GRADE EFFICIENCY AND EDDY DIFFUSIVITY MODELS

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Abstract

Particle transport in electrical precipitators modeled by the convective diffusion equation is governed by two dimensionless quantities: Peclet-number $w_{th}s/D$ and electrical drift parameter w_{th}/v. What is concerning practical aspects, in particular grade efficiency, it does not make sense to keep e.g. the electrical drift parameter constant and to vary the Peclet-number or vice versa because *both* quantities are functions of particle size. Therefore this paper shows calculated efficiency results as function of particle size for *different but corresponding* parameter settings by using published analytical solutions (case of a homogeneous electrical field) and numerical solutions (case of inhomogeneous electrical field).

Using the analytical solutions the grade efficiency especially for particle sizes <0,5 µm is almost independent of the value of the eddy diffusivity. Considering the local character of the electrical field by using a numerical solution the grade efficiency for particles <0,5 µm is always worse than before and the curves are indeed dependent of the eddy diffusivity value. The influence of a homogeneous ionic space charge on the grade efficiency can also be demonstrated.

Introduction

Modeling particle transport in electrical precipitators is generally enclosed by two limiting cases: laminar flow conditions and turbulent flow with an ideal back mixing of particles. In can be shown by different methods /1,2/ that in precipitators having a laminar velocity profile and a homogeneous electrical field, grade efficiency is determined by straight particle trajectories leading finally to Eq. 1. This situation is schematically illustrated in Fig. 1.

$$T(d_p) = \frac{w_{th}\left[Q_p^{\infty}(d_p, E), E\right] L_{NE}}{v_0 \, s} \tag{1}$$

For turbulent flows Deutsch could show already in 1922 /3/ that under certain assumptions (e.g. no gradients of particle concentration do exist across a precipitator duct because of ideal back mixing) grade efficiency can be calculated according to Eq. 2; the schematic illustration may be viewed in Fig. 2.

$$T(d_p) = 1 - \exp\left\{ - \frac{w_{th}\left[Q_p^{\infty}(d_p, E), E\right] L_{NE}}{v_0 \, s} \right\} \tag{2}$$

Beside precipitator length L_{NE}, half plate-to-plate distance s and mean gas velocity v_0 Laminar and Deutsch model as well include the migration velocity w_{th} of the particles emerging from a balance of drag force and electrical force (Eq. 3). It is a function of particle size d_p, particle charge Q_p and electrical field strength E, whereby b_p can be read as particle mobility. Particle charge is calculated according to the equation of Cochet /4/ (Eq. 4) which is discussed elsewhere /2/. (In all calculations a relative dielectric permittivity of $\varepsilon_r = 10$ and a mean free path of gas ions of $\lambda = 0{,}065$ µm was assumed.)

$$w_{th} = \frac{Q_p^{\infty} E}{3 \pi \eta d_p} \left(\cdot C u\right) \equiv b_p \cdot E \tag{3}$$

$$Q_p^{\infty} = \left\{ \left(1 + 2\lambda / d_p\right)^2 + \left(\frac{2}{1 + 2\lambda / d_p}\right) \cdot \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right) \right\} \cdot \pi \, \varepsilon_0 \, d_p^2 \, E \tag{4}$$

From early photographic studies and recently presented video tapes it is known that in reality concentration profiles do actually exist /5,6/. Therefore people have been trying to model particle transport in electrical precipitators by introducing a finite diffusivity value D_p for the particles since a long time (see chronological listing). All efforts undertaken lead to different types of the so-called convective diffusion equation while the most popular will be explained and analyzed in the next section.

1959	S. K. Friedlander /7/
1962	J. C. Williams, R. Jackson /8/
1971	P. Cooperman /9/; S. L. Soo,L. W. Rodgers /10/
1976	M. G. Marietta, G. W. Swan /11/
1977	J. Petroll /12/; P. L. Feldman, K. S. Kumar, G. D. Cooperman /13/
1979	H. Gross /14/
1980	G. Leonard, M. Mitchner, S. A. Self /15/
1982	R. P. Llewelyn /16/
1984	G. Cooperman /17/
1986	J. Petroll /18/
1987	K.D. Kihm, M. Mitchner, S.A. Self /19/;
	S. Hassid, A. Oron, C. Gutfinger /20/
1988	J. Petroll, H. Födisch /21/

Theoretical Background

Fundamentally a flux of a quantity r passing the surface A of a volume V is always correlated with the change -dr/dt or, equivalent with change in concentration $\partial c_r/\partial t$ inside of V (Eq. 5). Changing from integral to local formulation and regarding continuity delivers Eq. 6 and, in the present case, j represents the flux density of particles.

$$\int_A \vec{j}_r \, d\vec{A} = -\frac{dr}{dt} = \int_V \frac{\partial c_r}{\partial t} dV \qquad (5)$$

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

In electrical precipitation the particle flux density consists of three contributions: j_{el} is driven by the electrical field (Eq. 7), j_F is driven by the flow of the fluid (Eq. 8) and j_D is driven by molecular diffusion (Eq. 9). Obviously the last one is extremely small compared to j_{el} and j_F , therefore it can be neglected.

$$\vec{j}_{el} = c\, b_p \vec{E} \qquad (7)$$

$$\vec{j}_F = c\, \vec{v} \qquad (8)$$

$$\vec{j}_D = -\, D \operatorname{grad} c \qquad (9)$$

In steady state turbulent flow the local fluid velocity and the local particle concentration as well show fluctuations in time. Therefore it is common to split up the instantaneous values into an time averaged value (indicated by the bar) and a part depending on time (indicated by the prime) according to Eq. 10/11.

$$c(t) = \bar{c} + c'(t) \tag{10}$$

$$\vec{v}(t) = \bar{\vec{v}} + \vec{v}'(t) \tag{11}$$

Indroducing the Equations 7-11 into Eq. 6 and averaging in time lead to the following expression:

$$\text{grad}\,\bar{c} \cdot (b_p \vec{E} + \bar{\vec{v}}) + \text{grad}\,b_p \cdot (\bar{c}\,\vec{E})$$

$$+ \text{div}\,\bar{\vec{v}} \cdot (\bar{c}) + \text{div}\,\vec{E} \cdot (\bar{c}\,b_p) + \nabla \overline{c'\vec{v}'} = 0 \tag{12}$$

By using distinct assumptions Eq. 12 may be easiliy simplified; possible assumptions are:

a) *Incompressibility:* $\text{div}\,\bar{\vec{v}} = 0$ (13)

For all conditions where electrical precipitators are operated a realistic assumption.

b) *Homogeneous particle charge:* $\text{grad}\,b_p = 0$ (14)

Since particle charging happens usually in an extremely inhomogeneous electrical field even the charge of particle of identical size will be different, and therefore their particle mobility too. Thus Eq. 13 is a crude simplification of reality.

c) *No space charge:* $\text{div}\,\vec{E} = 0$ (15)

In single-stage precipitators onto which most of the industrial and scientific interest is focused, gas ions are present all over the duct influencing the electrical field, i.e. charging and transport conditions. Therefore the assumption of Eq. 14 cannot represent realistic operation conditions.

d) *Particle- or Eddy Diffusivity:* $\overline{c'\vec{v}'} = -D_p\,\text{grad}\,\bar{c}$ (16)

The product of two fluctuating quantities does not disappear if averaging in time. In transport theory this effect is sometimes called Reynolds-stress. In analogy to molcular transport theory it is a common method to model such a time average by a gradient in concentration and a transport coefficient. Concerning particle transport the coefficient D_p is called particle or eddy diffusivity, or simply mixing coefficient. In principle D_p is a quantity of local character and the term in Eq. 16 has to be modeled by Eq. 17. For simplification one usually assumes D_p = const. all over the space, so the term in Eq. 16 can be replaced by Eq. 18.

d1) D_p inhomogeneous: $$\nabla \overline{c'\vec{v}'} = - \operatorname{grad} D_p \cdot \operatorname{grad} \bar{c} - D_p \cdot \Delta \bar{c} \qquad (17)$$

d2) D_p homogeneous: $$\nabla \overline{c'\vec{v}'} = - D_p \, \Delta \bar{c} \qquad (18)$$

Analytical Solution

It is common to regard the particle transport in precipitators as a two-dimensional problem. The coordinate system together with the variables used are illustrated in Fig. 3. Assuming that the averge flow field and the electrical field are of vector type as given in Eq. 19, then the assumptions a, b, c , d (Eq. 18) lead to the well known convective diffusion equation (Eq. 20).

$$\bar{\vec{v}} = \begin{pmatrix} v_0 \\ 0 \end{pmatrix} \quad ; \qquad \vec{E} = \begin{pmatrix} 0 \\ E_{ps} \end{pmatrix} \qquad (19)$$

$$v_0 \cdot \frac{\partial \bar{c}}{\partial x} + w_{th} \cdot \frac{\partial \bar{c}}{\partial y} - D_p \cdot \left(\frac{\partial^2 \bar{c}}{\partial x^2} + \frac{\partial^2 \bar{c}}{\partial y^2} \right) = 0 \qquad (20)$$

Dedimensionalizing Eq. 20 with half plate-to-plate distance s, gas velocity v_0 and particle concentration at the entrance c(x'=0) reveals that the the convective diffusion equation (Eq. 21, for clarity the bars have been omitted) is governed by two dimensionless numbers: the ratio of the transversal particle velocities Ω (Eq. 22), what we call transport parameter (compare /22/), and the ratio of two countercurrent transport effects, namely electrical transport against eddy diffusivity, the Peclet number (Eq. 23).

$$\frac{1}{\Omega} \cdot \frac{\partial c'}{\partial x'} + \frac{\partial c'}{\partial y'} - \frac{1}{Pe} \cdot \left(\frac{\partial^2 c'}{\partial x'^2} + \frac{\partial^2 c'}{\partial y'^2} \right) = 0 \qquad (21)$$

$$\Omega = \frac{w_{th}}{v_0} \qquad (22)$$

$$Pe = \frac{w_{th} \cdot s}{D_p} \tag{23}$$

The way of finding the analytical solution was comprehensively described by Leonard et al. and a detailed solution is published in /15/. The particle concentration is given by a sum of m eigenfunctions (Eq. 24) and, unfortunately, the complex relations for the eigenvalues Θ_m and the constant C_m are tough to handle. When realizing Eq. 24 on a computer the effect of different eddy diffusivity values is easily to see as Fig. 4 demonstrates. For low diffusivity values $D_p \rightarrow 0$ the model tends to the Laminar case, while for high diffusivity values $D_p \rightarrow \infty$ the Deutsch model emerges. (The border condition is represented by Eq. 27 eqiuvalent with horizontal tangent at collecting plate; the question of appropriate border conditions is discussed e.g. in /15/).

$$c(x', y') = c(x'=0) \cdot \sum_{m=1}^{\infty} C_m \cdot \exp\left(-\Omega \cdot x' \cdot F_m\right) \cdot \exp\left(\frac{Pe \cdot y'}{2}\right) \cdot \left\{\cos\left(\Theta_m y'\right) + \frac{Pe}{2\,\Theta_m} \cdot \sin\left(\Theta_m y'\right)\right\} \tag{24}$$

$$C_m = \frac{C_Z}{C_N} \qquad \text{with:} \tag{25}$$

$$C_Z = \frac{\exp\left(-\frac{Pe}{2}\right)}{\Theta_m^2 + \frac{Pe^2}{4}} \cdot \left\{-Pe \cdot \cos\left(\Theta_m\right) + \left(\Theta_m - \frac{Pe^2}{4\,\Theta_m}\right) \cdot \sin\left(\Theta_m\right) + \frac{Pe}{\exp\left(-\frac{Pe}{2}\right)}\right\}$$

$$C_N = \frac{1}{2} + \frac{Pe}{4\,\Theta_m^2} + \frac{Pe^2}{8\,\Theta_m^2} + \frac{1}{4\,\Theta_m} \cdot \left(1 - \frac{Pe^2}{4\,\Theta_m^2}\right) \cdot \sin\left(2\Theta_m\right) - \frac{Pe}{4\,\Theta_m^2} \cdot \cos\left(2\Theta_m\right)$$

$$F_m(\Omega, Pe) = \frac{1}{\Omega^2} \cdot \frac{Pe}{2} \cdot \left\{\sqrt{1 + \Omega^2 \cdot \left[1 + \left(\frac{2\,\Theta_m}{Pe}\right)^2\right]} - 1\right\} \tag{26}$$

$$\tan \Theta_m = \frac{-2\left(\frac{2\,\Theta_m}{Pe}\right)}{1 - \left(\frac{2\,\Theta_m}{Pe}\right)^2} \tag{27}$$

Results

An analytical integration of the concentration profile at precipitator's exit will easily lead to the grade efficiency (Eq. 28).

$$T(d_p) = 1 - \sum_{m=1}^{\infty} C_m \cdot \exp\left(- \Omega \cdot \frac{L_{NE}}{s} \cdot F_m\right) \cdot \frac{\sin\Theta_m}{\Theta_m} \exp\left(\frac{Pe}{2}\right) \qquad (28)$$

For practical aspects the grade efficiency curves are important to know, but the particle size of Eq. 28 is hidden behind the transport paramter Ω and the Pe-number. This is why the values for both parameters cannot be varied independently. In Fig. 5 grade efficiencies for a precipitator of 2s = 200 mm, L_{NE} = 500 mm, v_0 = 1,0 m/s and U = 50 kV can be viewed, calculated according Eq. 28 .

The efficiency minimum in all curves is caused by the Cochet equation considering diffusional effects in the field charging process of particles. It may surprise that the difference in efficiency for particles below 1μm is rather small, while the largest difference is to observe around 2μm. Of course the absolute trends are depending on the operating conditions used for calculation.

Would this behaviour significantly change when the local structure of the electrical field is taken into account?

Numerical Solution

Considering the local character of the electrical field means that two components E_x and E_y appear in the convective diffusion equation and, instead of Eq. 19 we now have Eq. 29. The components of the electrical field are derived according to Eq. 30 from a potential function (Eq. 31), whereby φ_L represents the pure electrostatic part and φ_N the contribution of the ionic space charge. This space charge is determined by the electrical current density, which can be derived according to the formula of G. Cooperman /23/. The explicit formulas of the potential functions used have already been discussed in an earlier publication to which the interested reader may refer /24/; the space charge distribution discussed is assumed to be homogeneously distributed over the duct, which is in reality not the case but simplifies the calculation procedure because of the existence of an analytical expression for the electrical field.

$$\vec{v} = \begin{pmatrix} v_0 \\ 0 \end{pmatrix} \quad ; \quad \vec{E} = \begin{pmatrix} E_x \\ E_y \end{pmatrix} \qquad (29)$$

$$\vec{E} = - \operatorname{grad} \varphi(x,y) \qquad (30)$$

$$\varphi(x,y) = \varphi_N(x,y) + \varphi_L(x,y) \qquad (31)$$

Taking again the assumptions a, b, c, d (Eq. 18) a modified convective diffusion equation (Eq. 32) emerges. The same dedimemensionalizing procedure as before brings up Eq. 33 (again the bars have been omitted for clarity).

$$(v_0 + b_p E_x(x,y)) \cdot \frac{\partial \overline{c}}{\partial x} + b_p E_y(x,y) \cdot \frac{\partial \overline{c}}{\partial y} - D_p \cdot \left(\frac{\partial^2 \overline{c}}{\partial x^2} + \frac{\partial^2 \overline{c}}{\partial y^2} \right) = 0 \qquad (32)$$

$$\left(\frac{1}{\Omega} + E'_x(x',y') \right) \cdot \frac{\partial c'}{\partial x'} + E'_y(x',y') \cdot \frac{\partial c'}{\partial y'} - \frac{1}{Pe} \cdot \left(\frac{\partial^2 c'}{\partial x'^2} + \frac{\partial^2 c'}{\partial y'^2} \right) = 0 \qquad (33)$$

In addition to the work of Kihm et al. the ionic space charge (resulting from a current densitiy corresponding to the applied voltage) was considered when solving this convective diffusion equation. This was done although the existence of an ionic space charge contradicts to assumption c, i.e. working with a space charge leads in a rigorous treatment to a different differential equation. Since the studies serve for the present as first order approximation this fact has been ignored. The rigorous treatment has to solve the Maxwell equations for the electrical field and the space charge distribution (e.g. done in /25/) and these data fields have to be incorporated into the convective diffusion equation, which needs obviously an immense computational effort.

Results

Incorporating the local electrical field, Eq. 33 was solved by Kihm et al. /19/ with a numerical method and concentration profiles were calculated as functions of different Pe-numbers and transport parameters. In this paper the same numerical method was used to calculate grade efficiencies for different but corresponding Pe-numbers and transport parameters Ω. For each parameter setting the computation procedure leads to the distribution of particle concentration within the duct.

Fig. 6 examplarily illustrates the transport of 1 μm particles in the single-stage precipitator discussed (Fig. 3) at room conditions and a gas velocity of 1,0 m/s. Plotted are lines of constant concentrations and in this example the particle diffusivity was set to 5,0 cm^2/s. The applied voltage of 50 kV generates at the collecting plates a current density of 2,9 mA/m^2. It is clearly to see that the high electrical field strengths around the discharge wires cause a strong deflection of the particles towards the plates resulting in very low concentrations near the wires. After passing one wire the eddy diffusivity remixes the remained particles so that concentration increases again until the next high electrical field strength of the following wire appears. This leads to the step-like structure of concentration in the middle of the duct. For y' > 0,2 there is almost no influence of the inhomogeneous character of the electrical field on the particle transport detectable; it increases continously towards the collecting plate and it decreases along the axis of gas flow. Since 1 μm particles migrate rather slow, at the collecting plate the reduction is observable not before x' ≈ 3,0. After passing the precipitation zone of L_{NE} = 5s a distinct concentration profile exist which will remixe further downstream because of the eddy diffusivity. Therefore the grade efficiency has to be calculated by numerically integrating the concentration profile at precipitator's exit (and relate it to the entrance profile).

The difference between calculating grade efficiency once with pure electrostatic field and once with a homogeneously distributed space charge as mentioned above is demonstrated in Fig. 7. Obviously in the fine particle region there is only a small effect of the field enhancement by the space charge. For the parameter settings shown a distinct increase is to observe between 0,6 μm and 3 μm. Thus all results presented later on in this paper are based on numerical calculations considering the space charge.

For the same operational settings used to get the analytical results of Fig. 5 (gas velocity of 1,0 m/s and applied voltage of 50 kV, but now a space charge of a current density of 2,9 mA/m^2 is considered), the numerical procedure was performed and the grade efficiency results are shown in Fig. 8. The five curves which can be viewed represent five values for particle diffusivity 1/5/10/50/100 cm^2/s. As to expect the lowest diffusivity values show the highest efficiencies. In opposite to the analytical solution, now in the fine particle region (< 1 μm) there is a distinct dependence beteween diffusivity value and efficiency. Even the efficiencies for the lowest diffusivity are worse than the Deutschian values. For D_p = 100 cm^2/s there is almost no precipitation at all. Looking at particles > 1 μm there seems to be a strong decrease in efficiency between diffusivites of 10 and 100 cm^2/s, while the difference between D_p = 1 and 10 cm^2/s is not severe.

It may surprise that with a consideration of local structures in the calculation procedures efficiencies become worse than the Deutschian limit. A similar result, in certain respect has been earlier found by Kihm et al. /1/. With an interpretation especially what is concerning practical effects one should be careful, however, since the convective diffusion equation does only model particle transport, and nothing else. While in real precipitators the reasons for efficiencies lower than the Deutschian ones are presumably caused by secondary effects such as reentrainment, sneakage or back corona. Grade efficiency measurements in laboraory precipitators, intentionally excluding all secondary influences and thus looking only at the effect of electrical field on particle transport, can even show higher efficiencies than the Deutsch Model predict /22/. In particular in the fine particle region below 1 µm the measured efficiencies are looking even better than the predictions of the Laminar Model /2/. These facts inevitably raise the question, if the common forms of the convective diffusion equation considering local structures are principally appropriate to model particle transport.

Conclusions

Describing particle transport in electrical precipitators with a convective diffusion equation analytical solvable, grade efficiencies are limited by the Laminar and the Deutsch Model. The effect of particle diffusivity is distinct in the particle range 1 - 10 µm, while in the fine particle region below 1 µm its influence is surprisingly low.

Describing particle transport with a convective diffusion considering the local structure of the electrical field strength (with or without space charge) the grade efficiencies show a dramatic decrease for diffusivities > 10 cm^2/s, so that the values fall far below the Deutschian limit. In the fine particle region even the values for low diffusivities (1 cm^2/s) lay below the Deutschian values. In an application of these results to real precipitators one should be careful, however.

Since measurements of particle transport (published elsewhere /22/) indicate that pure particle transport works even better than Deutschian or Laminar (fine particle region) theory, the helpfulness of convective diffusion models is principally questionable what is concerning practical aspects, in particular when taking into account the computational effort. An improvement may be expected when neglecting unrealistic assumptions such as "No Space Charge" or "Homogeneous Particle Charge" when deriving the differential equation; unfortunately the mathematical effort increases still more dramatically.

Acknowledgements

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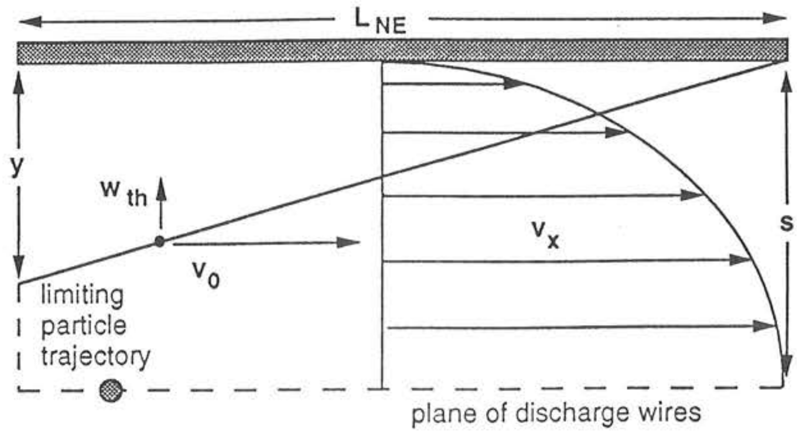

Fig. 1: Schematic illustration of the Laminar Model

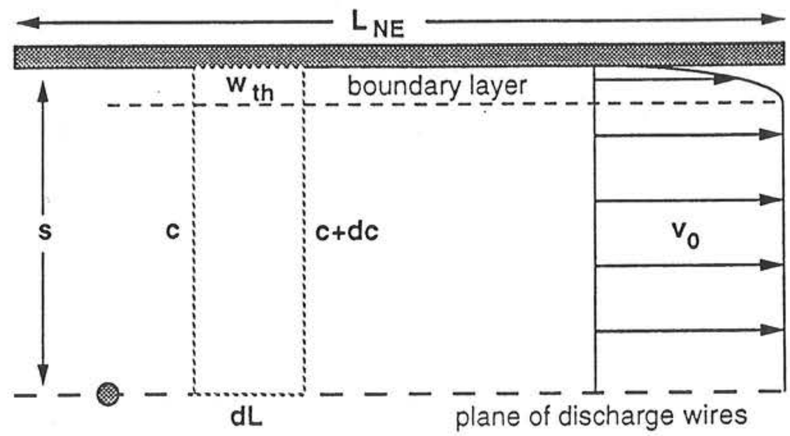

Fig. 2: Schematic illustration of the Deutsch Model

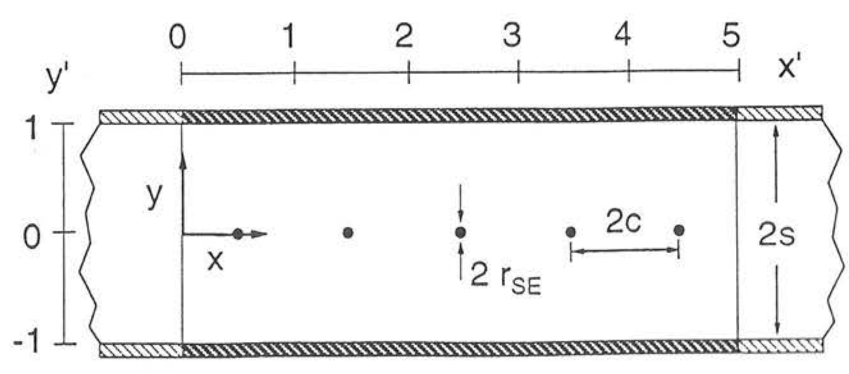

Fig. 3: Precipitator geometry

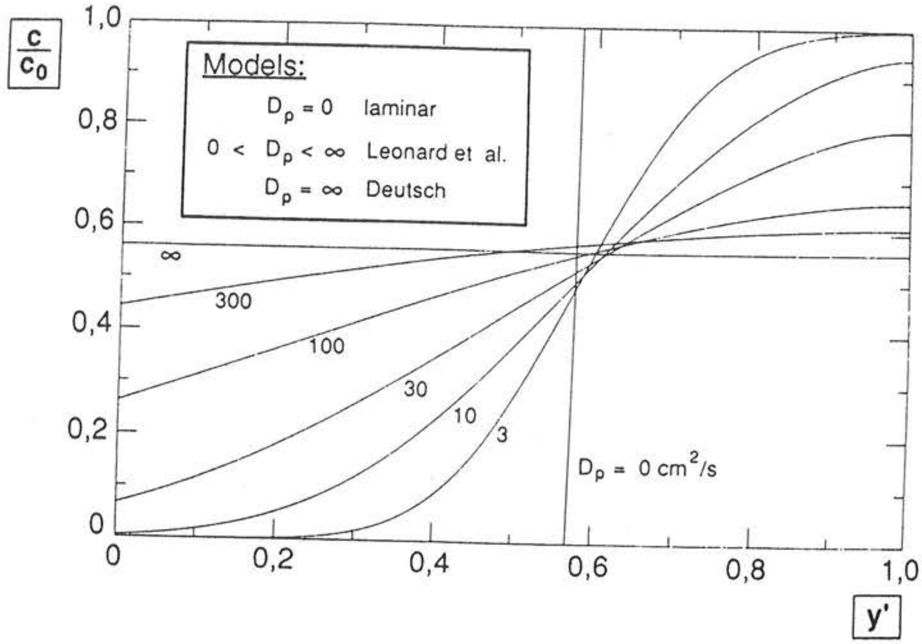

Fig. 4: Effect of eddy diffusivity on particle concentration profiles in precipitator duct

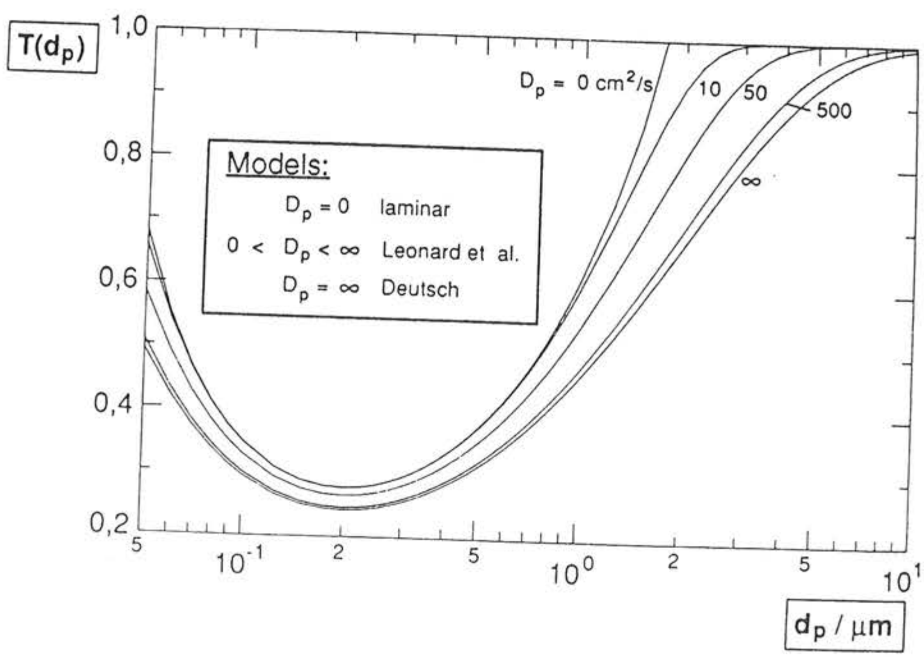

Fig. 5: Grade efficiencies calculated according to the analytical solution of the convective diffusion equation (Eq. 28) for a precipitator with 2s = 200 mm, L_{NE} = 500 mm, v_0 = 1,0 m/s and U = 50 kV.

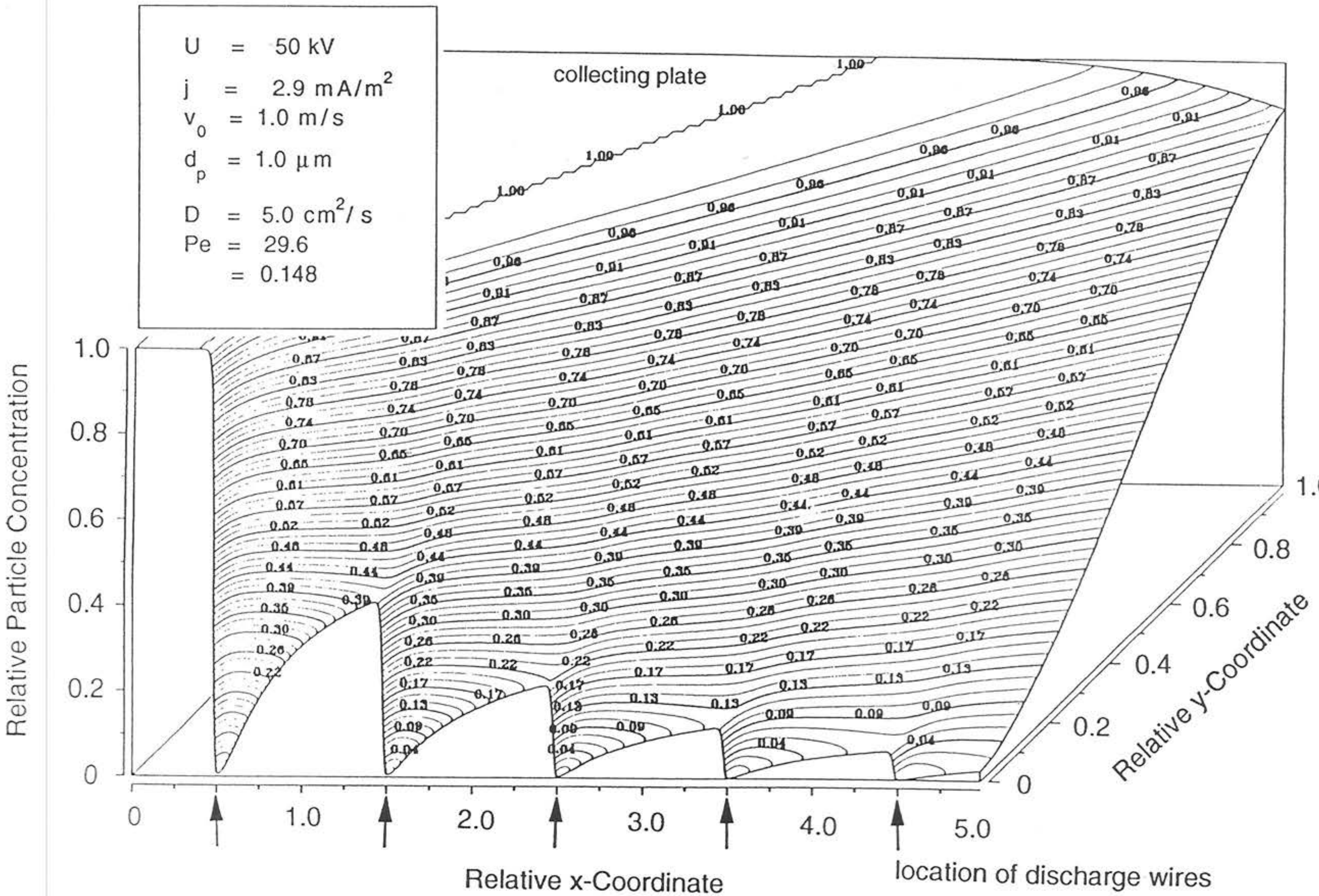

Fig. 6: Calculated concentration profiles in a electrical precipitator with five corona wires and inhomogeneous electrical field; the parameters are given in the table and the ionic space charge was considered.

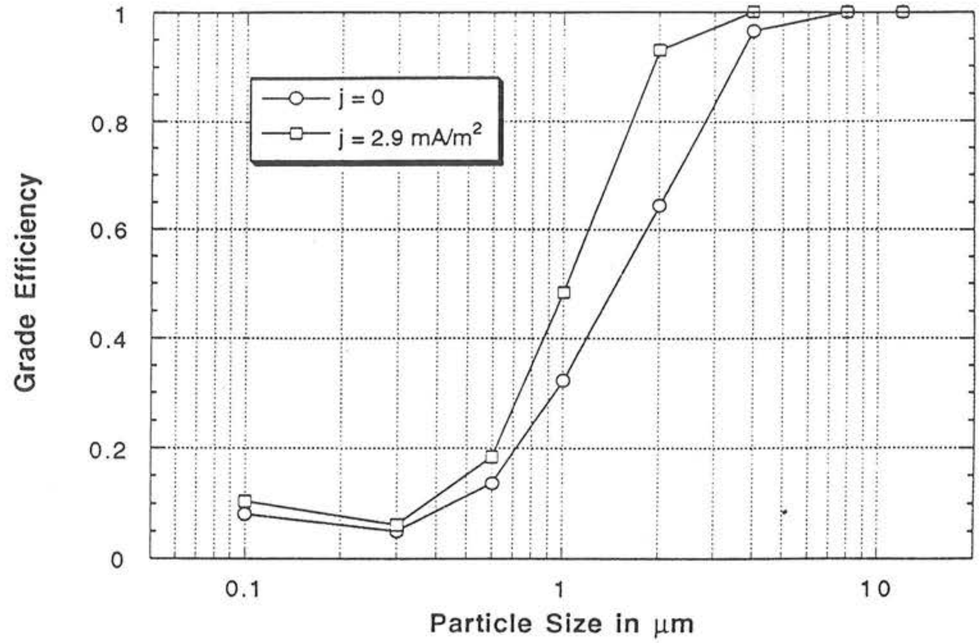

Fig. 7: Effect of an homogeneously distributed ionic space charge on grade efficiency compared with the result of a numerical solution of the convective diffusion equation when considering the local structure of a pure electrostatic field.

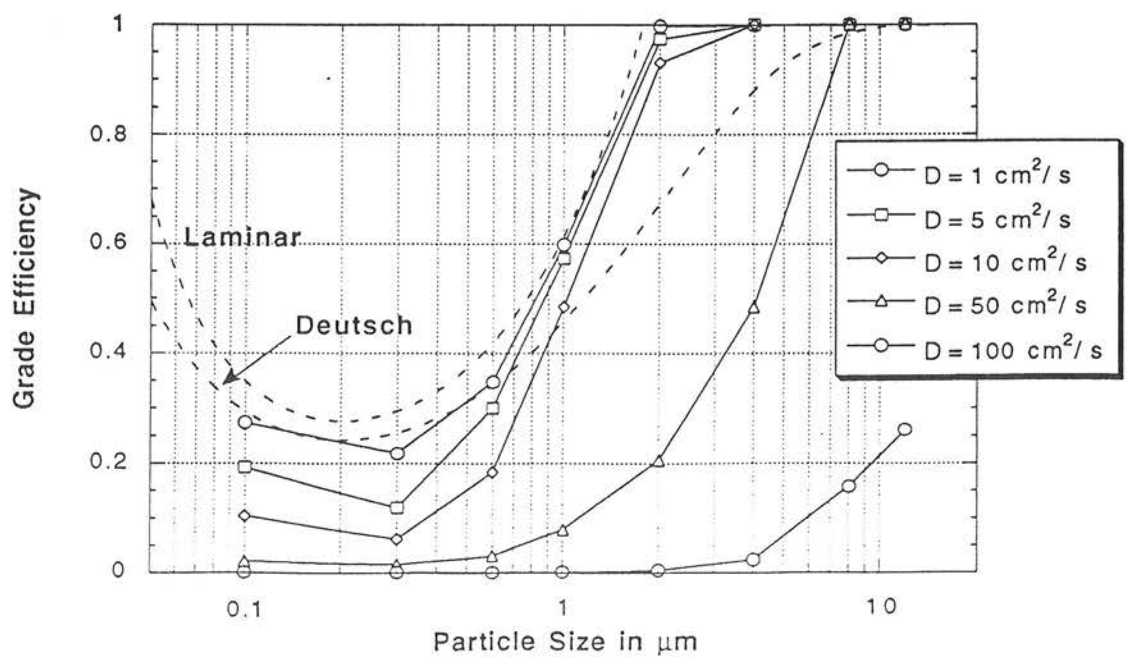

Fig. 8: Grade efficiencies calculated by numerically solving the convective diffusion equation considering the local strucure of the elctrical field (Eq. 33) with particle diffusivity as parameter. The precipitator is operated with 2s = 200 mm, L_{NE} = 500 mm, v_0 = 1,0 m/s and U = 50 kV generating a current density of 2,9 mA/m² (i.e. space charge). Also shown are the corresponding values of the Deutsch and the Laminar Model.