Modelling the Air Cleaning Performance of Negative Air Ionisers in Ventilated Rooms

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SUMMARY

Negative air ionisers have seen increasing use as devices for improving indoor air quality, including some success in clinical environments for reducing the transmission of infection. This study uses a ventilation model and a CFD model to examine the physical effects of negative ionisers in indoor environments. The results demonstrate how the negative ion distribution and electric field due to an ioniser are influenced by both the room airflow and the ion generation rate. It is shown that ion concentrations greater than 10^{10} ions/m^3 are necessary for the electrical effects to be significant. The effect on particles is also considered, with the results demonstrating that the ioniser will only increase the deposition of particles when the particle concentration is high enough to contribute to the space charge in the room.

INTRODUCTION

In recent years public concerns over indoor air quality have led to device manufacturers producing a huge range of domestic and commercial air purifiers that claim to remove dust, allergens and bioaerosols from room air. Many of these devices produce negative ions and seek to redress the ion imbalance in room air as well as removing pollutants. Outdoor air contains approximately equal numbers of positive and negative ions with concentrations ranging from 300-500 ions/cm^3 for polluted city centre air to 1000-1200 ions/cm^3 in clean rural environments. However, in indoor environments concentrations may be reduced by as much as 80% due to removal in metal ventilation ducts and charged surfaces within rooms [1].

Despite the research community showing some interest in the potential benefits of air ionisers, including combating hospital infection [2], little attention has been given to understanding and quantifying the physical behaviour of ions in indoor environments and evaluating the effectiveness of such air cleaning devices. Experimental studies have demonstrated that negative ionisers have the potential to significantly reduce the concentration of particulates in indoor air [3,4,5], however theoretical models to complement these studies are very limited. Analytical models describing generic ion behaviour and the ion balance in outdoor air are presented by a number of authors [6,7,8], however the only notable work modelling ioniser behaviour in indoor air are the analytical studies of Mayya et al [4] evaluating negative ions and particles under time dependant conditions. Published CFD modelling of air ions focuses on industrial

applications where corona discharge is used to facilitate an electrostatic precipitation process [9,10,11]. Although the theory of this process is identical to ion generation in indoor air, it is a small scale process where diffusion is negligible and convection plays a minimal role compared to the electrical effects and the models are therefore simplified accordingly.

The study presented in this paper seeks to explore the behaviour of ions in indoor air by using analytical and CFD modelling techniques to simulate the effect of an ioniser in a ventilated room. A simplified version of Mayya et al's [4] analytical model is extended to include positive ions and used to examine key factors such as ventilation rate, particle concentration, wall deposition and relative concentration of positive and negative ions. This is used to demonstrate the relative effectiveness of air ions and the ventilation system at removing small particulate contaminants from the room air, in particular bioaerosols. A CFD model incorporating the full electrodynamics of negative ions is presented and used to show how the effectiveness of an ioniser is influenced by the room air flow and ion generation rate.

METHODS

Ventilation model

The balance of negative, n, and positive, p, ions in a fully mixed space of volume V (m^3) ventilated at a rate of Q (m^3/s) can be described by considering the generation and removal mechanisms to give

$$\frac{dn}{dt} = q_n - \alpha np - \beta nA + n_o \frac{Q}{V} - n\frac{Q}{V} - \lambda_i n \qquad (1)$$

$$\frac{dp}{dt} = q_p - \alpha np - \beta pA + p_o \frac{Q}{V} - p\frac{Q}{V} - \lambda_i p \qquad (2)$$

Here q_n and q_p (ions/s) are the generation rate of negative and positive ions in the room and n_o and p_o (ions/m^3) are the negative and positive ion concentrations external to the room. α and β are rate factors where α represents the recombination rate of ions with those of opposite polarity, and β is the rate of combination of ions with aerosol particles, A (particles/m^3). Typical values for α and β are given by Horrak [7] as $\alpha \approx 1.5$ x 10^{-12} m^3/s and $\beta \approx 1.2$ x 10^{-12} m^3/s .

The presence of aerosol particles in the space can also be modelled by a similar equation where q_A represents the generation of particles in the space and A_o is the external particle concentration.

$$\frac{dA}{dt} = q_A + A_o \frac{Q}{V} - A\frac{Q}{V} - \lambda_p A \qquad (3)$$

In addition to the ventilation removal and ion-ion/ion-particle interactions, both ions and particles experience additional removal mechanisms through diffusive and gravitational deposition at walls and enhanced electrostatic deposition due to the ion induced electric field. Gravitational and diffusive deposition are not included in this model as the primary interest is in small particles that normally remain airborne for long periods, in particular, bioaerosols which are typically <2μm diameter. The electrostatic deposition is however of interest and is included in the above equations through the additional rate terms, λ_i and λ_p.

In the case of ions, equations for negative ions [4] can be modified to include positive ions and express the removal rate in terms of the total ionic space charge, q_e, the ion mobility b and the permittivity of free space ($\varepsilon_0 = 8.854 \times 10^{-12}$ C^2/Nm^2)

$$\lambda_i = \frac{b}{\varepsilon_o}(q_e + q_c eA) \quad (4)$$

For small air ions the mobility is typically 2.4×10^{-6} m^2/Vs [7]. The space charge density depends on the relative positive and negative ion concentrations and the elementary charge, $e = 1.6 \times 10^{-19}$ C through the expression.

$$q_e = en - ep \quad (5)$$

The enhanced deposition of particles due to the electric field can be approximated [4]

$$\lambda_p = \frac{D_p}{D_i}q_c\lambda_i \quad (6)$$

where D_p and D_i represent the particle and ion diffusion coefficients respectively and have typical values of $D_p = 1.3 \times 10^{-10}$ m^2/s and $D_i = 1 \times 10^{-7}$ m^2/s.

The parameter q_c represents the characteristic number of charges acquired by particles due to diffusion charging in the ion field. This is a complex process that depends on the physics of the ion-particle interactions and the duration of the particle in the space. However to get a feel for the relative impact of the ions on particle behaviour an approximation is made based on the charging equations presented by Harrison [8] to give

$$q_c = \frac{4\pi\varepsilon_o d_p kT}{e^2}\left[\ln\left[1+\frac{d_p c p e^2 t}{4\varepsilon_o kT}\right] - \ln\left[1+\frac{d_p c n e^2 t}{4\varepsilon_o kT}\right]\right] \quad (7)$$

Here k is the Boltzmann constant ($= 1.381 \times 10^{-23}$ J/K) and T is the absolute temperature (~300 K) and c is the thermal speed of the ions (~300 m/s). The particle diameter is given by d_p and the time, t, is the average time the particle spends in the room which can be approximated by the reciprocal of the ventilation rate.

Equations (1-7) represent a complex non-linear system which cannot be solved analytically. A time dependant numerical solution is presented in a related article [12], however in this study the equations are used in conjunction with the following CFD model to examine the relative importance of the different removal mechanisms under a range of conditions.

CFD Model

A CFD model was developed to gain a greater understanding of the various factors that influence the distribution of negative ions in a ventilated room. The model assumes that all ions carry a single negative charge and can be modelled as scalar concentration in air. Positive ions and particles are not included in the model. It is assumed that ions are generated at a constant rate by an ioniser located in the room, and that the conditions in the room are steady state.

Electric Field
The space charge due to ions in the room generates an electric field, $\underline{E}$, which is governed by Gauss's equation

$$\nabla \cdot \underline{E} = \frac{q_e}{\varepsilon_0} \qquad (8)$$

As previously q_e represents the space charge density (C/m^3), however this is now only a function of the negative ion concentration and varies spatially within the domain.

$$q_e(x, y, z) = -en(x, y, z) \qquad (9)$$

Expressing the electric field in terms of a scalar potential, ϕ (V) yields the Poisson equation from equation (7)

$$\nabla^2 \phi = -\frac{q_e}{\varepsilon_0} \qquad (10)$$

Ion concentration/space charge
The steady-state distribution of negative ions (and hence space charge) is given by the scalar transport equation:

$$\nabla \cdot (n(b\underline{E} + \underline{u}) - \nabla \cdot (D_i \nabla n) = 0 \qquad (11)$$

The convective component is due to the velocity of the bulk air ($\underline{u}$) plus the ion drift velocity due to the electric field and ion mobility ($b\underline{E}$). The diffusion coefficient, D_i, is as in the ventilation model.

Momentum
The electric field creates forces on both charged (electrophoretic force) and uncharged (dielectrophoretic force) particles travelling in the field. These forces are both relevant for larger particles, however only the electrophoretic force is important with respect to ions. The resulting volume force due to air ions is therefore given by

$$\underline{F} = q_e \underline{E} \qquad (12)$$

The change in momentum that results from this force can be included in the momentum equations as a source term to give

$$\rho \frac{D\underline{u}}{Dt} = -\nabla p + \nabla \cdot (\mu \nabla \underline{u}) - q_e \nabla \phi \qquad (13)$$

Here ρ is the air density and μ is the viscosity.

Application in a CFD model
The model was developed using Fluent 6.2 CFD software for a 2D room 4.5 x 2.5m high as shown in figure 1. This enabled the behaviour of the model to be evaluated without the additional complexity of 3D airflow. The room was ventilated at a constant rate equivalent to 6 AC/h with the supply at low level defined by a normal velocity, $v = 0.047$ m/s, into the room and the high level extract defined as a zero pressure outlet. A simplified ioniser was defined near to the supply air vent, which was assumed to generate ions at a constant rate, blown into the room with a normal velocity 0.01 m/s. It was assumed that this is the only source of ions in the room; the ventilation supply air had a zero concentration of ions. The flow was modelled on a rectangular grid with boundary refinement containing 3000 cells, and turbulence modelled using the k-ε approach with standard wall functions.
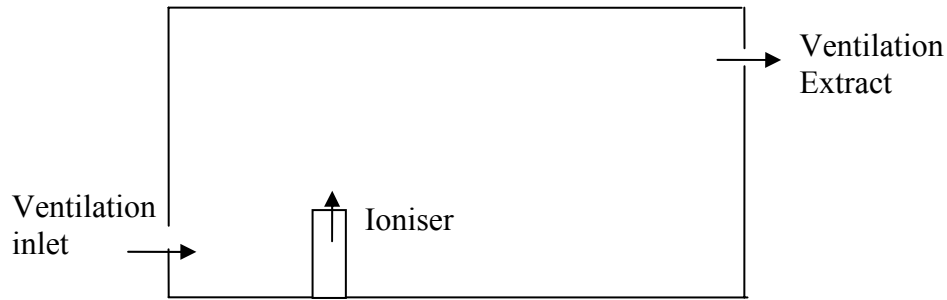
Figure 1: Schematic of the 2D CFD model room

The ion concentration and electric potential were both included in the fluent model by defining them as user scalars; the electric potential as a non-transported scalar, with a source term to incorporate the space charge, and the negative ion distribution as a transported scalar with a modified flux term to include the drift velocity. The walls are assumed to be grounded with boundary conditions on the electric potential and ion concentration given by $\phi = 0V$ and $\partial n/\partial s = 0$ respectively [9] where s is the normal to the walls of the domain. Solutions were found for a range of negative ion generation rates between 7×10^6 and 7×10^{10} ions/s. The simulations were carried out using an implicit segregated solver, with all the equations discretised using a second order scheme. The solutions were assumed to be converged when the momentum, turbulence and scalar residuals were less than 10^{-6} and in all cases the mass imbalance was less than 5×10^{-10} kg/s

RESULTS

Behaviour of Ions
The models presented above are first used to examine the factors that influence the concentration of negative ions in the space. In the absence of particles three removal mechanisms act on the negative ions; recombination with positive ions, ventilation removal and wall deposition. From equation (1) these can be defined as rate terms relative to a base ventilation rate $N_o = Q_o/V$ to give $\alpha p/N_o$, N/N_o and $\lambda_i = (n-p)be/N_o \varepsilon_o$ respectively. Table 1 shows the effects of the positive and negative ion concentrations and room ventilation on these rate terms, relative to a base ventilation rate of 1.5 Air changes per hour ($= 4.1667 \times 10^{-4}$ s^{-1}).

Table 1. Effect of ventilation rate and ion concentrations on relative negative ion removal rates

Negative ion concentration (ions/m³)	Relative ion removal rate due to:								
	Room ventilation when air change rate (AC/h) is:			Recombination when positive ion concentration (ions/m³) is:			Wall removal when positive ion concentration (ions/m³) is:		
	1.5	3	6	1.E+08	5.E+08	1.E+09	1.E+08	5.E+08	1.E+09
1.E+09	1.00	2.00	4.00	0.36	1.80	3.60	0.09	0.05	0.00
1.E+10	1.00	2.00	4.00	0.36	1.80	3.60	1.03	0.99	0.94
1.E+11	1.00	2.00	4.00	0.36	1.80	3.60	10.40	10.36	10.30
1.E+12	1.00	2.00	4.00	0.36	1.80	3.60	104.1	104.0	104.0
1.E+13	1.00	2.00	4.00	0.36	1.80	3.60	1040.9	1040.8	1040.8

It is clear from these results that at relatively low negative ion concentrations the ventilation rate and ion-ion interactions are the dominant factors determining the concentration of ions in the room. These are unaffected by the negative ion concentration and hence generation rate. However the electrostatic deposition of ions on the wall is very strongly dependant on the negative ion generation with an order of magnitude increase in the relative removal rate for every order of magnitude increase in the ion concentration. Indeed, electrostatic deposition is the dominant removal mechanism at ion concentrations above 1×10^{11} ions/m^3. In reality the non-linearity in the equations mean that this increased removal rate will impact back on the ion concentration in the room and therefore will be below the values stated above. In the absence of particles and positive ions this effect can also be explored using equation (1). Under steady state conditions with the wall removal from equation (4) this reduces to a quadratic equation for the negative ion concentration:

$$\frac{be}{\varepsilon_o}n^2 + n\frac{Q}{V} - q_n = 0 \qquad (14)$$

Figure 2 shows the solution of this equation with the negative ion generation rate q_n. It is assumed that $n_o = 0$. Plotting the effects of the removal mechanisms shows that at low ion generation rates the electric deposition at the wall has little influence with the concentration determined by the ventilation removal. However as the ion generation rate increases, wall deposition becomes increasingly dominant, with the result that the rate of growth in the overall ion concentration becomes progressively less and less as more and more ions are removed by room surfaces.
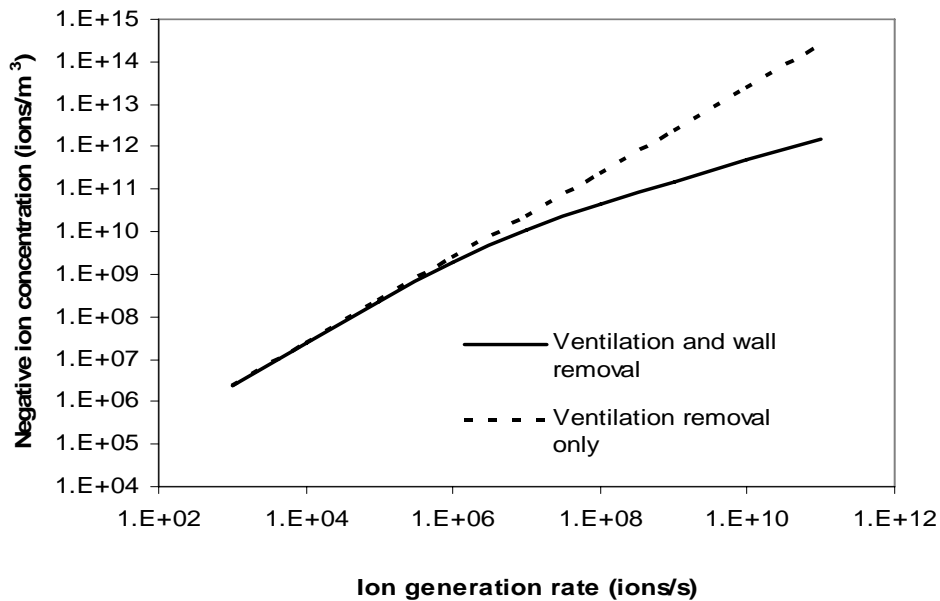

Figure 2: Effect of electrical wall deposition on the concentration of negative ions in the room at a ventilation rate of 1.5 AC/h

The results from the CFD model yield further insight into the behaviour of negative ions in a ventilated room. Figure 3 shows contour plots obtained from simulations with the ion generation rate at 7×10^6 ions/s (a) and 7×10^{10} ions/s (b). In each case three plots are presented; a transported scalar equivalent to the ions but with no electric effects, the negative ion concentration and the electric potential. As expected

the two contour plots for the uncharged scalar (a(i) and b(i)) are very similar with the dispersion controlled by the convection of the air and the only difference in the magnitude of the concentration due to the difference in generation rate. However the negative ion concentration contours are noticeably different at the two generation rates (a(ii) and b(ii)). Although convection still plays a key role in the distribution of the ions, the higher generation rate results in relatively less dispersion through the room. This concurs with the results presented in figure 2, and calculation of volume averaged ion concentrations from the CFD model results in a very similar plot to figure 2. The final contour plots (a(iii) and b(iii)) show the electric potential and its dependence on the ion distribution. With a uniform ion concentration throughout the room the expected electric potential would take the form of centrally positioned concentric circles. The non-uniform distribution results in a similar pattern however it is skewed between the ioniser and the ventilation extract to reflect the relative ion concentration throughout the room. As the ion generation rate increases both the magnitude of the electric potential and the amount of distortion increase.
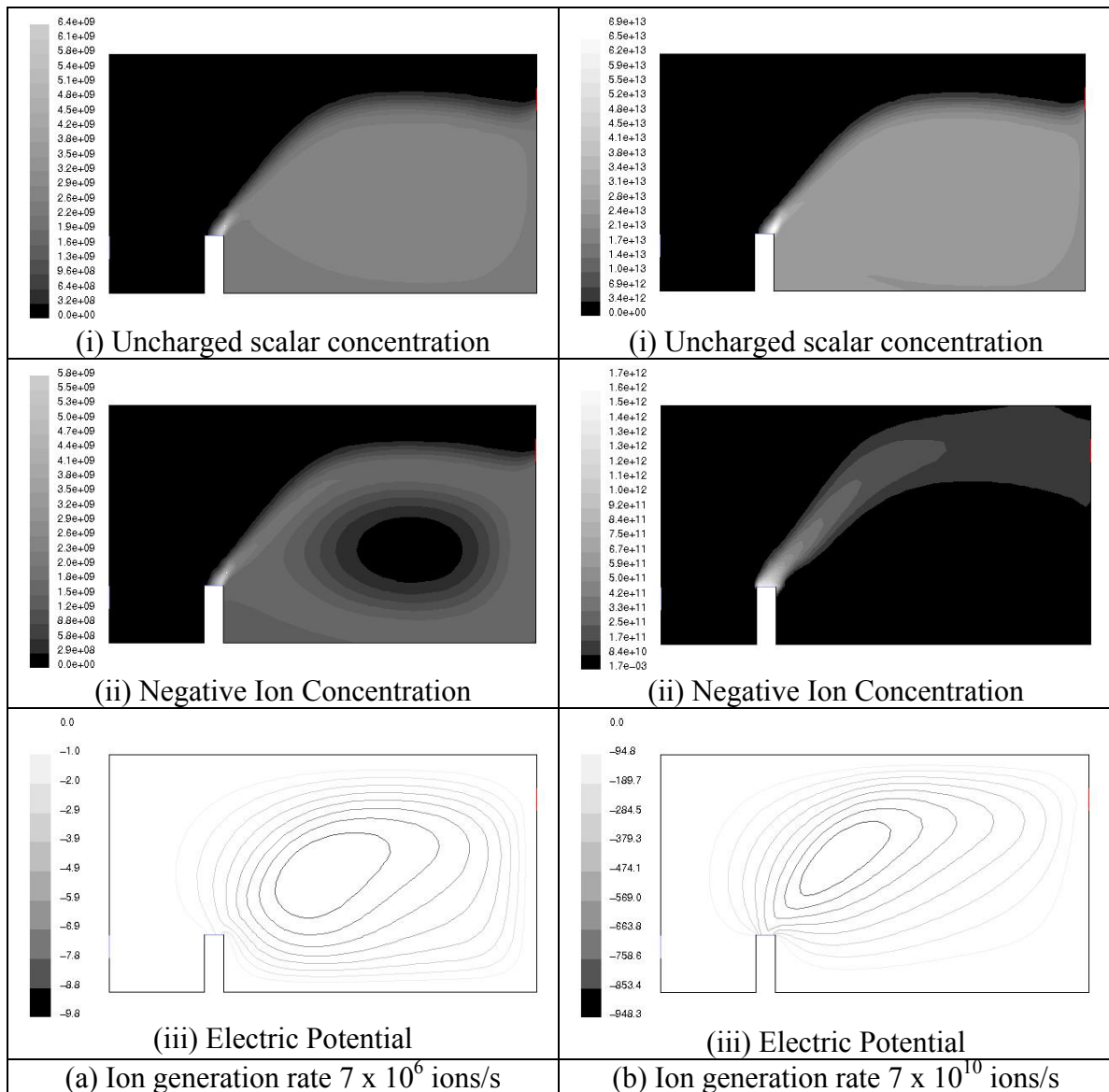
(i) Uncharged scalar concentration	(i) Uncharged scalar concentration
(ii) Negative Ion Concentration	(ii) Negative Ion Concentration
(iii) Electric Potential	(iii) Electric Potential
(a) Ion generation rate 7×10^6 ions/s	(b) Ion generation rate 7×10^{10} ions/s

Figure 3: CFD model results

Removal of Particles

In a similar manner to the above, the effect of negative ions on particles in the room space is explored through examining the relative removal rates in the ventilation model, this time in equation (3). Here there are only two mechanisms, ventilation removal and enhanced electrical deposition, however this is a complex process that depends on the charge acquired by the particle, which in turn will affect the space charge and electrodynamic processes.

Figure 4 uses equation (7) to show the influence of particle diameter and ion concentration on the number of unit charges acquired by a particle after 600s in the room space, the average time a particle spends in a room with an air change rate of 6 AC/h. This figure is plotted by assuming a constant positive ion concentration of 1 x 10^8 ions/m^3. The results demonstrate that it is likely that a 1μm particle in a ventilated room containing a negative ioniser will acquire in excess of 100 unit charges during its time in the room.

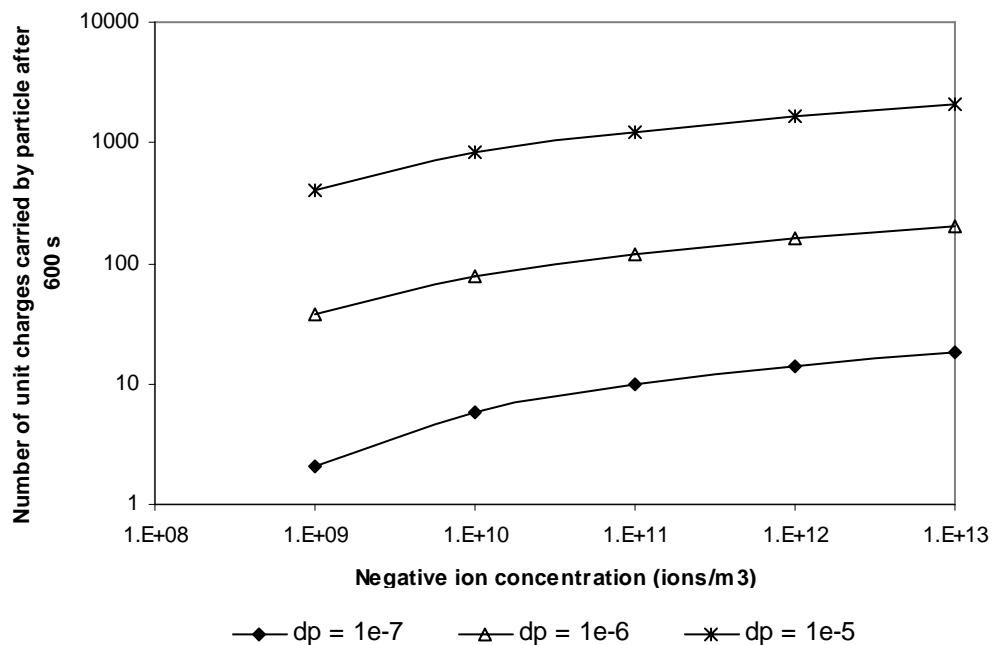Figure 4: Effect of ion concentration and particle diameter, d_p (μm), on particle charge

To examine the relative removal mechanisms for particles the ventilation and electrical deposition rate terms in equation (3) are also defined relative to a base ventilation rate $N_o = Q_o/V$ of 1.5 Air changes per hour (= 4.1667 x 10^{-4} s^{-1}). Table 2 shows the effect of the ventilation rate, particle concentration and negative ion concentration on both rate terms. These calculations assume 1μm diameter particles carrying 100 unit charges and the effects of positive ions are neglected.

It is clear from Table 2 that at low particle concentrations the removal of particles from the air is dominated by the ventilation rate, regardless of the negative ion concentration. However when the particle concentration exceeds 1 x 10^9 particles/m^3 the electrical deposition effect becomes increasingly important, with the removal rate increasing by an order of magnitude with each tenfold increase in the particle concentration.

Table 2. Effect of ventilation rate, particle concentration and negative ion concentration on particle removal mechanisms

Particle concentration (particles/m^3)	Relative particle removal rate due to:					
	Room ventilation when air change rate (AC/h) is:			Deposition when negative ion concentration (ions/m^3) is:		
	1.5	3	6	1.E+09	1.E+10	1.E+11
1.E+05	1.00	2.00	4.00	0.01	0.14	1.35
1.E+06	1.00	2.00	4.00	0.01	0.14	1.35
1.E+07	1.00	2.00	4.00	0.03	0.15	1.37
1.E+08	1.00	2.00	4.00	0.15	0.27	1.49
1.E+09	1.00	2.00	4.00	1.37	1.49	2.71
1.E+10	1.00	2.00	4.00	13.55	13.67	14.88
1.E+11	1.00	2.00	4.00	135.33	135.45	136.67
1.E+12	1.00	2.00	4.00	1353.16	1353.29	1354.50
1.E+13	1.00	2.00	4.00	13531.52	13531.65	13532.86

DISCUSSION

The results presented above yield some useful insights into the actions of negative air ionisers in indoor air. Although the analysis carried out here using the ventilation model is considerably simplified, the results demonstrate the relative magnitude of the electrical and ventilation effects under different conditions.

In the case of the ions the ventilation model shows the same trends as the CFD simulations, highlighting the significance of the electric effects as the ion generation rate increases. Although both models show that increased ion generation has progressively less effect on average room ion concentration, the CFD model reveals that the increase in generation continues to increase the electric potential and hence the magnitude of the electric field. It is this that acts upon both the charged ions and charged particles in the space, resulting in the increased electric deposition. The results in figure 2 also suggest that for ionisers to have this electric effect in a room, the ion generation rate must be greater than ~10^7 ions/s yielding ion concentrations of the order of 10^{10} ions/m^3 or greater.

The influence of the ions on particle removal mechanisms is also simplified in the ventilation model to evaluate the various effects without the issues of non-linearity. Despite this, the results provide considerable insight into the mechanisms of particle removal in the presence of ionisers. The high electrical removal rates at high particle concentrations explain why ionisers have had considerable success as devices for removing dense particulate concentrations such as cigarette smoke, yet are disputed for their effects on bioaerosols which tend to be in much lower concentrations [13]. However, evidence that ionisers can reduce the rate of some infections in hospitals [2] suggests there may be mechanisms other than the physical effects described here that act on bioaerosol. It is hoped that the findings from ongoing research by the authors will explain this and provide greater guidance on the benefits of ionisers in the clinical environment.

REFERENCES

1. Hawkins LH 1982. Air ions and office health. Occupational Health. Vol 34(3), pp.116-124
2. Kerr KG, Beggs CB, Dean SG et al 2006. Air ionisation and colonisation/infection with methicillin-resistant Staphylococcus aureus and Acinetobacter species in an intensive care unit. Intensive Care Medicine. Vol 32(2), pp.315-317.
3. Lee BU, Yermakov M, Grinshpun SA 2004. Removal of fine and ultrafine particles from indoor air environments by unipolar ion emission. Atmospheric Environment. Vol 38, pp 4815-4823
4. Mayya YS, Sapra BK, Khan A, Sunny F 2004. Aerosol removal by unipolar ionization in indoor environments. Journal of Aerosol Science. Vol 35, pp 923-941
5. Grabarczyk Z 2001. Effectiveness of indoor air cleaning with corona ionisers. Journal of Electrostatics. Vol 51-52, pp. 278-283
6. Hoppel WA 1985. Ion-aerosol attachment coefficients, ion depletion and the charge distribution on aerosols. Journal of geophysical research, Vol 90, pp 5917-5923
7. Horrak U 2001. Air ion mobility spectrum at a rural area. PhD thesis, University of Tartu, Estonia
8. Harrison RG 1992. Aerosol charging and radioactivity. PhD thesis, University of London
9. Choi BS, Fletcher CAJ 1997. Computation of particle transport in an electrostatic precipitator. Journal of Electrostatics. Vol 40-41, pp. 413-418
10. Adamiak K 1994. Adaptive approach to finite element modelling of corona fields. IEEE Transactions on Industry Applications. Vol 30(2), pp. 387-393
11. Caron A, Dascalescu L 2004. Numerical modelling of combined corona-electrostatic fields. Journal of Electrostatics. Vol 61, pp. 43-55
12. Fletcher LA, Noakes CJ, Sleigh PA, Beggs CB 2007. Air ion behaviour in ventilated rooms. Submitted to Journal of Aerosol Science
13. Roberts K, Hathway A, Fletcher LA et al 2006. Bioaerosol production on a respiratory ward. Indoor and Built Environment, Vol 15(1): p. 35-40.