ON THE VERTICAL ELECTRICAL STRUCTURE OF A DUST CLOUD IN THE ATMOSPHERIC BOUNDARY LAYER

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ABSTRACT

We consider a dust cloud combined of identical dust particles of fixed size. The dust charges by the attachment of ions from the surrounding weakly ionized air. The system of equations considered has been numerically and analytically examined. It has been shown even in a simple homogenous case, the charge of dust depends on dust density and ions conductivities. The case of dust cloud (under the external electric field) elevated over the ground is characterized by electric field amplification inside due to the inner conductivity decrease. Also the two opposite situations have been tested for the cloud lying on the ground: 1) total current on the ground is a constant, 2) electric field on the ground is a constant. Space and dust charges versus the height have been numerically calculated for all cases above.

INTRODUCTION and PROBLEM STATEMENT

As a rule, the Earth's boundary layer contains dust grains and fine dust particles. All these impurities are charged due to the presence of ions of both signs in the surrounding air. The magnitude of the stationary dust charge depends on dust size and surface properties, ion temperature and ratio of ion conductivities. The electric field and dust fall velocity can also affect charging processes. We have examined diffusion charging, neglecting electric field influence on single particle charging. This is valid for the dust particles with sizes less than 20 microns. As it has been shown in the numerous measurements, just these particles dominate in the boundary layer in the case of urban pollution or typical fog events.

We will consider two types of dust clouds: dust cloud lying on the ground and dust cloud elevated to the fixed height. Without the dust the vertical electric field profile is well-known and described by the theory of the electrode effect [1]. Due to the negative ion concentration decreasing near the ground, space charge becomes positive, and electric field magnitude increases. But such a profile of space charge and electric field may change in the presence of dust particles.

We suppose that the main dust charging mechanism is the diffusion one, [2], that is for dust with radius less than 20μ and electric field no higher than $10\,V/cm$. Ions current on particles in this case can be expressed as [2],[3] :

$$\tilde{\beta}_{\pm} = \pm Q \frac{\exp\left(\pm Q/2Q_T\right)}{2sh(Q/2Q_T)} \nu_{\pm},\ \nu_{\pm} = 4\pi n_{\pm} e B_{\pm}, \tag{1}$$

where $Q_T = T_i R/e$ is the characteristic "diffusion" charge , T_i is the ion temperature in energetic units, R is the dust radius, e is the elementary charge. The continuous regime is supposed to be valid ($R \gg l$, l_i is the ions free path) and the screening charge contribution to the electric field is neglected.

From the stationary condition for Q: $dQ/dt = \tilde{\beta}_+ + \tilde{\beta}_- = 0$, it is simply to find stationary charge for one isolated dust particle emmersed into weakly ionized gas:

$$Q_0 = Q_T \ln\left(\frac{B_+ n_+}{B_- n_-}\right). \tag{2}$$

But in the atmospheric boundary layer the formula (2) does not work for the dense dust clouds. The presence of a dust may alter ions concentration and height profile, that will turn dust charges itself. Therefore, we will consider self-consistent system of equations to find out dust and ions charge densities and the electric field profiles. It helps us also to set up validity limits for (2).

BASIC EQUATIONS and STATIONARY STATE OF UNIFORM DUST CLOUD

Let us assume dust concentration,N, is the stationary and homogenous quantity except cloud upper boundary, where it decrease exponentially. Diffusivity is some function of height, ionization rate also depends on cloud height and time. So, in a more general case the source system is:

$$\frac{\partial E}{\partial z} = 4\pi n_0(\varepsilon_Q \tilde{Q} + \tilde{n}_+ - \tilde{n}_-), \tag{3}$$

$$\frac{\partial \tilde{n}_{\pm}}{\partial t} \pm B_{\pm}\frac{\partial(\tilde{n}_{\pm}E)}{\partial z} - \frac{\partial}{\partial z}(\tilde{n}_{\pm}D_{\pm}(z)\frac{\partial \tilde{n}_{\pm}}{\partial z}) = \frac{1}{\tau_i}(\tilde{I}(z,t) - \tilde{n}_+\tilde{n}_-) \pm \varepsilon_Q \tilde{\beta}_{\pm}, \tag{4}$$

$$\frac{\partial \tilde{Q}}{\partial t} + \frac{\partial (V_Q \tilde{Q})}{\partial z} = \tilde{\beta}_- + \tilde{\beta}_+; \tag{5}$$

$$\text{where}\tilde{Q} = \frac{Q}{Q_T},\ \tilde{n}_\pm = \frac{n_\pm}{n_0},\ n_0^2 = \frac{I_0}{\lambda},\ \frac{1}{\tau_i} = \sqrt{I_0\lambda},\ \varepsilon_Q = \frac{Q_T N}{e n_0},\ \tilde{I}(z,t) = \frac{I(z,t)}{I_0}, \tag{6}$$

where I_0 is the ionization rate on the ground, n_0 is the stationary ions concentration in absence of dust, ε_Q is the important parameter describing an amount of dust charge density, V_Q is the dust sedimentation rate, it determines by the Stokes law.

Practically, the natural dust cloud contains rather uniform regions where we can set $d/dz = 0$, then ions concentration and dust charges can be found from the following system (we supposed $\tilde{I} = 1$):

$$\frac{d\tilde{n}_\pm}{dt} = 1 - \varepsilon_{1\pm}\tilde{n}_\pm^2 - \tilde{n}_+\tilde{n}_-(1-\varepsilon_{1\pm}) - \tilde{n}_\pm\varepsilon_Q\varepsilon_{1\pm}(\beta(\mp\tilde{Q}) \pm \tilde{Q}), \tag{7}$$

$$\frac{d\tilde{Q}}{dt} = \beta(-\tilde{Q})n_+\varepsilon_{1+} - \beta(\tilde{Q})n_-\varepsilon_{1-},\ \beta(\tilde{Q}) = \frac{\exp(\tilde{Q}/2)}{(\tilde{Q}/2)}\tilde{Q}/2,\ \varepsilon_\pm = \frac{B_\pm}{4\pi e\lambda}. \tag{8}$$

The analytical stationary solution of the system (7) - (8) can be obtained by expansion it into series of ε_Q or ε_Q^{-1}. The case of light dust cloud, $\boldsymbol{\varepsilon_Q \ll 1}$. For $n_\pm$ and $\tilde{Q}$ we can write

$$\tilde{n}_\pm = 1 + \varepsilon_Q n_{1\pm},\ \tilde{Q} = \tilde{Q}_0 + \varepsilon_Q\, Q_1, \tag{9}$$

where $\tilde{Q}_0 = ln(\varepsilon_{1+}/\varepsilon_{1-})$ is the 0-order solution, unperturbed. If we left only first order terms than the result is

$$\tilde{n}_+ = 1 - \frac{\varepsilon_Q}{2}\left(\varepsilon_{1+}\beta(-\tilde{Q}_0)) + \tilde{Q}_0\right),\ \tilde{n}_- = 1 - \frac{\varepsilon_Q}{2}\left(\varepsilon_{1-}\beta(\tilde{Q}_0)) - \tilde{Q}_0\right),\ \tilde{Q} = \tilde{Q}_0(1-\varepsilon_Q). \tag{10}$$

Therefore, $|\tilde{Q}|$ is decreasing when ε_Q (or dust concentration, N_Q) rises. However, dust charge density, $\tilde{Q}\varepsilon_Q$, is increasing by the absolute value.

The case of dense dust cloud, $\boldsymbol{\varepsilon_Q \gg 1}$. Now we should expand the solution into series of value $1/\varepsilon_Q$. The result can be written as:

$$\tilde{n}_\pm = \frac{1}{\varepsilon_{1\pm}\varepsilon_Q}\left(1 - \frac{\varepsilon_{1+}^2}{\varepsilon_Q(\varepsilon_{1+}+\varepsilon_{1-})}\right), \tilde{Q} = \frac{1}{\varepsilon_Q^2}\left(\frac{1}{\varepsilon_{1-}} - \frac{1}{\varepsilon_{1+}}\right). \tag{11}$$

And absolute value $|\tilde{Q}|\varepsilon_Q$ diminishes as $1/\varepsilon_Q$. That is a pointer to maximum presence on the curve $|\tilde{Q}(\varepsilon_Q)|\varepsilon_Q$. The maximum should be approximately in the transitional area, $\varepsilon_Q \sim 1$. Numerical stationary solution of the system (7) - (8) is presented in the Fig.1. The full space charge, $\tilde{n}_+ - \tilde{n}_- + \tilde{Q}\varepsilon_Q$, is formally equal to zero here. But presence of absorbtion boundaries may cause a rearrangement of charges and appearance of stable inhomogeneous regions with uncompensated space charge.

A HEIGHT PROFILE OF DUST CLOUD: NUMERICAL RESULTS

We will consider slightly disturbed fair weather conditions, when the turbulent diffusion can be neglected. Such case is widespread when fog or common night temperature inversion occurs and lower turbulence is suppressed. It is comfy to use completely dimensionless system:

$$\frac{\partial\tilde{E}}{\partial\tilde{z}} = \tilde{n}_+ - \tilde{n}_- + \varepsilon_Q\tilde{Q}; \tag{12}$$

$$\frac{\partial\tilde{n}_\pm}{\partial\tau} \pm \varepsilon_{1\pm}\frac{\partial(\tilde{n}_+\tilde{E})}{\partial\tilde{z}} = \tilde{I}(t) - \tilde{n}_+\tilde{n}_- - \tilde{n}_\pm\varepsilon_{1\pm}\varepsilon_Q\beta(\mp\tilde{Q}); \tag{13}$$

$$\frac{\partial\tilde{Q}}{\partial\tau} + \tilde{V}_Q\frac{\partial\tilde{Q}}{\partial\tilde{z}} = \beta(-\tilde{Q})n_+\varepsilon_{1+} - \beta(\tilde{Q})n_-\varepsilon_{1-}; \tag{14}$$

where $\tilde{z} = z/z_0$, $\tilde{E} = E/E_0(t=0, z=0)$, $\tilde{V}_Q = V_Q\tau_i/z_0$. $z_0 = 4\pi e n_0/E_0$ is the characteristic height of filed change near the ground in the absence of the dust. For $n_0 = 25001/cm^3$ and $E_0 = 1\,V/cm$ z_0 it is about 2.2 meters, that is an order of Electrode Effect space charge layer (with no turbulent diffusion). Let us consider a dust cloud elevated on the fixed height over the ground. Also this height is assumed to be much greater than the cloud thickness. The numerical results for the dust cloud with depth $6z_0$ are presented on Fig. 1.b). Cloud contains 1μ particles and it is sustained on the fixed height by very slow updraft gas flow. This figure is for stationary distribution: $dj_z/dz = 0$. Also it is interesting to analyze very high dust cloud lying on the ground, see Fig 2. The electric field on the ground is fixed: $E_0 = 1V/cm$. The electric current is not fixed and it changes from one ε_Q value to another. The opposite case, when j is fixed but $E(z=0)$ changes is presented in Fig. 3. The dust cloud has a fixed height and two layers of a positive space charge. One of them

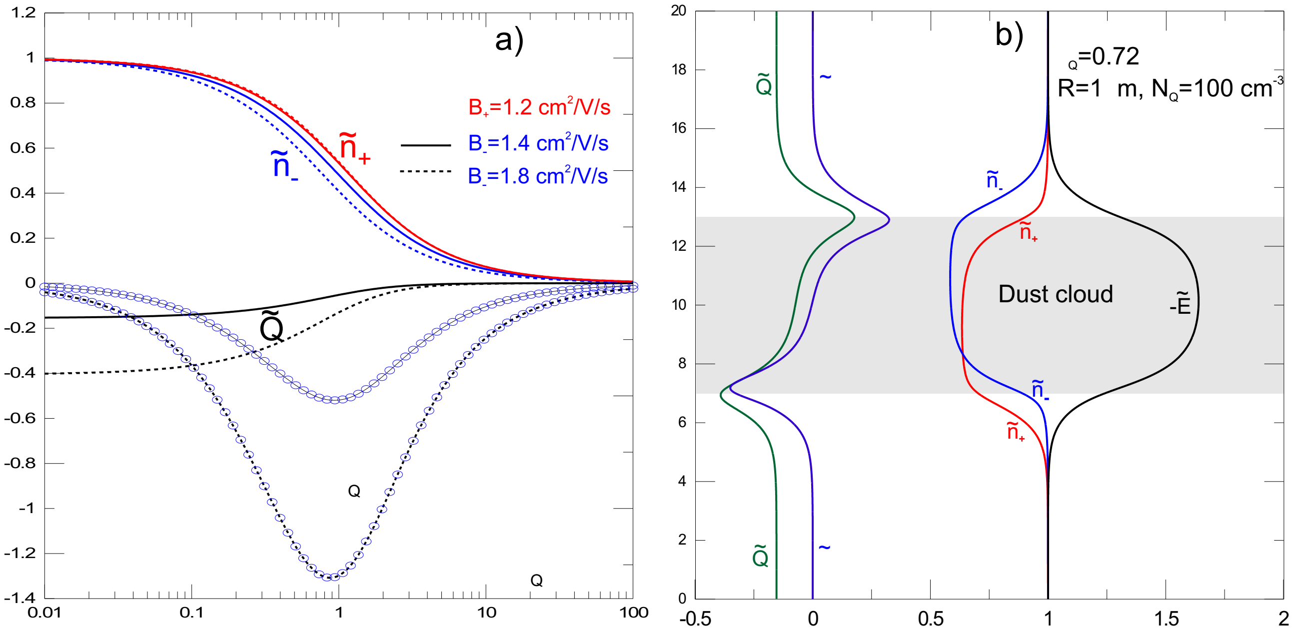

Figure 1: a) Stationary homogeneous space charges and dust charge versus control parameter ε_Q. b) Charge distribution for the elevated dust cloud

is on upper cloud boundary. The magnitude $\rho(\tilde{z} \approx 10)$ is determined by ions concentration decreasing entire the cloud. This concentration can be calculated as for stationary homogeneous case, see Fig 1.a).

As a rule, the dust charge (for small particles $R < 10\mu$) changes its polarity inside electrode layer, $\sim z_0$. It is connected with a fact that above electrode layer $B_- > B_+$ and $n_+ = n_-$ so the dust has a negative stationary charge. While moving toward the Earth dust penetrates the electrode layer where $n_+B_+ > n_-B_-$, and this is the main reason for presence of positively charged particles near the ground. Surely, it depends on dust fall down velocity, and large particles (with $R > 50\mu$)can keep its negative charge even moving through electrode layer.

CONCLUSIONS

The results obtained in this work allow us to predict electric field changes when dust pollution or fog events occur. In addition, it gives the necessary information to calculate the electric current on thin wire antenna (used for the geoelectrical monitoring) in the case of fog events or presence of dust pollution in the Earth's boundary layer [4].

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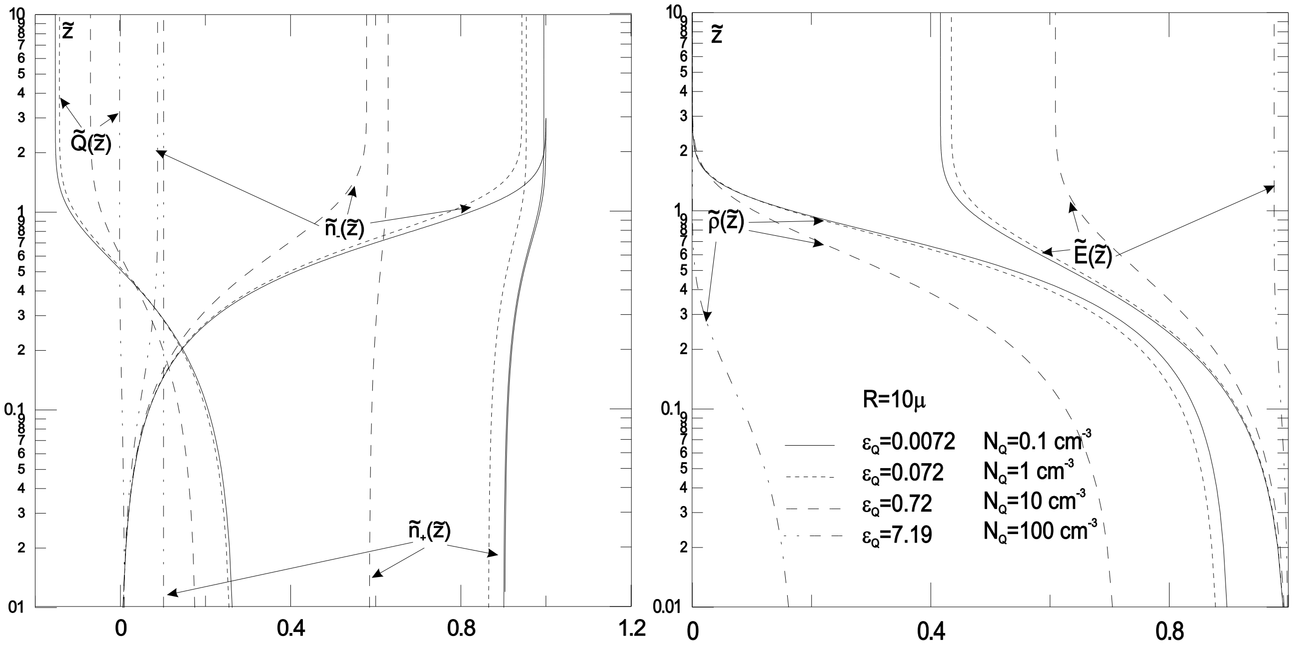

Figure 2: Stationary inhomogeneous space charges electric field and dust charge versus height. The ”infinite” dust cloud lying on the ground, E_0=Const.

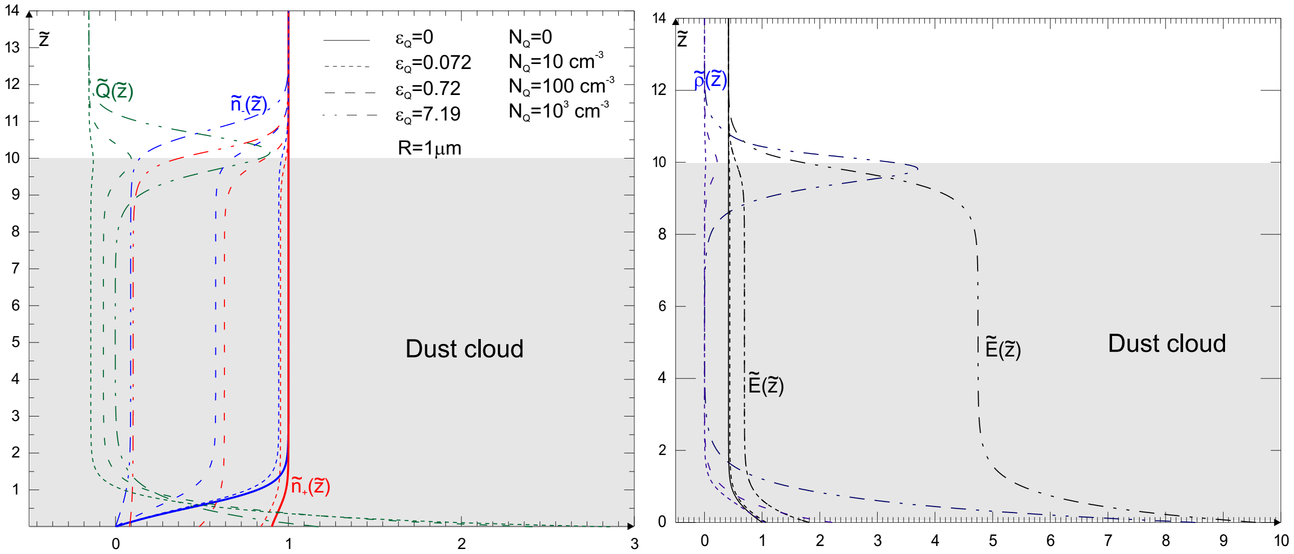

Figure 3: Stationary inhomogeneous space charges, electric field and dust charge versus height. The dust cloud is limited $z = 10z_0$ height, j_0=Const.