OVERALL COLLECTION EFFICIENCY OF A PLATE-WIRE ELECTROSTATIC PRECIPITATOR OPERATING ON THE REMOVAL OF PM2.5

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Abstract **–The collection efficiency of a laboratory scale plate-wire electrostatic precipitator, operating in the removal of airborne $PM_{2.5}$, was carried out. The variables investigated were the applied potential (V), the gas velocity (v_o), the diameter of the discharge electrodes ($2r_{SE}$), the distance between electrodes (2c) and of the total precipitator length (L_{NE}). The test particles were high grade alumina with median diameter of 0.6 micrometers and maximum diameter of 2.5 micrometers. The results showed, qualitatively, a good agreement with the theory of electrostatic precipitation. Quantitatively, the results were compared to predictions from two existing correlations from the literature and both underestimated the precipitator overall efficiency when using the assumption of pseudo-homogeneous electrical field strength. The predictions improved significantly when the field strength was calculated with the equation proposed by Kihm *et al.* (1985, 1987) and included a homogeneous space charge, as proposed by Riehle (1997).**

Keywords**: electrostatic precipitator, overall collection efficiency, gas cleaning, $PM_{2.5}$.**

I. INTRODUCTION

The concern with the environment is becoming more and more present in the daily life of everyone. An increasing involvement with the environmental issue is demanded from the governments, companies and, eventually, from the society as a whole. Conscious decisions need to be taken to preserve the ecosystems with minimum interference in the development of the nations. These ideas are contained in the Declaration of Rio on the Environment and Development approved in the ECO´92 (UNEP, 2005), which assumes as a principle the acquisition and improvement of the necessary scientific knowledge for promoting the sustainable development.

Of the several aspects involved in the study of air pollution, the presence in the atmosphere of particles smaller than 2.5 μm in diameter is becoming a matter of great concern. These particles, known as PM2.5 or high risk respirable particles, have been proved to be very harmful to the human health, especially to the children, the elderly and the sick (Ferin *et al.*, 1990; Oberdörster *et al*., 1990; Pui and Chen, 1997). These particles possess a high superficial area, thus favoring the adsorption of toxic substances and increasing the potential harmful effects to the human organism (Donaldson *et al*., 1998, Harrison and Yin, 2000). PM2.5 is directly associated to asthma, bronchitis, loss of the breathing capacity and has been pointed as responsible for the decrease of the life expectation in some areas (Donaldson *et al*., 1998; Preining, 1998; US-EPA, 2000).

Therefore, a more rigorous control of PM2.5 is necessary and the electrostatic precipitator (ESP) stands out as an air cleaning equipment with high removal efficiency in a wide size range, including sub-micron particles (Parker, 1997).

Although relatively well studied, the behavior of the electrostatic precipitators lacks experimental data on their performance due to the high number of influential parameters, that include: particle properties (density, electrical resistivity, size distribution, etc.), process variables (gas velocity, particle concentration, etc.), construction and geometrical elements (electrode type and geometry, space between the plates and electrodes, etc.), and operational variables (applied potential, corona polarity, dc and pulse energization, cleaning frequency, etc).

Attempting to maximize the performance of the precipitators, many researchers (for example, Chang and Bai, 1999; Miller *et al*., 1998; Navarrete *et al*., 1997; Acha *et al*., 1996; Abdel-Sattar, 1991) have addressed the problem of quantifying the influence of some of these variables. However, the quantity of experimental data on the performance of electrostatic precipitators is still relatively scarce, even more in PM2.5 size range (Kocik *et al*., 2005; Bacchiega *et al*., 2006).

The present work evaluates experimentally the influence of the gas velocity, the field strength, the diameter of the discharge electrodes and of the distance between them in the performance of a plate-wire precipitator (see basic dimensions in Fig. 1) operating in the removal of very fine particles. Theoretical predictions are presented and discussed.

II. COLLECTION EFFICIENCY

Evald Anderson's pioneer work in 1919 and Walther Deutsch in 1922, gave origin to the classic equation of collection efficiency for electrostatic precipitators, known as equation of Deutsch-Anderson (e.g. White, 1963), given by:

$$\eta_{dpi} = 1 - \exp\left(-\frac{w_{th}\, A_{NE}}{Q}\right) = 1 - \exp\left(-\frac{w_{th}\, L_{NE}}{v_0\, s}\right) = 1 - \exp(-De) \quad (1)$$

where: η_{dpi}- is the grade efficiency (dimensionless); w_{th} is the theoretical migration velocity (m/s); A_{NE} is the total collection area (m^2); Q is the volumetric flow rate (m^3/s); A_{NE} /Q is the specific collection area (m^{-1}); L_{NE} is the length of the collection plate (m); v_o is the gas velocity (m/s); s is the distance between the discharge and the collection electrodes (m); De is the Deutsch number (dimensionless).

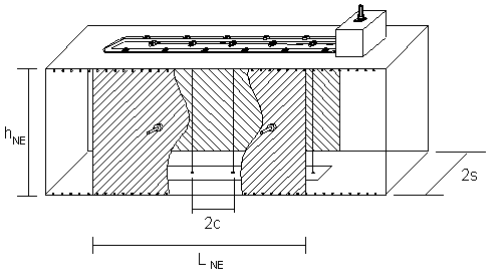

Figure 1- Basic dimensions of a plate-wire ESP.

The theoretical migration velocity w_{th}, which accounts for the trajectory of the particle towards the collecting electrodes, can be written as:

$$w_{th} = \frac{q_p\, E\, F_s}{3\,\pi\,\mu\, d_p} \quad (2)$$

where: q_p is the particle charge (C); E is the electric field (V/m); d_p is the particle diameter (m); μ is the gas viscosity (kg/ms); F_s is the Cunningham slip factor (dimensionless).

The electrical field E in wire-plate precipitator is not homogeneous, and depends on the equipment configuration, charged particles and ions in the gas phase. However, considering the difficulty in calculating the real field inside the equipment, it is common practice (Riehle, 1997) to utilize an approximation, called pseudo-homogeneous electrical field strength, E_{ps}, given by:

$$E_{ps} = \frac{V}{s} \quad (3)$$

where V is the applied voltage (V).

This equation, which, strictly, describes the electric field between flat parallel plates, is a rough approximation for the field formed between a wire and a plate. It has the advantage of simplicity.

Some authors proposed modifications to Eq. (3) so that an improvement in the prediction could be achieved without the need of high computational effort. Kihm *et al.* (1985, 1987) proposed the following correlations (Eqs. 4 to 15), that take into account the equipment geometry, such as the precipitator width and the relation s/2c:

$$E_x(x', y') = \frac{V}{s}\pi\cos(\alpha)\cdot\frac{\sum_{m=0}^{n}\frac{\operatorname{senh}(\beta)}{N1}}{N2} \quad (4)$$

$$E_y(x', y') = \frac{V}{s}\cdot\pi\,\operatorname{sen}(\alpha)\cdot\frac{\sum_{m=0}^{n}\frac{\cosh(\beta)}{N1}}{N2} \quad (5)$$

$$\alpha = \frac{\pi\cdot y'}{2} \quad (6)$$

$$\beta = \frac{\pi\cdot(x'-2mc')}{2} \quad (7)$$

$$N1 = \operatorname{senh}^2(\beta) - \operatorname{sen}^2(\alpha) \quad (8)$$

$$N2 = \sum_m \ln\left(\frac{\cosh(\gamma)+\cos(\delta)}{\cosh(\gamma)-\cos(\delta)}\right) \quad (9)$$

$$\gamma = \pi\cdot m\cdot c' \quad (10)$$

$$\delta = \frac{\pi\cdot r_{se}'}{2} \quad (11)$$

$$x' = \frac{x}{s} \quad (12)$$

$$y' = \frac{y}{s} \quad (13)$$

$$2c' = \frac{2c}{s} \quad (14)$$

$$r_{SE}' = \frac{r_{SE}}{s} \quad (15)$$

where E_x is the x component of the field (V/m); E_y is the y component of the field (V/m); m is the number of discharge de electrodes; r_{SE} is the electrode radius (m).

These correlations do not account for the spacial charge which, according to Abdell-Sattar (1991), induces to error. Thus, Riehle (1997) proposed the assumption of an homogeneous spatial charge in all the precipitator, which could be estimated from a correlation proposed by Cooperman (1971). According to this procedure, the final field is obtained by adding up the two terms, *i.e.* the field plus the spatial charge contributions, as described by Eqs. 16 to 20.

$$E'(x', y') = \frac{E(x', y')}{E_{ps}} \quad (16)$$

$$E_f'(x', y') = E'(x', y') + \frac{j_{ne}'\, 2c'y'}{\pi}\, ln\left(\frac{d}{r_{SE}}\right) \quad (17)$$

$$j_{NEe}' = \frac{j_{NE}}{\frac{\varepsilon_0 b V^2}{s^3}} = \frac{i}{\frac{\varepsilon_0 b V^2 A_{NE}}{s^3}} \quad (18)$$

$$d = 0.36c \times exp\left(\frac{2.96s}{2c}\right) \text{ for } 0.3 \le s/2c \le 1 \text{ or} \quad (19)$$

$$d = \frac{4s}{\pi} \text{ for } s/2c \le 0.3 \quad (20)$$

where: i is the total electric current (C/s); j_{NE} is the electric current density ($C/(sm^2)$); ε_0 is the permittivity of the vacuum (C/(Vm)); b is the ion electrical mobility (= 0.0002 m^2/Vs) for negative ions of air.

It is normally assumed that the particle charging occurs by two mechanisms, field charging and diffusion charging, and both are functions of the exposure time. The total particle charge is therefore the sum of these two contributions. Several correlations have been proposed for estimating particle charge and the approach described below is frequently adopted (Gooch and Francis, 1975; Kim and Lee, 1999). The diffusion and field charging, in differential form, are given by Eqs. 21 and 22, respectively:

$$\frac{dq_p}{dt} = \frac{q_s}{\tau_f}\left(1 - \frac{q_p}{q_s}\right) \tag{21}$$

$$\frac{dq_p}{dt} = \frac{q^*}{\tau_d}\left(1 - \frac{q_p}{q^*}\right) \tag{22}$$

$$q_s = \frac{12\pi\,\varepsilon_0\,E_{ps}\,(d_p/2)^2}{\varepsilon_r + 2} \tag{23}$$

$$\tau_f = \frac{4\,\varepsilon_0}{\rho_i\,b} \tag{24}$$

$$q^* = \frac{4\pi\,\varepsilon_0\,k\,T\,(d_p/2)}{e} \tag{25}$$

$$\tau_d = \frac{4\,\varepsilon_0\,k\,T}{\rho_i\,e\,c_i\,d_p/2} \tag{26}$$

where: q_s is the saturation charge for field charging (C); q* is the satur. charge for diffusion charging (C); τ_f is the time constant for field charging (s); τd is the time constant for diffusion charging (s); t is the time (s); ε_r is the particle dielectric constant (dimensionless); e is the electronic unit charge (C); k is the Boltzmann Constant (kg $m^2/(s^2$ K)); T is the absolute temperature (K); c_i is the mean thermal velocity of ion (m/s); ρ_i is the ionic charge density (C/m^3).

The mean thermal velocity of ion, c_i, can be estimated from equation 27 (Adachi *et al*., 1985):

$$c_i = \sqrt{\frac{8kT}{\pi\left(\frac{M}{N_a}\right)}} \tag{27}$$

where N_a is the Avogrado number and M is the molecular weight of the ion, which is approximately 0.050 kg/mol for negative ions in the air (the Vohra relation, according to Adachi *et al*., 1985).

The ionic charge density, ρ_i, can be estimated by equation 28 (Riehle, 1997), which depends of the precipitator configuration.

$$\rho_i = \frac{i}{E\,A_{NE}\,b} \tag{28}$$

The integration of Eqs. (21) and (22) are normally used to calculate the charge acquired by the particle in the time of exposure of the aerosol to the electric field. However, it is also common practice to adopt the saturation charge as the charge of the particles, since there is not a big difference between them. According to Riehle (1997) the particles reach the saturation charge in a few seconds inside the charging zone.

Note that Eq. 1, the Deutsch-Anderson equation for collection efficiency, is dependent on particle size (implicit in w_{th}). Therefore, for an aerosol formed by polydispersed particles, the overall efficiency can be taken as:

$$\eta_T = \sum_{i=1}^{n} f(i)\eta_i \tag{29}$$

where *f*(*i*) is the mass fraction of particles in the *ith* size range, fed to the system.

Several researchers developed alternative equations for prediction of collection efficiency, and papers by Zhao and Pfeffer (1996) and Riehle (1997) give a thorough review on the subject. However, according to Zhao and Pfeffer, although many of these correlations present satisfactory results, their use has been restricted by their complexity, by the limiting aspect of the assumptions in which they are based, and also by the presence of empirical constants that depend on the operational conditions.

It is worth mentioning a number of theoretical approaches that consider in more detail the flow field inside the precipitator, instead of the perfect mixing assumed by Deutsch and Anderson. There is a rich literature on this elaborate approach, with works like the ones of Cooperman (1971), Leonard *et al.* (1980) and Zhibin and Guoquan (1992). Kim and Lee (1999) evaluated the correlations proposed by these authors and concluded that the Zhibin and Guoquan approach was the one that best represented the experimental data. Their expression for the collection efficiency is given by:

$$\eta_{dpi} = 1 - \frac{\sqrt{Pe}}{2s\sqrt{\pi De}}\int_0^s exp\left[-\frac{Pe}{4De}\left(\frac{y}{s} - De\right)^2\right]dy \tag{30}$$

where: Pe is the dimensionless Pèclet number (= $\frac{w_{th}\,s}{\Psi}$),;Ψ is the particle turbulent diffusivity (m^2/s).

The authors suggest that the particle turbulent diffusivity could be calculated by a correlation proposed by Yoo *et al.(*1997):

$$\Psi = 0.12\,v_t\,s \tag{31}$$

$$v_t = \sqrt{\frac{f_f\,v^2}{8}} \tag{32}$$

$$\frac{1}{f_f^{1/2}} = -1.8\log\left(\frac{6.9}{Re}\right) \tag{33}$$

where: v_t - friction velocity (m/s); f_f is the friction factor (dimensionless); Re is the duct Reynolds number (dimensionless).

III. MATERIALS AND METHODS

A. Experimental set-up

Figure 2 shows a schematic view of the experimental module used in this work. The air was driven through the system by a blower, and the alumina was fed by a rotating disk powder dispenser. A high potential source with continuous current Spellman, SL1200 was connected to the active electrodes and provided

potential levels and current that could vary within the range from 0 to 50 kV and from 0 to 20 mA, respectively. All the tests presented here were performed with negative corona.

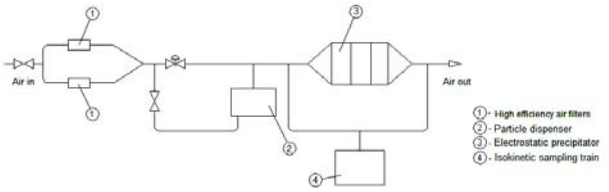

Figure 2 - Scheme of the experimental rig

The collection efficiency was measured isokinetically, by sampling the flowing gas through probes installed in the entrance and in the exit of the precipitator. The sampling system also comprised a membrane filter, a flow meter/controller and a vacuum pump. The gas velocity in the sampling point was previously measured with a Pitot tube.

Two precipitators with different lengths were utilized. Figure 3 depicts the longer one, with 0.30 m. The shorter had 0.15 m in length, with all other dimensions identical. The number of electrodes could be varied.

B. Test powder

The particulate material used in this work was a high grade alumina (A-1000SG), supplied by Alcoa whose physical properties are presented in Table 1. The resistivity of the particulate material was obtained experimentally according to the methodology described by Coury (1983) and the density measured in a helium pycnometer AccuPyc 1330, from Micromeritics. The alumina dielectric constant was taken from the literature (Lide, 1977). The size distribution was measured in a SediGraph 5000D, also from Micromeritics, and is shown in Fig. 4.

C. Variables and ranges

The values of the applied voltage (V), the gas velocity (v_o), the diameter of the active electrodes ($2r_{SE}$), the distance between electrodes (2c) and of the total precipitator length (L_{NE}), on the precipitator efficiency utilized in this work are listed in Table 2. The precipitator width (2s = 0.04 m) was kept constant, so that s/2c=1.0 and 0.5.

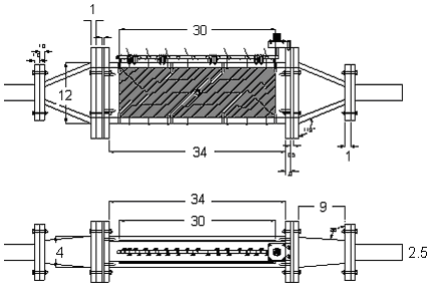

Figure 3 – The precipitator side and top views, dimensions in cm.

Table 1 - Properties of the utilized alumina.

Property	Value
Resistivity (Ω×m)	3.85×10^{7}
ε_r (-)	6.45
Density (kg/m^3)	3.69×10^{3}
d_{m50} (m)	0.58×10^{-6}

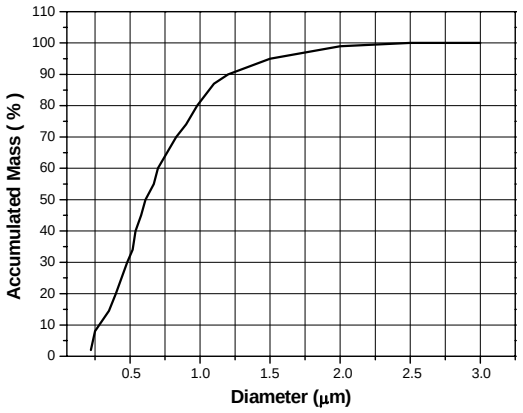

Figure 4 – Size distribution of the alumina obtained in the Micromeritics SediGraph 5000D.

Table 2 – Variables and the tested values.

Variable	values
V (kV)	12 and 16
v_o (m/s)	1.0 and 1.5
$2r_{SE}$ (m×10^3)	0.25 and 0.45
2c (m×10^2)	2 and 4
L_{NE} (m)	0.15 and 0.30

D. Experimental procedure

The experimental overall collection efficiency, η_T, was calculated as:

$$\eta_T(\%) = \frac{c_e - c_s}{c_e} \times 100 \qquad (34)$$

where: c_e is the particle mass concentration (kg/m^3); c_s is the outlet part. mass concentration (kg/m^3).

The inlet particle mass concentration was kept constant in each test at a value of 1.5×10^{-3}kg/m^3 ± 10%. The average values for the relative humidity, pressure and temperature of the gas for all the tests were 33±3%, 9.31×10^4 Pa and 30 ± 3 °C, respectively. The duration of each test was of 10 minutes and no particle removal from the plates was made during the test. The plates were cleaned between tests.

IV. RESULTS AND DISCUSSION

The experimental results of the global efficiency measured in this work are listed in Table 3. It is noticeable that most of the general trends are in accordance to the theory of electrostatic precipitation: (a) higher efficiencies occurred in the longer precipitator; (b) higher efficiencies occurred for the lower gas velocity; (c) higher efficiencies occurred in the higher electrical field; (d) higher efficiencies occurred with the thinner electrode. The effect of the electrode spacing (s/2c) did not show a clear trend. The

influence of this parameter is controversial, as can be seen in the works of Riehle (1997), Miller *et al*. (1998) and Nóbrega (2002).

A. The pseudo-homogeneous field, E_{ps}

A comparison of the experimental results with predict-tions from theoretical correlations was made and is shown in Figs. 5 and 6. For the theoretical predictions, the pseudo-homogeneous field, E_{ps} (Eq. 3) was assumed in all calculations. The particle charge was calculated by the integrating and adding Eqs. 21 and 22, taking the particle residence time between the plates as reference. The efficiency was assumed to be time-independent

Figures 5a and 5b compare the experimental efficiencies obtained here with the ones calculated from the classical Deutsch correlation (Eq. 1). For these calculations the particle size distribution was divided in several ranges, and the overall efficiency obtained from Eq. 29. Figure 5a shows the comparison for the shorter precipitator and Fig. 5b for the longer one. It can be seen that the theoretical prediction underestimates the overall efficiency in both cases.

Figures 6a and 6b compare the experimental efficiencies obtained in this work with the ones calculated from the correlation proposed by Zhibin and Guoquan (1992), Eq. 30 (integrated in the whole size range), taken here as representative of a range of authors that include the gas-particle flow field in more detail in their model. Again here the particle size distribution was taken into account and the overall efficiency was calculated as a sum of efficiencies. It can be noticed that the underestimate of the efficiency by the theory remains. In this case, the precipitator length seems to have a more pronounced effect on the discrepancy: the shorter precipitator (Fig. 6a) shows a wider dispersion when compared to the longer one (Fig. 6b) than in the respective cases in Figs. 5a and 5b.

B. The Kihm et al. field, with homogeneous space charge, E_f

Of the simplifying assumptions considered in the efficiency calculations performed in the previous section, the pseudo-homogenous field seems to be the one that need further attention. Although frequently utilized for its simplicity, this assumption neglects the effect of the space charge which, in the case of particles in the size range typically above 10 microns, can lead to reasonable results. In the sub-micron particle size range, however, the total electric field is severely underestimated, and so is the particle collection efficiency. To account for this effect, the efficiency was re-calculated with the use of Eq. 17 that includes the space charge. It was considered that the appropriate field inside the precipitator was the one estimated in the proximity of the walls, *i.e.* x≈s, as suggested by Kihm *et al.* (1985).

Table 4 lists the calculated mean field E_f for the operational conditions of this work. It can be noticed that E_f is appreciably higher than the pseudo-homogenous field E_{ps} in most cases. This had direct

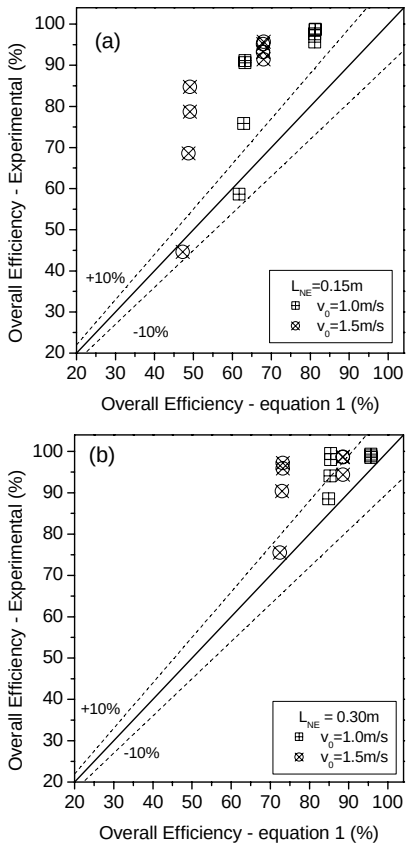

Figure 5 – Experimental results vs. prediction by eq. 1, for: (a) L_{NE} = 0.15m; (b) L_{NE} = 0.30m.

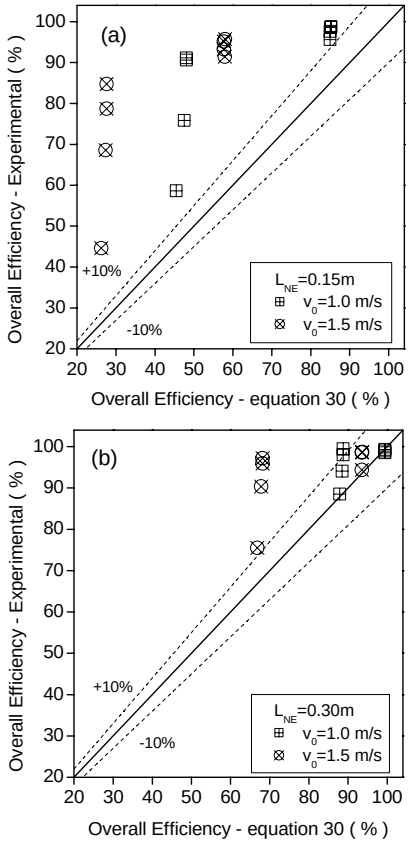

Figure 6 – Experimental results vs. prediction by eq. 30, for: (a) L_{NE} = 0.15m; (b) L_{NE} = 0.30m.

Table 3 - Results of the overall efficiencies (in %) measured in this work.

L_{NE}=0.30 m								
	$2r_{NE}=0.45\times10^{-3}$ m				$2r_{NE}=0.25\times10^{-3}$ m			
	s/2c=1.0		s/2c=0.5		s/2c=1.0		s/2c=0.5	
	6 kV/m	8 kV/m	6 kV/m	8 kV/m	6 kV/m	8 kV/m	6 kV/m	8 kV/m
Efficiency (%)								
v_o=1.0m/s	88.50	98.91	94.07	98.50	99.48	*	98.00	99.32
v_o=1.5m/s	75.50	94.36	90.38	98.59	97.20	*	95.89	98.70
L_{NE}=0.15 m								
	$2r_{NE}=0.45\times10^{-3}$ m				$2r_{NE}=0.25\times10^{-3}$ m			
	s/2c=1.0		s/2c=0.5		s/2c=1.0		s/2c=0.5	
	6 kV/m	8 kV/m	6 kV/m	8 kV/m	6 kV/m	8 kV/m	6 kV/m	8 kV/m
Efficiency (%)								
v_o=1.0m/s	58.63	97.60	75.85	95.60	90.60	98.74	91.12	98.66
v_o=1.5m/s	43.24	93.21	68.60	95.15	84.77	95.74	78.72	91.44

*sparking occurred

Table 4 – Calculated values of the field E_f for the operational conditions of this work.

E_f (kV/m)								
Variables	r_{SE} = 0.25×10^{-3} (m)				r_{SE} = 0.45×10^{-3} (m)			
	E_{ps} = 600 (kV/m)		E_{ps} = 800 (kV/m)		E_{ps} = 600 (kV/m)		E_{ps} = 800 (kV/m)	
	s/2c =0.5	s/2c =1.0	s/2c =0.5	s/2c =1.0	s/2c =0.5	s/2c =1.0	s/2c =0.5	s/2c =1.0
L=0.15m	11.71	8.65	24.79	18.49	7.27	4.27	17.30	12.86
L=0.30m	12.71	9.22	26.29	20.20	8.17	4.78	18.65	13.64

effect on the re-calculated collection efficiencies, which are compared to the experimental values in Figs. 7 and 8. These figures are equivalent to Figs. 5 to 6, so that Figs. 7a and 7b refer to the Deutsch-Anderson efficiency (Eq. 1) whilst Figs. 8a and 8b refer to the Zhibin and Guoquan approach (Eq. 30).

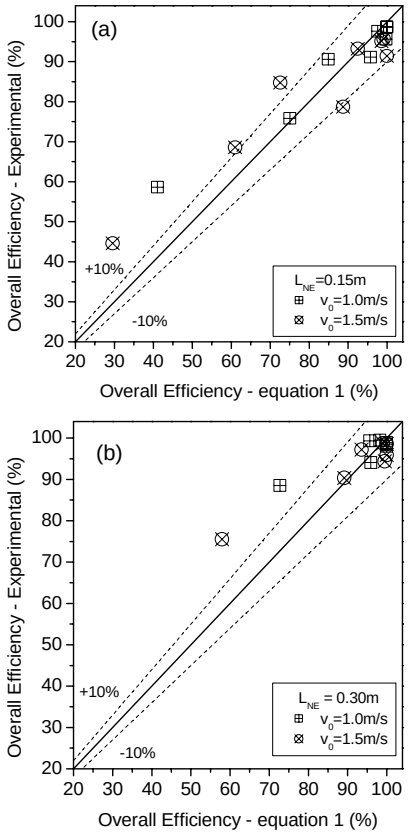

Figure 7 – Experimental results vs. prediction by eq. 1, with the modified electrical field E_f, for: (a) L_{NE} = 0.15m; (b) L_{NE} = 0.30m.

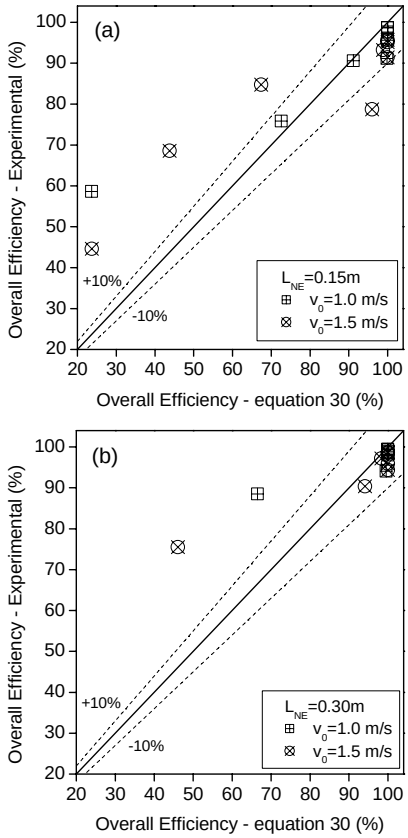

Figure 8 – Experimental results vs. prediction by Eq. 30, with the modified electrical field E_f, for: (a) L_{NE} = 0.15m; (b) L_{NE} = 0.30m.

It is noticeable the improvement of the theoretical predictions in all cases: most of the predictions fall within ±10% of the experimental values. The larger deviations still occur in the lower efficiency range. It is interesting to note that the predictions of the Deutsch-

Anderson correlation (Fig. 7) are somewhat better than the ones from the Zhibin and Guoquan approach (Fig. 8). It is apparent that the effects of the complexities of the flow field inside the precipitator, accounted for by the latter, do not reflect in the precipitator behavior, and the more simple approach of fully mixed aerosol still holds fine.

V. CONCLUSION

The results of collection efficiency of the laboratory-scale electrostatic precipitator operating in the removal of fine particles ($PM_{2.5}$) conducted here have shown, qualitatively, that the effects of geometrical and operational parameters were those predicted by theory. Quantitatively, however, the experimental efficiencies were considerably higher than predicted by two correlations from the literature when using the pseudo-homogeneous electrical field strength. However, the predictions improved markedly when the field correlation proposed Kihm *et al.* (1985, 1987) modified by Riehle (1997), was used in the efficiency calculations. Of the two models tested, better predictions were attained when utilizing the classical Deutsch-Anderson model for collection efficiency. Considering the wide spectrum of experimental variables tested, the combination of equations here suggested can result in an appreciable improvement in the prediction of the ESP in this size range were data is scarce.

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