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DYNAMICS MODELING OF TRAFFIC-RELATED EXHAUST AEROSOLS

Lesya Sheludchenko

13, Shevchenka Str., Kamyanets-Podilsky, Khmelnitsky region, 32300, Ukraine
seludcencoleca@gmail.com

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Abstract. The results of analytical researches of migration processes and turbulent diffusion of exhaust aerosols, produced by traffic flows within reserve technical lanes of highways are given. It is concluded that rotors, determined as some areas of the rotary motion of an aerosol, are always formed within the diffusion divergence field of turbulent flows of exhaust aerosol.

Key words: Exhaust cloud, aerosol, diffusion, migration.

Introduction. Mineral or gaseous admixtures generated by traffic in the form of aerosols after emission into the atmosphere start migrating, as a result of air masses movement (airstreams). In this case, the admixtures are involved both in laminar, and in turbulent atmospheric air flows [3].

According to the structural characteristics of the internal combustion engines [1], we assume that at the initial moment of time the entire amount of admixture simultaneously fills the volume of an emission plum in the form of exhaust cloud. Under the action of natural movement of air masses this admixtures start diffusive spreading through the atmosphere [3].

Analytically, this 'sudden' one-stage process of emission, that was absent (equal to zero) before the given time point, starts right after the exhaust cloud formation, may be given by so-called Unit Step Function *H* (*t*) (Heaviside function), presented as a single interrupter.

The Heaviside function graph, shown in Fig. 1, determines that one-moment emission of an aerosol cloud is equal to zero for $t<0$ and is equal to unity for $t>0$. That is expressed as [2, 4]:

$$H(t)=\begin{Bmatrix} 0, & t<0 \\ 1, & t\geq 0 \end{Bmatrix}. \tag{1}$$

Generally, the concentration *q* of emissions in an aerosol cloud that diffuses in the atmospheric air and migrates together with the natural movement of air masses (wind flows) is a function of time coordinate *t* and spatial position coordinates (*x, y, z*), the origin of which lies in the instantaneous center of mass of the cloud, formed at the moment of emission *H* (*t*):

$$q=q\left(x,y,z,t\right) \tag{2}$$

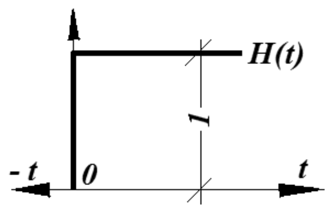

Fig. 1. Unit step function H(t) graph

Theoretical studies and results. In this case diffusion (Fig. 2) is determined by measuring the mass of the substance ΔM that diffuses per time unit through the unit surface area of the exhaust cloud, emitted into atmospheric air. In this case, the bigger is the decline of concentration Δq per unit length along the entire set of directions, in which diffusion occurs, the bigger magnitude of ΔM is. The sign (-) at $H = -q(t)$ indicates decrease in the concentration of Δq in the gas-dust exhaust cloud.

Thus, the diffusion process is characterized by the proportionality of the averaged displacement of aerosol diffusers and the square root of the time t. That is:

$$\left\{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2\right\}\propto t\,, \tag{3}$$

where *x, y, z* are coordinates of the aerosol diffusing particle at the initial time *t* (see 2); x_i, y_i, z_i are coordinates of the aerosol diffusing particle at the moment of time from the beginning of diffusion of an exhaust cloud.

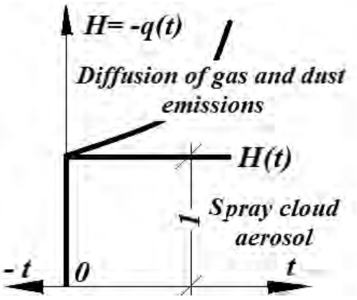

Fig. 2. Diffusion behavior of an exhaust cloud in atmosphere

Correlation (3) allows us to define the characteristics of the diffusion quantity ΔM by diffusion coefficient *D* [3]:

$$D = \frac{1}{6 \cdot t}\left\{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\right\}. \qquad (4)$$

With allowance to the postulate on the thermodynamic equilibrium and as a consequence of the equation of continuity, the process of diffusion of an exhaust cloud, leveling aerosol concentration at atmospheric thermodynamic structure, may be given by:

$$\frac{\partial q}{\partial t} + \partial iv\, j = 0, \qquad (5)$$

where *j* is the stream of aerosol particles from the surface of an exhaust cloud.

If we take into account that the flow of aerosol particles is proportional to its concentration gradient *q* with the coefficient of proportionality D (4), we obtain:

$$j = -D\Delta q \qquad (6)$$

or, using the phenomenological distribution, the emission of an exhaust cloud diffusion may be given as:

$$\frac{\partial q}{\partial t} = D\Delta q\,, \qquad (7)$$

where $\Delta = div\ \nabla$ is the Laplace operator.

In the general case of spatially inhomogeneous aerosol diffusion of an exhaust cloud, produced by traffic, we obtain:

$$\frac{\partial q}{\partial t} = div(Dq\Delta m)\,, \qquad (8)$$

where μ is the potential for concentration leveling q of an exhaust cloud aerosol at atmospheric thermodynamic structure.

Equations (5)–(8) give the contribution to the Laplace operator:

$$\Delta = \nabla^2 = div\,\Delta \qquad (9)$$

that determines the nature of the dynamic equilibrium of pressure in an exhaust cloud (at the interface of phases) in the process of cloud diffusion in the atmospheric air at each specific time *t*.

Differential operator *div*, that represents a vector field on a scalar, is a divergence. In (5)–(7), divergence is a linear differential operator on a vector field that characterizes the flow of aerosol particles of the initial one-moment exhaust cloud through a surface (rather small) of this cloud on each point of its interior area:

$$div\,F = \lim_{V \to 0}\frac{\Phi_F}{V}\,, \qquad (10)$$

where Φ_F is the flow of the vector field *F* through the arbitrary surface *S* of an exhaust cloud, which outlines some volume of aerosol *V*. That is:

$$\Phi_F = \oint_S (\vec{F}, \vec{dS})\,, \qquad (11)$$

therefore, (11) has no binding to a particular coordinate system (in this case, to the spatial or landscape parameters of the natural/technogenic geo-ecosystem, the structural dimensions of the highway or technologically determined geometric factors of the transportation flow). From a physical point of view, the processes of aerosol mass transfer may be considered, taking into account the following possible options:

– *div F*> 0 – any point of an exhaust cloud generates aerosol;

– *div F* <0 – any point of an exhaust cloud concentrates aerosol;

– *div F* = 0 – generation and concentration points are absent or offset each other.

The third of the following variants (*div F*) determines the formation of rotors in zones of aerosol turbulent motion, and is given as:

$$div\{rot(F)\} = 0\,. \qquad (12)$$

The nature of the formation of rotors in zones of turbulence of exhaust aerosols produced by transport flows, in a view of air flow rates and corresponding landforms of highways, is given respectively in Fig. 3 and Fig. 4.

In the general case, the turbulent rotor of an exhaust cloud (12), which is produced by transport stream and diffuses in turbulent flows, in three-dimensional space (with coordinates – x, y, z) is defined as:

$$\begin{cases} (rot\,F)_x = \partial_y F_x - \partial_z F_y \equiv \dfrac{\partial F_z}{\partial y} - \dfrac{\partial F_y}{\partial z} \\ (rot\,F)_y = \partial_z F_x - \partial_x F_z \equiv \dfrac{\partial F_x}{\partial z} - \dfrac{\partial F_z}{\partial x} \\ (rot\,F)_z = \partial_x F_y - \partial_y F_x \equiv \dfrac{\partial F_y}{\partial x} - \dfrac{\partial F_x}{\partial y} \end{cases} \qquad (13)$$

or as:

$$(rot\,F)_{mn} = \partial_m F_n - \partial_n F_m\,, \qquad (14)$$

where *m*, *n* are the corresponding coordinates of the space under consideration.

According to the Cauchy-Helmholtz theorem, velocity distribution of aerosol mixture in an exhaust cloud near a certain center of mass is given by:

$$u(r) = u_n + w - r + \nabla - j + 0(r)\,, \qquad (15)$$

where v_0 is the vector of translational motion (movement of the turbulent rotor in the direction of the laminar flow); ω is the vector of angular rotation of the aerosol medium around the center of its mass *O*; *r* is averaged radius of the gas-dust cloud of emissions; φ is the potential for deformation of an exhaust cloud.

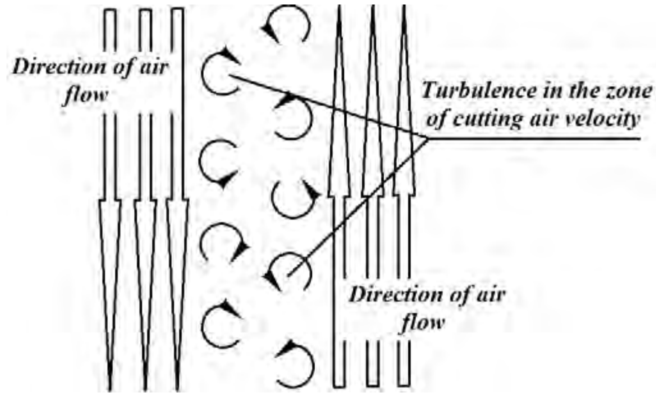

Fig. 3. The nature of turbulent rotors formation in a view of rates and directions of air flows generated by the stream of traffic

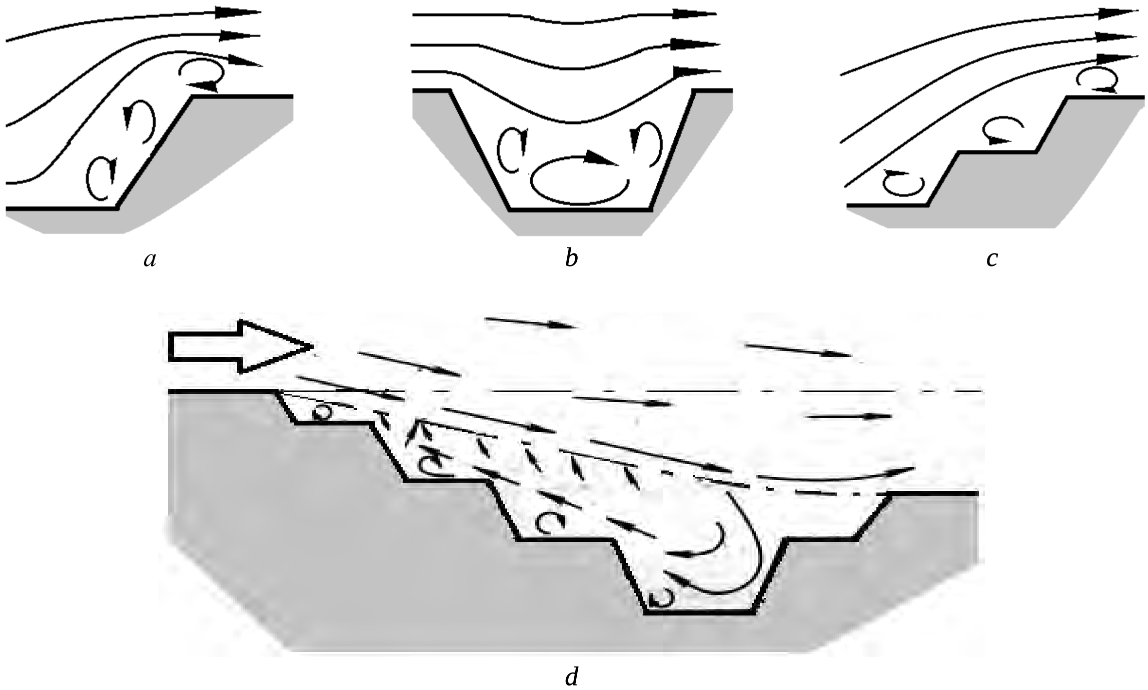

Fig. 4. Formation of turbulence rotors in different landforms (arrows indicate the direction of air masses movement): a – slope; b – a basin; c – a stepped slope; d – is the complex divergent mass transfer in the landscape

Thus, the movements of an exhaust cloud relative to the center O of its mass are determined by translational motion (vector v_0) in the laminar flows of atmospheric air, rotational motion ($\omega \cdot r$) of the cloud around *O* and the potential deformation, presented as a vector ($\nabla \cdot \varphi$). Applying to (15) the operation *rot* we obtain that for the center of mass of the cloud (for a point O) is defined as:

$$u = 2 \cdot w \tag{16}$$

and, as a result, we can conclude that the field of velocities of the turbulent rotor of an exhaust cloud produced by the traffic flow, relative to some center of the masses of an exhaust cloud (point O), is equal to the doubled vector of angular motion of an aerosol cloud with a center in the center of its masses. Graphically, the nature of the translational movement of the exhaust aerosol turbulent rotor, produced by the traffic flow, in the laminar flow of atmospheric air is shown in Fig. 5.

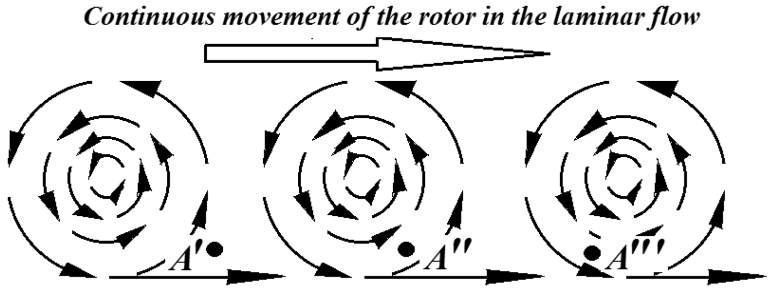

Fig. 5. The nature of the translational movement of the exhaust aerosol turbulent rotor in the laminar flow of atmospheric air (A ', A' ', A' " is the consecutive position of the point A in the rotor)

Conclusions

Thus, from the above considerations it follows:

– Rotors (areas of the rotary motion of an aerosol) are formed in the diffusion divergent field of turbulent movements of an exhaust aerosol cloud produced by traffic flows. Rotors are involved in the progressive movement of laminar air flows formed in easement areas of highways (road network) within the framework of natural/ technogenic geo-ecosystem;

– Inside the rotor, air flows rotate around the center of the masses of exhaust aerosol cloud and necessarily have a non-zero rotor near the center of masses of the cloud;

– Depending on the nature of the vector field flow of aerosol particles through the control (conditional) surface of the exhaust cloud (divergent), aerosol rotor can be a source or a drain of this field (accumulate inside or generate an aerosol cloud outside the rotor);

– Under certain conditions generation and concentration points are absent or offset each other in aerosol rotor (neither accumulation nor generation of an exhaust cloud occur in the rotor);

– For vector field v of the velocities of the aerosol rotor motion, rot v is the same over the entire field (volume) of the rotor and is equal to the vector of the double angular speed of rotation of the rotor;

– If we describe traffic flows (with unsteady velocity) and the landscape elements of highways as certain defined vector fields, the velocity of rotors in laminar flow, determined by these elements, will always be non-zero.

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