Surface Layer Electrodynamic Structure under Severe Aerosol Pollution

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ABSTRACT: The non-stationary electrodynamic model of turbulent surface layer with multi-charged aerosol particles was developed with taking into account the current of large ions. Distributions of electric characteristics near the surface were received depending on aerosol particles concentration, turbulent mixing rate, air ionization degree, aerosol particles size and number of charges on them.

INTRODUCTION

The non-stationary electrodynamic model of turbulent surface layer was observed in [1] with taking into account the presence of charged aerosol particles. The model included ionization-recombination equations for small ions according to its interaction with aerosol particles, turbulent transport equation of large ions produced as a result of interaction and Poisson equation with taking into account the concentrations of small and large ions. Increasing of aerosol particles size leads to the growth of elementary charges quantity on the large ions [1]. The charged aerosol particles impact in the electric conductivity was theoretically estimated in the paper. It was received that the impact becomes significant under concentrations not less than 10^{14} m^{-3}. However, the current produced by large ions was not investigated.

THEORETICAL BACKGROUND

The model similar to developed in [1] considering the large ions current and turbulent transfer of neutral aerosol particles is the following:

$$
\begin{aligned}
&N_0+\sum_{k=1}^{m}N_1^{(k)}+\sum_{k=1}^{m}N_2^{(k)}=N=\text{const},\\
&\frac{\partial N_0}{\partial t}-\frac{\partial}{\partial z}\left(D_T(z)\frac{\partial N_0}{\partial z}\right)=n_1\beta_{12}^{(1)}N_2^{(1)}+n_2\beta_{21}^{(1)}N_1^{(1)}-n_1\beta_{10}^{(0)}N_0-n_2\beta_{20}^{(0)}N_0,\\
&\frac{\partial N_1^{(k)}}{\partial t}+\frac{\partial}{\partial z}\left(B_1^{(k)}\cdot N_1^{(k)}\cdot E\right)-\frac{\partial}{\partial z}\left(D_T(z)\cdot\frac{\partial N_1^{(k)}}{\partial z}\right)=n_1\beta_{11}^{(k-1)}N_1^{(k-1)}-n_1\beta_{11}^{(k)}N_1^{(k)}+n_2\beta_{21}^{(k+1)}N_1^{(k+1)}-n_2\beta_{21}^{(k)}N_1^{(k)},\\
&\frac{\partial N_2^{(k)}}{\partial t}+\frac{\partial}{\partial z}\left(B_2^{(k)}\cdot N_2^{(k)}\cdot E\right)-\frac{\partial}{\partial z}\left(D_T(z)\cdot\frac{\partial N_2^{(k)}}{\partial z}\right)=n_2\beta_{22}^{(k-1)}N_2^{(k-1)}-n_2\beta_{22}^{(k)}N_2^{(k)}+n_1\beta_{12}^{(k+1)}N_2^{(k+1)}-n_1\beta_{12}^{(k)}N_2^{(k)},
\end{aligned}
\tag{1}
$$

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$$\begin{aligned}
&\frac{\partial n_1}{\partial t}+\frac{\partial}{\partial z}(b_1\cdot n_1\cdot E)-\frac{\partial}{\partial z}\left(D_T(z)\cdot\frac{\partial n_1}{\partial z}\right)=q(z)\text{-}\alpha\, n_1 n_2-n_1\sum_{k=0}^{m-1}\beta_{11}^{(k)}N_1^{(k)}-n_1\sum_{k=1}^{m}\beta_{12}^{(k)}N_2^{(k)},\\
&\frac{\partial n_2}{\partial t}-\frac{\partial}{\partial z}(b_2\cdot n_2\cdot E)-\frac{\partial}{\partial z}\left(D_T(z)\cdot\frac{\partial n_2}{\partial z}\right)=q(z)\text{-}\alpha\, n_1 n_2-n_2\sum_{k=0}^{m-1}\beta_{22}^{(k)}N_2^{(k)}-n_2\sum_{k=1}^{m}\beta_{21}^{(k)}N_1^{(k)},\\
&\frac{\partial E}{\partial z}=\frac{e}{\varepsilon_0}\cdot\left(n_1-n_2+\sum_{k=1}^{m}k\,N_1^{(k)}-\sum_{k=1}^{m}k\,N_2^{(k)}\right),
\end{aligned}\tag{1}$$

where $n_{1,2}$ is the volume concentration of small ions, $b_{1,2}$ is the mobility of small ions, E – electric field, α – small ions recombination coefficient, E_0 – value of electric field near the surface, $N_1^{(k)}$, $N_2^{(k)}$ – volume concentrations of positive and negative large ions, N_0 – concentrations of neutral large ions; N – aerosol particles concentrations, $\beta_{ij}^{(k)}$ – coefficients of small and large ions interactions [2], $B_{1,2}^{(k)}$ – large ions mobility, k – number of elementary charges on large ion, m – maximum possible number of elementary charges on large ion, e is the elementary charge, ε_0 – electric constant.

The first equation in set (1) is the equilibrium condition of large ions. The second, the third and the fourth – are the equations of transferring neutral, positive and negative large ions. The fifth and the sixth are the ionization-recombination equations for small ions. The seventh expression in set is the Poisson equation.

Turbulent diffusion coefficients of small and large ions were considered as equal: $D_T(z)=D_1\cdot z$. The profile of ion production rate was set as [3]: $q(z)=\left(q_1+q_0e^{-z/h}\right)\cdot 10^6$, where h is the typical scale.

The set of equation (1) was numerically calculated with appropriate initial and boundary conditions [1] updated with the term for N_0:

$$\begin{aligned}
&n_{1,2}(t=0)=\frac{-BN+((BN)^2+4\alpha q)^{1/2}}{2\alpha}\cdot\left(1-e^{-\frac{(z-z_0)}{L_0}}\right),\ n_{1,2}(z=z_0)=0,\\
&n_{1,2}(z=l)=\frac{-BN+((BN)^2+4\alpha q)^{1/2}}{2\alpha},\ N_{1,2}^{(k)}(t=0)=B_k,\ \left.\left(\frac{\partial N_{1,2}^{(k)}}{\partial z}\right)\right|_{z=z_0}=0,\ N_{1,2}^{(k)}(z=l)=B_k,\\
&N_0(t=0)=\text{N-}\left(\sum_{k=1}^{m}N_1^{(k)}+\sum_{k=1}^{m}N_2^{(k)}\right),\ N_0(z=z_0)=\text{N-}\left(\sum_{k=1}^{m}N_1^{(k)}+\sum_{k=1}^{m}N_2^{(k)}\right),\ N_0(z=l)=B'_k,\\
&E(t=0)=E_0, E(z=z_0)=E_0,
\end{aligned}\tag{2}$$

where L_0 = 1 m is the typical scale of turbulent electrode layer, $z_0 = 2{,}5\cdot 10^{-3}$ m – roughness parameter of the surface, l – top boundary of electrode layer (altitude where the following conditions are met: $\partial n_1/\partial z\to 0,\partial n_2/\partial z\to 0,\partial N_1^{(k)}/\partial z\to 0,\partial N_2^{(k)}/\partial z\to 0$), B_k, B'_k – parameters depending on the interaction coefficients of small ions and k-charged large ions. While founding boundary conditions it was took into account that $n_1(z=l)=n_2(z=l)=n$. Asymptotic conditions of large and small ions were received from stationary solutions of the appropriate equations of set (1).

For calculation of positive and negative large ions mobility the following expression was used [4]:

$$B_{1,2}^{(k)} = \frac{1}{6\pi r\eta} ke\left(1+\frac{R}{pr}\right), \tag{3}$$

where p – atmospheric pressure, $R = 6.17\cdot10^{-4}$, r – particles radius, η = 18,7 µPa·s – air viscidity (normal conditions).

The electric current density has two components in the presence of aerosol particles in the atmosphere:

$$j = j_1 + j_2 = e(b_1 n_1 + b_2 n_2)\cdot E + e\left(\sum_{k=1}^{m} kB_1^{(k)} N_1^{(k)} + \sum_{k=1}^{m} kB_2^{(k)} N_2^{(k)}\right)\cdot E, \tag{4}$$

where j_1, j_2 – current densities formed by small and large ions accordingly.

For the density of electric space charge we obtained:

$$\rho = \rho_1 + \rho_2 = e(n_1 - n_2) + e\left(\sum_{k=1}^{m} k\, N_1^{(k)} - \sum_{k=1}^{m} k\, N_2^{(k)}\right), \tag{5}$$

where ρ_1, ρ_2 are the densities of space charge produced by small and large ions accordingly.

RESULTS AND DISCUSSION

Spatio-temporal characteristics of the surface layer were received and investigated using developed model (1) – (2) in dependence of aerosol particles concentrations, turbulent mixing rate, air ionization degree, values of electric field near the Earth surface, aerosol particles size and number of charges on it according to its size.

The equilibrium condition between concentrations of charged and neutral particles and exchange coefficient of small and large ions are [1, 2] were assumed. Researched diapason of the model (1) – (2) parameters is given in Table 1.

Table 1 Model parameters diapason

b_1, m^{2}V^{-1}s^{-1}	b_2, m^{2}V^{-1}s^{-1}	α, m^{3}s^{-1}	E_0, V·m^{-1}	e, C	ε_0, F/m
$1.36\cdot10^{-4}$	$1.56\cdot10^{-4}$	$1.6\cdot10^{-12}$	-(50-300)	$1.6\cdot10^{-19}$	$8.85\cdot10^{-12}$
q_1, m^{-3}s^{-1}	N, m^{-3}	D_1,m·s^{-1}	q_0, m^{-3}s^{-1}	m	r, µm
7.0	(10^8-10^{14})	(0.01-0.1)	(4.8-80)	(1-5)	(0.002-0.2)

Theoretical investigations showed that when the aerosol particles size is r = 0.002 µm the maximum possible number of elementary charges on the large ion m = 1, if r = 0.01µm the value is m = 2, if r = 0.2 µm the value is m = 3.

The height distributions of electric field density are represented in Figure 1 for the situation when $E_0 = -100$ Vm^{-1}, air ionization rate $q_0 = 4{,}8$ m^{-3}s^{-1} in condition of weak (*a,b,c,d,e,f* for D_1 = 0.01 m·s^{-1}) and advanced (*g,h,i,j,k,l* for D_1=0.1 $m\cdot s^{-1}$) turbulent mixing. If aerosol particles size is r = 0.002 µm: m = 1,

$B_1^{(1)} = B_2^{(1)} = 9.271 \cdot 10^{-7}$ m^{2}V^{-1}s^{-1}, $\beta_{11}^{(0)} = \beta_{22}^{(0)} = \beta_{10}^{(0)} = \beta_{20}^{(0)} = 0{,}0192 \cdot 10^{-12}$ m^{3}s^{-1}, $\beta_{12}^{(1)} = \beta_{21}^{(1)} = 1{,}4 \cdot 10^{-12}$ m^{3}s^{-1}.

When r = 0.06 μm: m = 2, $B_1^{(1)} = B_2^{(1)} = 1.669 \cdot 10^{-8}$ m^{2}V^{-1}S^{-1}, $\beta_{11}^{(0)} = \beta_{22}^{(0)} = \beta_{10}^{(0)} = \beta_{20}^{(0)} = 2{,}25 \cdot 10^{-12}$ m^{3}s^{-1}, $\beta_{12}^{(1)} = \beta_{21}^{(1)} = 3{,}57 \cdot 10^{-12}$ m^{3}s^{-1}, $\beta_{11}^{(1)} = \beta_{22}^{(1)} = 1{,}42 \cdot 10^{-12}$ m^{3}s^{-1}, $\beta_{12}^{(2)} = \beta_{21}^{(2)} = 5{,}17 \cdot 10^{-12}$ m^{3}s^{-1}.

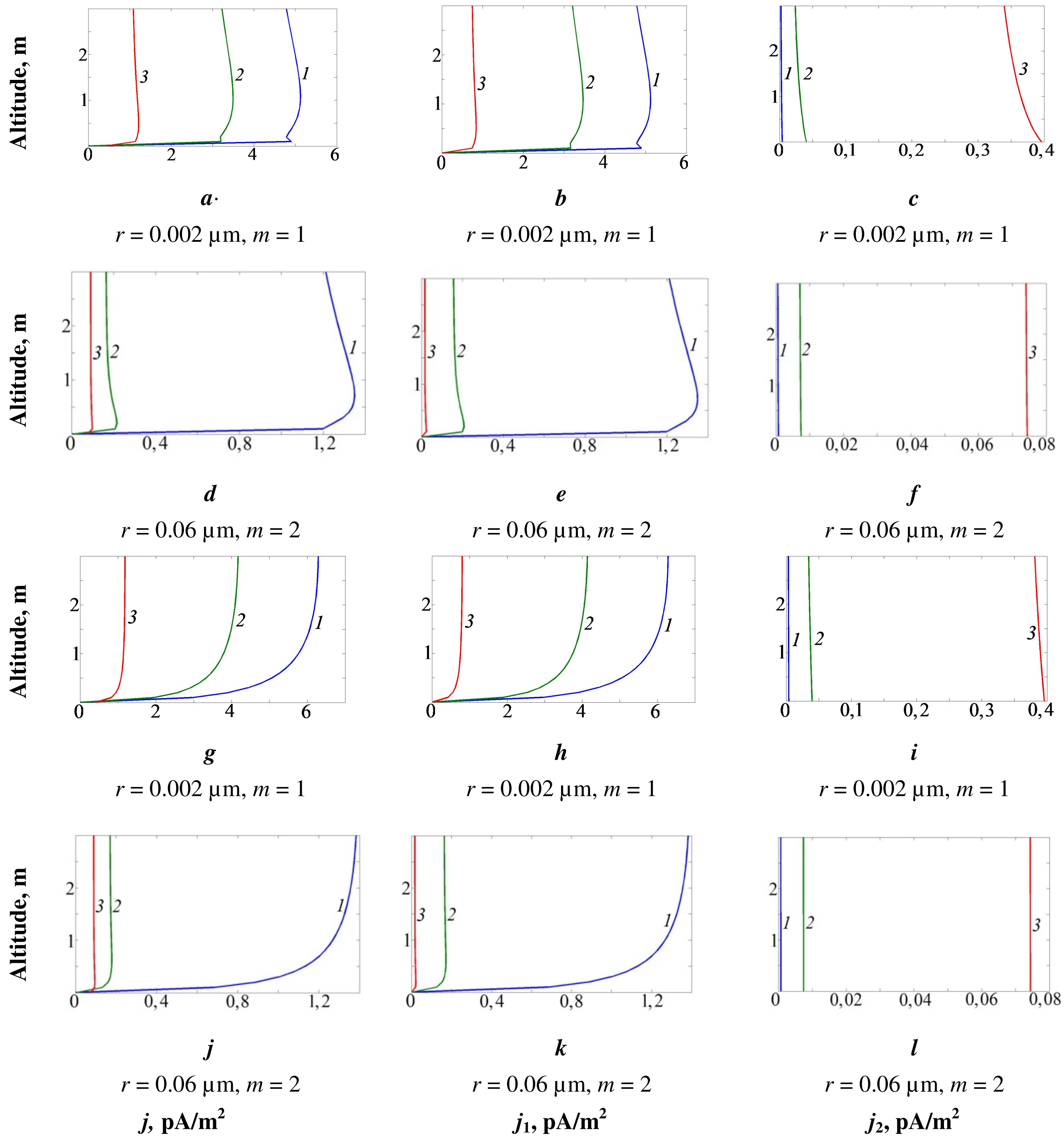

Fig. 1. Electric current density under different aerosol particles concentrations (curves 1,2,3 for $N = 10^{10}$; 10^{11}; 10^{12} m^{-3} accordingly)

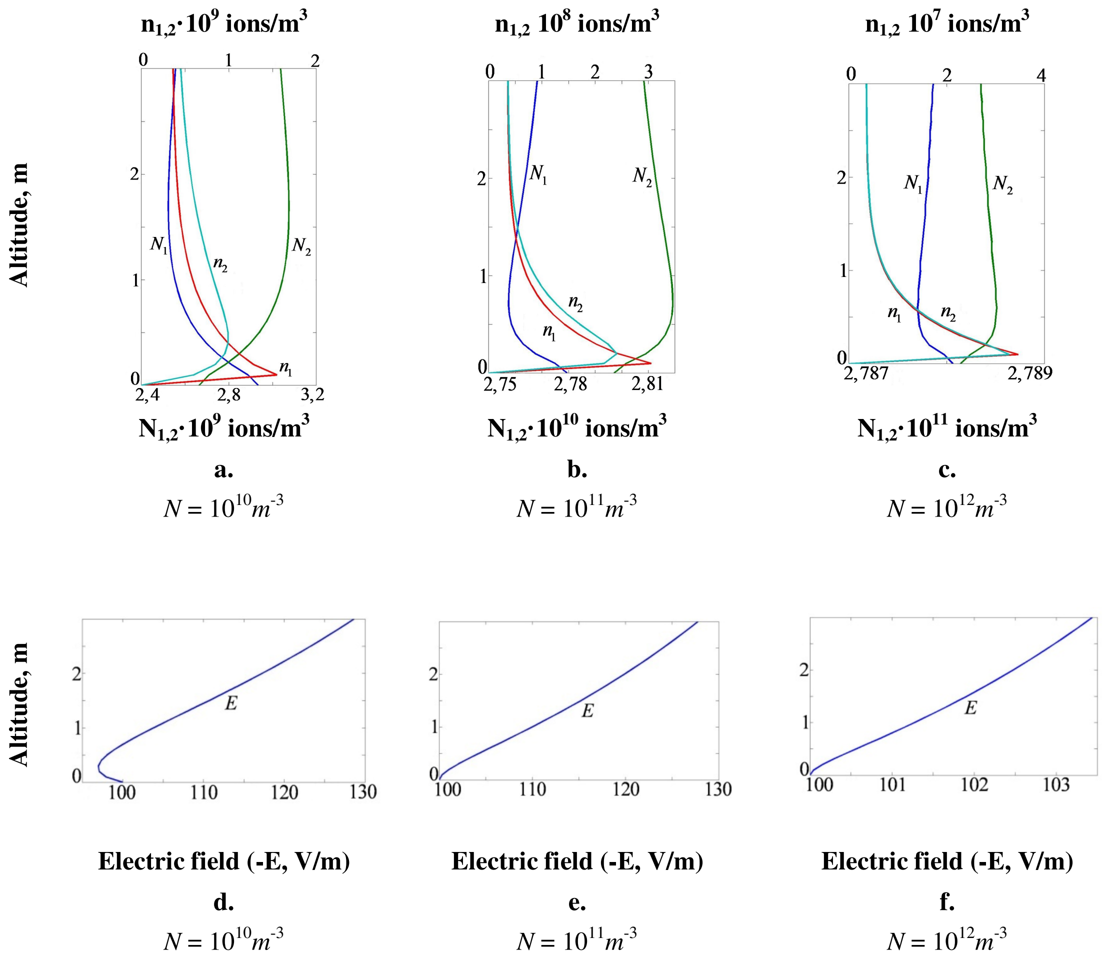

Fig. 2. Electric characteristics of surface layer under strong ionization and weak turbulence with different aerosol particles concentrations (q_0 = 80 m^{-3}s^{-1} , m = 2, D_1 = 0.01 $m{\cdot}s^{-1}$)

The analysis of received profiles demonstrates that if the values of aerosol particles concentration is $N = 10^{10}$ m^{-3}then the current component produced by large ions is in 1000 times less then the current of light ions, i.e. it is negligibly small (Fig. 1, curve 1). The current produced by large ions is increased with the growth of aerosol particles concentration as illustrated in Figure 1, curve 2. If N = 10^{12}m^{-3}the currents of small and large ions are became practically equal (Figure 1, curve 3). However, when aerosol particles size is r = 0.002 μm the current of small ions near the surface exceeds the large ions current in approximately two times. Increase of aerosol particles size (r = 0.06 μm) leads to the situation when the current of large ions are more than small ions in more than 4 times. The current component produced by small ions could be neglected if the aerosol particles size more than 10^{13} m^{-3}. Comparative analysis of Fig. 1 (*a*, *b*, *c*, *g*, *h*, *i*) and Fig. 1 (*d*, *e*, *f*, *j*, *k*, *l*) demonstrates that increasing of aerosol particles size by one order (from r = 0.002 μm to r = 0.06 μm) leads to decrease of current density values. Current components produced by small and large ions near Earth surface are decreased in 5 times. This situation evolves for all sizes of aerosol particles and does not depend on turbulent mixing rate in the atmosphere.

It should be noted that when $N = 10^{14}$ m^{-3} the electric current is determined only by large ions.

Numerical calcualtion results received under less aerosol particles concentrations ($N \leq 10^{10}$ m^{-3}) are in a full agreement with results of work [1].

Calculated profiles of space charge and electric field under weak turbulent mixing (D_1 = 0.01 $m \cdot s^{-1}$), strong ionization degree (q_0 = 80 m^{-3}s^{-1}) and different aerosol particles concentrations in the atmosphere are illustrated in Figure 2. It was received that when $N = 10^{10}$ m^{-3}the overall space charge and charge generated by small ang large ions has positive sign in thin layer near the surface ($h < 0.5$ м). The space charge becomes negative at higher altitude (Fig. 2a) that reflects on the electric field profile (Fig. 2d). Increasing of aerosol particles concentrations up to $N = 10^{12}$ m^{-3} leads to the total disappearance of positive space charge and insrease of negative space charge (Fig. 2, *b, e*, *c, f*) shifted to the surface.

Increasing of turbulent mixing rate leads to the disappearance of negative space charge that is in agreement with results of work [1].

CONCLUSION

Analysis of modeling results demonstrated that the large ions current is necessary to be factored when the concentrations of aerosol particles are in the order of 10^{12} m^{-3} and higher. The increase of aerosol particles size causes the decrease of small and large ions current density near the surface. The large ions current exceeds the small ions current when the aerosol particles size is more than 0.01 μm and concentrations are less than 10^{12} m^{-3}. Under strong ionization condition and aerosol concentration more than 10^{9} m^{-3} the negative space charge is generated in the surface layer at 3 m altitude and higher. The increasing of aerosol particles concentrations leads to appearance of negative space charge over the whole surface layer.

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