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Electrostatic Precipitators Modelling and Analytical Verification Concept

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Assumptions

Electrostatic Precipitators

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- spherical particles
- fluid (air) incompressible, ideal gas behavior, turbulent flow
- fully developed velocity profile
- isothermal flow
- buoyancy neglected
- · convective and diffusive terms neglected
- free slip electrode

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Electrostatics

Numerical Model

$$\nabla \cdot \boldsymbol{E} = \frac{\rho_{el}}{\varepsilon_0} \tag{1}$$

$$\boldsymbol{E} = -\nabla\phi \tag{2}$$

$$abla \cdot \boldsymbol{J} = \boldsymbol{0}$$
 (3)

$$\boldsymbol{J} = \rho_{el}(\boldsymbol{w} + b\boldsymbol{E}) - \mathcal{D}\boldsymbol{\nabla}\boldsymbol{\rho_{el}} \tag{4}$$

$$\nabla^2 \phi = -\frac{\rho_{el}}{\varepsilon_0}$$
(5)
$$E \nabla \rho_{el} = -\frac{\rho_{el}^2}{\varepsilon_0}$$
(6)

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Outlet Outlet Free Slip Wall No Slip Wall Ζ Stick Bounce $\rightarrow r$ ϕ_2 : Ground $\phi_1 = 18 \, kV$ **Turbulent Flow** $\frac{J_0}{b E_0}$ $\rho_{el_0} =$ computational domain R_1 R_2 Particle Tracing Inlet Inlet

COMSOL Setup

Boundary Conditions





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Electric Field Strength along the radius



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Space Charge Density along the radius



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Flow Simulation

• no slip - BC on emitting electrode

COMSOL Setup

- iteration scheme computation time efficient and robust
- automation of the iterative procedure fully coupled approach (solver-tuning)
- include diffusion and convection in the physical model

Analytical Verification

- physical model is *mathematically* correct
- experimental validation is delicate



Source: Poppner, Marc et al. (2005): Electric Fields coupled with ion space charge. Part 1 + 2. Journal of Electrostatics. Volume 63. S.775-787. Amsterdam: Elsevier.

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Completed Points

- Simulation of an entire ESP including
 - Flow Simulation
 - Electrostatics + Charge Conservation
 - Particle Charging Processes
 - Particle Motion + Deposition Efficiency

Conclusions

- Customizable code needed (user-defined PDEs)
- Concept numerically robust and practical
- Analytical verification appropiate
- Experimental validation quite delicate

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Thank you for your attention.

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Cunningham Coefficient

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Industrial Standard



Source: http://www.neundorfer.com/knowledgebase/electrostaticprecipitators. Accessed on 13/10/2015

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Appendix Coupled Physics in ESPs



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Analytical Verification

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Naumann-Drag

Charging

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Dimensionless Equations

$$\frac{E}{E_{o}} = \hat{E} = \frac{1}{\hat{r}}\sqrt{1 + \hat{A}(\hat{r}^{2} - 1)}$$

$$\frac{\rho_{el}}{\varepsilon_{0}E_{o}} = \hat{\rho}_{el} = \frac{\hat{A}}{\sqrt{1 + \hat{A}(\hat{r}^{2} - 1)}}$$

$$\hat{A} = \frac{j_{o}r_{E}}{\varepsilon_{0}bE_{o}^{2}}$$
(9)

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Experimental Validation I

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Space Charge Density



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Experimental Validation II

Electric Potential



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Maxwells Equations

$$\nabla \cdot \boldsymbol{D} = \rho_{el} \tag{10}$$
$$\nabla \times \boldsymbol{H} - \frac{\partial \boldsymbol{D}}{\partial t} = \boldsymbol{J} \tag{11}$$
$$\nabla \times \boldsymbol{E} + \frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{0} \tag{12}$$
$$\nabla \cdot \boldsymbol{B} = \boldsymbol{0} \tag{13}$$

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Schiller-Naumann Drag Model

$$F_D = \frac{1}{\tau_p} m_p w_p \tag{14}$$
$$4\rho_n {d_n}^2 \tag{14}$$

$$\tau_p = \frac{4\rho_p a_p}{3\mu C_D R e_p} \tag{15}$$

$$C_D = \frac{24}{Re_p} (1 + 0.15 Re_p^{0.637})$$
(16)

$$Re_p = \frac{\rho w_p d_p}{\mu} \tag{17}$$

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Charging Processes $\lambda \sim 10^{-8} {\rm m}$

$$C_c = 1 + \frac{\lambda}{d_p} \Big[2.34 + 1.05 \ exp\Big(-0.39 \frac{d_p}{\lambda} \Big) \Big]$$
(18)



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Cunningham Coefficient

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Deposition Efficiency

$$\eta_{ESP} = 1 - \frac{N_{out}}{N_0} = 1 - exp\left(\frac{-w_p A_c}{\dot{V}}\right) \tag{19}$$

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Appendix Corona Onset Field Strength

$$E_0 = 3 \times 10^6 f_r \left(m_s + 0.03 \sqrt{\frac{m_s}{\frac{d_e}{2}}} \right)$$
(20)
$$m_s = \frac{p}{p_{ref}} \frac{T_{ref}}{T}$$
(21)

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Particle Charging Processes

Diffusion Charging

$$q_d(t) = \frac{2\pi\varepsilon_0 kT d_p}{e} ln \left(1 + \frac{t}{\tau_d}\right)$$
(22)

Field Charging

1

$$q_f(t) = \left(\frac{3\varepsilon}{\varepsilon + 2}\right) \pi \varepsilon_0 E d_p^2 \frac{t}{t + \tau_f}$$
(23)

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Demo (Source: youtube.com/pentenrieder)



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