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DEPOSITION OF INHALED CHARGED ULTRAFINE PARTICLES IN A SIMPLE TRACHEAL MODEL

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INTRODUCTION

The deposition of ultrafine ($d \leq 200$ nm) particles on airway surfaces is an important determinant of the radiation dose that results from inhalation of radon progeny. The activity median diameter of particles to which radon daughters attach is small (10 - 140 nm).

In the absence of charge, deposition in the upper airways of the respiratory system occurs by impaction for large particles and diffusion for small particles. Sedimentation is negligible due to the high flow rates in these airways.

Experiments conducted in hollow casts and in vivo in humans have all shown an increase in deposition due to the particle charge [1-4]. In vivo experimental results showed that there exists a threshold value of charge on the particle (q_c) above which the electrostatic charge enhances deposition. These experiments were performed for particles for which deposition by diffusion is small ($d \geq 300$ nm).

Deposition of ultrafine particles in the airways may occur by a combined mechanism of diffusion and electrostatic charge.

There are two electrical forces which cause particles to deposit on the airway surfaces. One is due to interaction between the particle and the wall (image force) and the other is due to the mutual repulsion between particles with like charge (space charge force). The image force is a single particle effect and increases as the particle nears the wall. The space charge force on the other hand depends on the particle concentration and is found to be much smaller than image force in the lung due to low particle concentration [5-6].

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2 Melandri, C., Prodi, V., Tarroni, G., Formignani, M., DeZaiacomo, T., Bompane, G.F., and Maestri, G. Inhaled Particles IV, Ed., W.H. Walton, Pergamon Press, Oxford, pp. 193-200 (1977).

3 Melandri, C., Tarroni, G., Prodi, V., DeZaiacomo, TG., Formignani, M., and Lombardi, C.C. J. Aerosol Sci. 14: 657-669 (1983).

4 Tarroni, G., Melandri, C., Prodi, V., DeZaiacomo, T., Formignani, M., and Bassi, P. Am. Ind. Hyg. Assoc. J. 41: 826-831 (1980).

5 Yu, C.P. J. Aerosol Sci. 8: 237-241 (1977).

6 Yu, C.P. Am. Occup. Hyg. 29: 219-227 (1985).

EXPERIMENTAL METHODS

The deposition of charged and neutral ultrafine particles was compared in simple tracheal models.

Nebulized NaCl particles were passed through a 2 stage cascade impactor, then size classified with an Electrostatic Classifier (ESC) to produce monodisperse, singly charged, particles with diameters from 15 to 95 nm.

To "neutralize" the charges the particle stream was passed through a deionizer (DEI) consisting of a 3" diameter copper tube containing a radioactive alpha particle emitter, ^{210}Po. Particles are neutralized to Boltzmann equilibrium. The resulting charge distribution is shown in Table 1.

Aerosol flow rates were monitored throughout each experiment by a mass flow meter incorporated into the ESC.

For each particle size from 15 to 95 nm, tests were done for the singly charged particles then immediately repeated with charge neutralized particles.

The monodisperse singly charged, or "neutralized", particles were passed through a 1.9 cm diameter conducting copper pipe 10, 23, or 30 cm long, or an equivalent path without the pipe, to either a CPC (TSI Model 3025) or a Faraday cup. The test sections compare with tracheal dimensions measured in lungs obtained at autopsy of 10 cm length, 1.9 cm diameter for a human, and 23 cm length, 2.0 cm diameter for a mongrel dog.

Percent deposition was calculated as follows:

$$\eta = 100 \frac{C_{nt} - C_t}{C_i} \qquad (1)$$

where, C_t = concentration at outlet of path with the tracheal tube;
C_{nt} = concentration at outlet of the alternate path (without tracheal tube);

For Faraday cup measurements, C is replaced by N, as the FC measured the total number of charged particles collected per unit time. These were normalized for any change in flow rate when necessary.

ANALYTICAL

The fraction deposited by diffusion was estimated from the equation of Cohen and Asgharian [7]

$$\eta_d = 2.968\,\Delta^{0.5677} \qquad (10^{-4} > \Delta > 10^{-9}) \qquad (2)$$

where

$$\Delta = \frac{\pi L D}{4Q} \qquad (3)$$

in which L is the airway length, Q is the flow rate through the airway, and D is the diffusion coefficient.

This empirically derived expression gives higher values than the analytical expression obtained by Ingham [8] for fully developed laminar flow, however, it approaches Ingham's as Δ increases.

The deposition efficiency due to image force alone, was calculated based on the expression of Pich [9]

$$\eta_i = (6\tau_e)^{1/3} \qquad (4)$$

where

$$\tau_e = \frac{Bq^2t}{4\pi\varepsilon_o R^3} \qquad (5)$$

in which q is the charge on the particle, t is the elapsed time in the airway, B is the particle mechanical mobility, ε_o is the permittivity of air, and R is the radius of airway.
This expression is a simplified form of the expression obtained by Yu [5] for deposition of particles in a cylindrical tube that applies when $\tau_e \ll 1$.

Deposition by image forces for the charged particle fraction of the neutralized aerosol was accounted for by applying equation 5 to the fraction shown in table 1. Then

$$\eta_i = \frac{(\eta_{exp} - \eta_d)}{(1 - \eta_d)} \qquad (6)$$

7 Cohen B. S., Asgharian, B. J. Aerosol Sci. 21: 789-797 (1974).
8 Ingham, D. J. Aerosol Sci. 6: 125-132 (1974).
9 Pich, J. Comments on the paper. J. Aerosol Sci. 9: 275-278 (1978).

CONCLUSIONS

Differences in deposition between charged and charge neutralized particles were detected for particles < 30 nm in diameter in 10, 23 and 30 cm long tubes, and for particles up to 95 nm for the longest (30 cm) tube tested.

As expected, deposition efficiency increased with decreased particle size and substantially exceeded that predicted for deposition from parabolic flow.

If total measured deposition is attributed to diffusive plus image forces these results suggest that deposition of the charged particles by image forces exceed predicted values by an order of magnitude.

For these experiments It is likely that convective eddies contributed to the excess deposition.

An increase in experimental sensitivity is needed for quantitative measures of the fraction deposited by image forces.

Diffusion is the dominant mechanism for deposition of very small particles. The amount deposited in the airways is generally very low amounting to a few percent for particles from 50 to 200 nm. Therefore, even a small enhancement in deposition resulting from image forces on charged particles can be significant.

Table 1
Percent of Particles Carrying n_p Units of Charge at Boltzmann Equilibrium [a]

Particle Diameter (nm)		Percent of Particles with Indicated Charge						
	n_p =	-3	-2	-1	0	1	2	3
10				0.34	99.32	0.34		
20				5.23	89.53	5.23		
40			0.23	16.22	67.10	16.22	0.23	
60		0.01	1.25	21.30	54.88	21.30	1.25	0.01
80		0.08	2.78	23.37	47.53	23.37	2.78	0.08
100		0.26	4.39	24.09	42.52	24.09	4.39	0.26

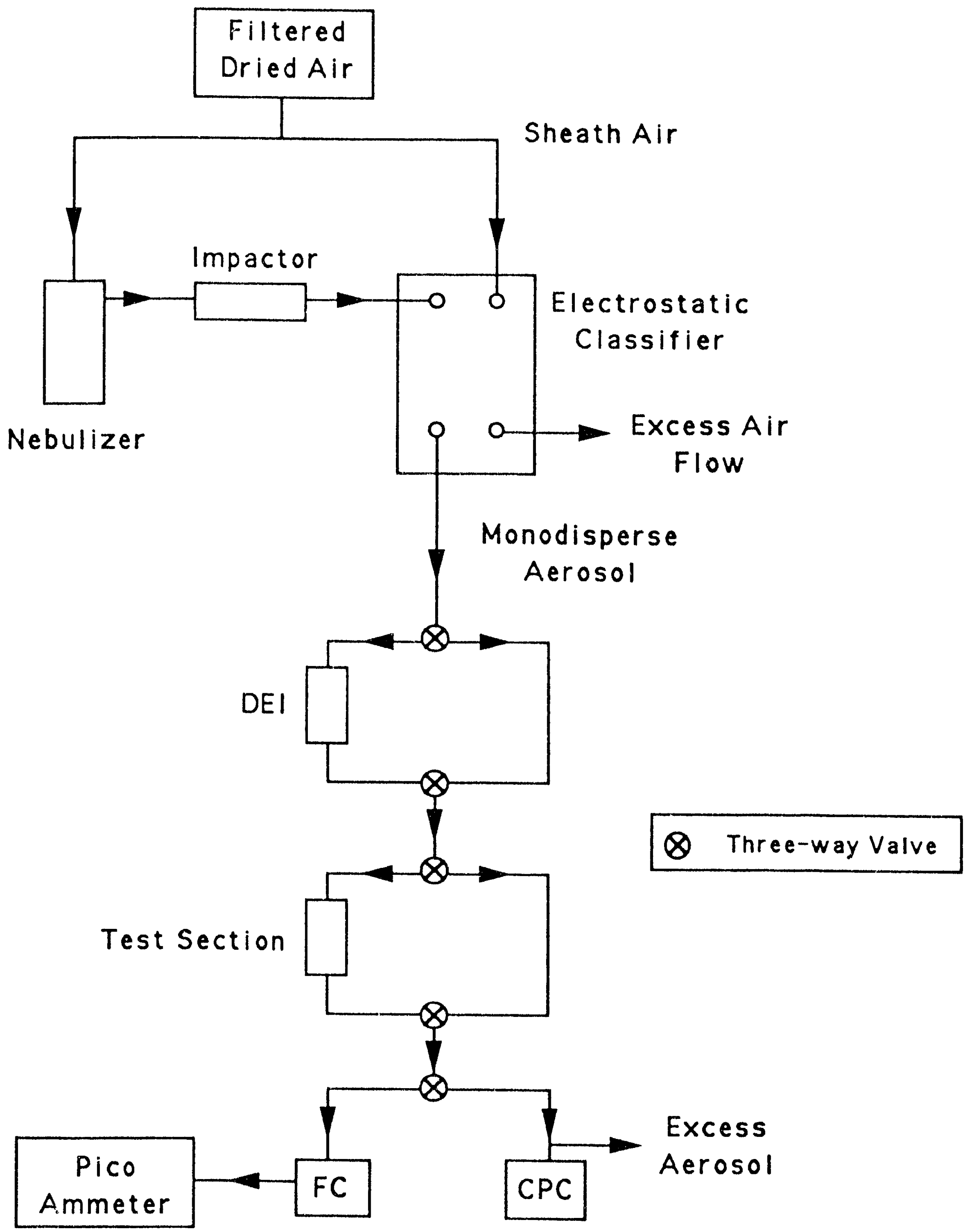
[a] Adapted from D.Y.H. Pui and B.Y.H. Liu: Electrical Aerosol Analyzer: Calibration and Performance. Presented at Aerosol Measurement Workshop, Univ. of Florida, Gainesville, Florida, Mar. 24 - 26, 1976. Particle Technology Laboratory Publication No. 304.)

Deposition Efficiency (DE) Measured by Condensation Particle Counter (CPC) and Faraday Cup (FC) in 10, 23 and 30 cm Copper Surrogate Tracheas.

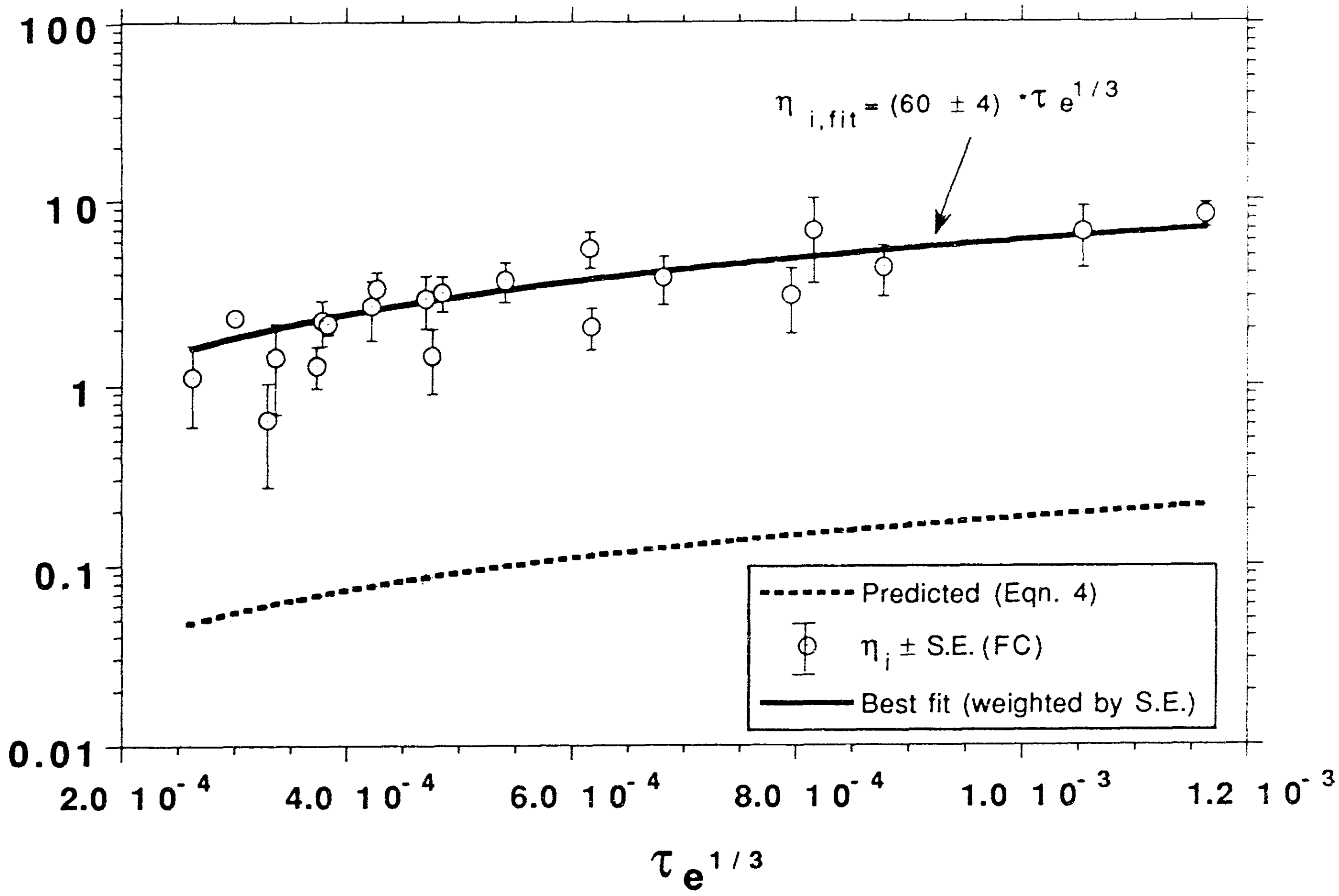
d_p[a]	$DE^b \pm se^c$ (CPC)			$DE^b \pm se^c$ (DEI^d, CPC)			$DE^b \pm se^c$ (FC)		
(nm)	10 cm	23 cm	30 cm	10 cm	23 cm	30 cm	10 cm	23 cm	30 cm
15.5	4.84 ± 1.94	3.36 ± 1.95	2.59 ± 2.06	3.68 ± 0.83	1.45 ± 1.40	2.28 ± 0.82	7.48 ± 3.30	7.68 ± 2.43	9.46 ± 1.25
24.0	4.71 ± 1.04	2.02 ± 0.61	1.56 ± 1.32	1.91 ± 0.52	0.90 ± 0.61	0.90 ± 0.49	5.86 ± 1.21	3.71 ± 1.17	5.05 ± 1.29
35.7	0.88 ± 0.60	0.80 ± 0.64	1.58 ± 0.46	1.37 ± 0.73	1.34 ± 0.50	0.74 ± 0.36	1.72 ± 0.55	2.47 ± 0.52	4.30 ± 1.09
51.7	1.04 ± 0.65	0.97 ± 0.41	1.60 ± 0.79	1.31 ± 0.44	1.27 ± 0.32	1.30 ± 0.73	2.41 ± 0.62	3.43 ± 0.67	4.01 ± 0.88
64.5	0.67 ± 0.40	1.13 ± 0.69	1.04 ± 0.36	0.07 ± 0.75	0.64 ± 0.32	0.19 ± 0.19	0.80 ± 0.38	2.90 ± 0.95	3.19 ± 0.91
75.7	0.62 ± 0.53	0.35 ± 0.66	1.43 ± 0.58	0.32 ± 0.28	0.61 ±0.30	0.29 ± 0.29	2.43 ± 0.11	2.32 ± 0.28	3.54 ± 0.73
95.3	0.32 ± 0.32	0.45 ± 0.45	0.00 ± 0.00	0.43 ±0.48	-0.54 ±0.78	0.00 ± 0.00	1.21 ± 0.53	1.57 ± 0.72	1.46 ± 0.32

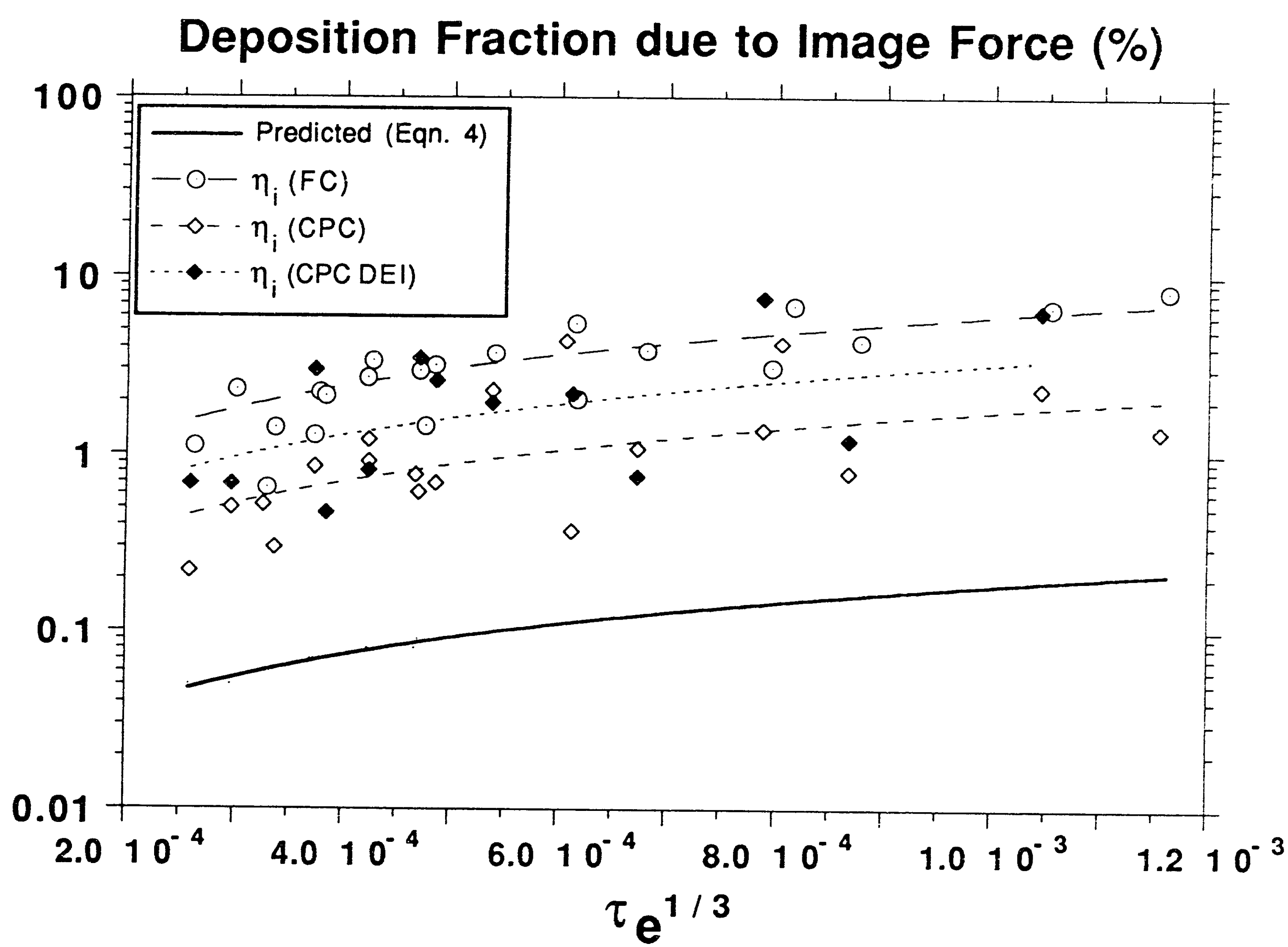
a: Particle size, b: Percent deposition efficency, c: Standard error, d: Charged neutralized with deionizer.

Experimental Setup



Deposition Fraction due to Image Force (%)




Deposition Fraction due to Image Force (%)
Predicted (Eqn. 4)
ηi (FC)
ηi (CPC)
ηi (CPC DEI)
100
10
1
0.1
0.01
2.0 10-4
4.0 10-4
6.0 10-4
8.0 10-4
1.0 10-3
1.2 10-3
τe1/3

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