in the *flow field*.

2.1. Calculating the electric field
The early models supposed a uniform electric field through the whole channel[3]. Later analytical approximation[4, 5], then the finite differences method[6], the finite elements method[7] and the combination of the latter two with the finite volume method were used. Nowadays combined methods such as the combination of finite differences method and finite elements method[8, 9], and the boundary element method combined with finite volume method are used.

It is highly important to include the effects of ionic and dust space charge in the calculation of electric field. Based upon practical experience and measurements, the dust space charge has a notable influence on the electric field and therefore on the corona current, back corona formation and on the efficiency of the precipitation.

2.2. Particle charging
For the calculation of the particle charge in numerical models there evolved two major ways. One assumes for a given particle diameter a constant saturation charge through the whole ESP. The particles are assumed charged to the saturation charge from their entry in the ESP. Numerous models use this method[10, 11]. The other possibility is to calculate the charge of the particles in a time and position dependent way, taking into account the local electric field and the charge distribution. This method was also used by P. A. Lawless and later in a Lagrangian particle movement simulation by Meroth[12] and Schmid et al.[13]. There are just a few models which calculate the dust space charge using the Lagrangian method (one example is the model from I. Gallimberti[14]). The best solution is the use of the combined charging model and the Lagrangian approach for the particle movement[15].

2.3. Flow field
Simple models assume constant gas velocity profile in the cross-section of the channel (e.g. Deutsch[16] and Ramadan & Soo[17]). Beside the laminar flow models there were numerous different turbulent flow models created, such as $k-\varepsilon$ turbulence model: Kallo & Stock[9]; DNS: Soltani et al.[10]; LES: Ullum[11]. These CFD simulations made the models more accurate, and through the determination of the diffusion coefficient ($\mathrm{D_p}$) it is possible to calculate important turbulent flow parameters, for example the flow modification effect of the corona electrode geometry.

Nowadays the effect of the ionic wind on the turbulent gas flow can be better analysed. The differences in the EHD simulations are in the details of how they take into account the charge densities (ρ_i and ρ_d). One example of a model where the space charges and the ionic wind are also taken into account is the LES model created by Ullum[11]. Because of the large computational demand it just calculates an ESP section with 2 corona electrodes.

3. Long-time modelling
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

To have an accurate model it is necessary to model these phenomena as accurately as possible and holding the computational needs of the simulation as low as possible. For the long time models it is necessary to generate a model, which calculates the processes in a non stationary manner i.e. it takes the short time (fast) changes and also the long time (slow) changes into account, especially in the case of pulse energization.

If there is a change in the parameters of the incoming dust (e.g. by fuel changes) the collection efficiency changes. In such cases the relative permittivity, particle size and resistivity of the dust changes, which influences the saturation charge, cohesion of the collected dust and back corona formation. Also, rapping has an influence on the dust emission. Closer to the inlet, larger particles are collected while closer to the outlet small particles[18], so the collected dust layer is different.

The different dust layer formation needs a different rapping cycle. The rapping of the sections closer to the outlet has greater influence on the dust emission, since the re entering dust particles are closer to the outlet and have smaller particle size which needs longer to collect. However the rapping cycle has a longer time period, because less dust reaches the last sections of the ESPs.

Also the back corona formation depends highly on the collected dust layer thickness, therefore the back corona occurrence is supposed closer to the inlet.

There are dust deposits on the corona electrodes which should be handled in the long-time modelling also. These dust deposits can be handled as changes in the corona wire diameter.

4. Conclusions

In the long-time modelling it is essential to track the amount of dust collected on the collecting electrode and modelling the effect of rapping. Practical experience shows that, the changes in the dust properties can generate lower efficiency periods for a while. The model should be able to handle dust mixtures with different electric properties and different concentrations. These property changes should be tracked on the collected dust layer also, to get reliable results.

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Table 1. The main parameters of Electrostatic Precipitator models (numerical simulation)[15]

	Modelling of electric field				Charging of particles		Modelling of flow field					Modelling of two-phase flow	
	Uniform, constant electric field intensity	Analitical approximation	Numerical simulation	Including of ion- and particle space charge	Determination of saturation chgarge	Modelling of charging process	Constant velocity profile	Analitical velocity profile	CFD	Including the ionic-wind	Including discharge electrode geometry in simulation	Eulerian modelling $0 < D_p < \infty$	Lagrangian modelling
Literature 1922–2007													
Deutsch (1922)												∞	
Anderson (1924)							□					∞	
Williams & Jackson (1962)												Const.	
White (1963)	□						□					Const.	
Ramadan & Soo (1969)				I+P						∗			
Feldman (1975)												∞	
Cooperman, P. (1971, 1977)	□											Const.	
McDonald et al. (1977)			FD / FD			F + D							
Yabe et al. (1978)			FD / FD	I					Lam.	∗			
Bernstein & Crowe (1979)			FD / FD	I					Lam.	∗			
Leonard et al. (1980, 1982, 1983)												Const.	
Yamamoto & Velkoff (1981)			FD / FD	I					Lam.	∗			
Yamamoto (1984, 1989)			FD / FD	I					Lam.	∗		0	
Berta (1984)			FD / FD	I					Lam.	∗			PTM
Self et al. (1984)												Const.	
Shaughnessy et al. (1985)			FD / FD	I					TH	∗			
Davidson & Shaughnessy (1986)			FD / FD	I					TH	∗			
Kihm et al. (1985, 1987)												Const.	
Petroll & Födisch (1988)						F + D						Const.	
Watanabe (1989)				I									PTM
Zamany (1992)			FD / FD			C			k − ε			Const.	
Riehle (1992)	□			I		C						Const.	SRF
Zhibin et al. (1992, 1993, 1994)			FD / FD	I		C	□			TH		Const.	
Kallio & Stock (1992)			FD / FE	I					k − ε	∗	⊙		
Riehle & Löffler (1993)	□			I		C						Const.	
Liang & Lin (1994)			FD / FD			C			k − ε			Loc.	
Bai et al. (1995)						F			Lam.			0	
Caňadas et al. (1995)				I + P		F + D							
Lami et al. (1995)			FD / FD	I + P						∗			
Riehle & Löffler (1995)	□			I		C						Const.	SRF
Palmer (1996)			FD / FE	I					k − ε	∗	⊙		
Khare & Sinha				I		F							
Lawless (1993, 1996)			FD / FD	I	□	FDM						Const.	
Schmid & Schmidt (1996)			FD / FD			C						∞	
Riehle (1996b)	□			I		C						Const.	SRF
Goo & Lee (1996, 1997)			FD / FD	I		F + D			k − ε		⊙		CRW
Choi & Fletcher (1997)			FD / FV	I + P		F			k − ε		⊙		EL
Egli et al. (1997)			FE / FE	I		F			Lam.	∗			PTM
Meroth (1997)			FE / FV	I		FMD			k − ε				EL
Gallimberti (1997)			FD / FD	I + P		FMD			k − ε	∗			PTM
Suda (1997) /M.Sc./	□			I + P	□	C			BL			Loc.	
Medlin (1998)			FD / FV	I + P		C			k − ε	∗	⊙	Const.	
Lu & Huang (1998)			FD / FD	I		C						∞	
Soltani et al. (1998)									DNS				PTM
Soldati et al. ('93, '97, '98, 2000, 2002)			FD / FD	I					DNS				CRW
Parasram (2001)			FD / FE	I		C			k − ε				CRW
Kim et al. (2001)			FD / FD	I		C						Loc.	
Böttner & Sommerfeld (2001)			FV	I		F			k − ε				PTM
Park & Chun (2002)						C						Const.	
Varonos et al. (2002)			FD			C			k − ε				PTM
Schmid et al. (2002)			FE / FV	I		FMD			k − ε	∗	⊙	Loc.	CRW
Böttner (2002, 2003)			FV	I		C			k − ε	∗			PTM
Ullum (2003)			FV	I + P		C			LES	∗			PTM
Lind et al. (2004)			FD / FD	I + P		F + D			k − ε	∗		Const.	
Fujishima et al. (2004)			FD / FD	I + P		F + D			k − ε	∗			PTM
Nikas et al (2005)			FD / FD	I		F + D			k − ε	∗			PTM
Zhang et al. (2005)			FV	I		F + D			k − ε	∗			CRW
Talaie et al. (2001, 2005)			FD	I + P		FMD			k − ε	∗			CRW
Skodras et al. (2006)			FV	I + P		C			k − ε	∗	⊙		PTM
Kiss & Suda (2007)			BEM / FV	I + P		C			k − ε	∗	⊙	Loc.	(PTM)

Legend:

(grey) model by the referenced author (grey) □ parameter of the previous version

Modelling of electric field

FD	Finite differences method
FE	Finite elements method
FV	Finite volume method
BEM	Boundary element method
I	Including ionic space charge
P	Including dust space charge

Modelling of particle charging

F	Field charging, impact ionization
D	Diffusion charging
C	Field and diffusion charging
FMD	Field modified diffusion charging theory
FCT	Flux Corrected Transport method

Modelling of flow field

⊙	Corona electrode geometry modelling
∗	Including ionic wind
TH	Theoretical examination
Lam.	Laminar model
k − ε	k − ε Turbulence model
BL	Boundary layer equation
DNS	Direct numerical simulation
LES	Large eddy simulation
EL	Eddy lifetime

Modelling of two-phase flow

Eulerian modelling

0 / ∞	D_p diffusion coefficient
Const.	Constant D_p value
Loc.	Local D_p value

Lagrangian modelling

CRW	Continuous random walk model
SRF	Simulated particle flow with random generated fluctuating velocity
PTM	Particle trajectory model