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STUDYING AN AIR VENTILATION AND POLLUTION IN AN ATMOSPHERE OF INDUSTRIAL CITY: ELEMENTS OF NEW MODELING APPROACH AND GREEN-CITY TECHNOLOGY

Olga Khetselius[1], Alexander Glushkov[1], Tamerlan Safranov[2], Vasily Buyadzhi[1], Yuliya Bunyakova[1], Anna Romanova[1]

[1]Department of Applied Mathematics and International Centre of New Mathematical Methods of Modelling Environment, Odessa State Environmental University, 15, Lvivska Str., Odessa, 65016, Ukraine, glushkovav@gmail.com , odeku.intsci@gmail.com
[2]Department of Ecology and Environmental Protection, Odessa State Environmental University, 15, Lvivska Str., Odessa, 65016, Ukraine, safranov@ukr.net

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Abstract. We develop the elements of a new generalized approach to natural air ventilation of the industrial city. It is based on the Arakawa-Shubert and Glushkov models which allow to give a quantitative reliable modelling an unsteady turbulence in the urban area and atmospheric ventilation dynamics. To calculate the air circulation for the cloud layer arrays, penetrating into the territory of the urban area, we apply the methods of a plane complex field theory. The method allows to calculate the convection parameters and shifting cumulus cloud ensemble from surrounung regions. An advanced mathematical method for modelling an unsteady turbulence in the city's area is developed and applied. As illustrative example, we apply our approach to computing the ventilation potential and current function for typical (quite simplified) sinopticl situation for the territory of the Odessa city.

Key words: environmental protection, industrial city, atmospheric ventilation, air pollution, mathematical analysis and modeling.

Introduction

It is well known that a growth of the world economics results in catastrophic increasing atmospheric pollution. The importance of public health and safety has paid more attention to environmental awareness concerning accidental or even intentional release of air pollutions. Search of effective methods and models to describe the processes of air pollution remains one of the most actual and important problem of a modern applied ecology and environment protection science. At present time there are different models and programs that allow to make quantitative estimating the temporal and spatial structure of air pollution [1–12]. In particular, one should remind about the known model packages such as models and programs of ISM (WMO), the American Environmental Protection Agency, Russian Geophysical Centre, Korean Centre for Environment, Health and Welfare etc. As a rule, the most of mathematical models to describe air pollution processes are based on the simplified physical molecular diffusion or statistical regression equations algorithms (see Refs. [1–45]).

However, for example, the known torch-like model of molecular diffusion does not work if the atmosphere contains elements of convective instability and vortex diffusion becomes the dominant factor. At present time it is obvious that the most of models especially for urban zones should be advanced. We go on our work on developing so called new "Green City" construction technology. It includes as monitoring, diagnosing and management measures, as a group of the mathematical, physical, chemical, ecological blocks to provide quantitative reliable modeling of atmospheric ventilation dynamics and urban air pollution.

In this paper we develop the elements of a new generalized approach to natural air ventilation of the industrial city. It is based on the Arakawa-Shubert and Glushkov models which allow to give a quantitative reliable modelling an unsteady turbulence in the urban area and atmospheric ventilation dynamics. To calculate the air circulation for the cloud layer arrays, penetrating into the territory of the urban area, we apply the methods of a plane complex field theory.

As illustrative example, we apply our approach to computing the ventilation potential and current function for typical (quite simplified) sinopticl situation for the territory of the Odessa city.

New general formalism for analysis and mathematical modelling an atmospheric ventilation of the industrial city

Within our approach to calculate the involving streams (the real involving masses effect is created due to a misbalance of vertical and down-running streams), reaching the territory of city, the Arakawa-Shubert equations system for humidity and warm flow equations is solved [1, 12–15]. Dynamics of the atmospheric ventilation in an urban zone by air flows in a presence of the cloud's convection is determined by the the known concurrent mechanism. If a square of the cloud base is substantially larger than a square of cross-section of the dry thermal top, a ventilation current captures several dry thermals or else compensates a mass-balance current by an involvement current from the periphery of the city. The convective clouds move to the city territory and in fact form by ridges on the secondary fronts or in the lines of convective instability arising in the synoptic processes. It is well known that the city area has a fairly complex geometric relief, so the application of our method in its pure form is possible only to a flat surface. However, the city itself creates complex flow in the area of the streets. Therefore, the air flows in the city are far from isotropic picture. Moreover, one should accurately solve a problem of the city's turbulence and quantitative description of the anisotropic flow vortex structures. It is easily to understand that the desiarable ventilation over the city's territory can be possible under performing the following dynamical condition. The speech is about the interaction resonant contact between the turbulent eddies over the urban area and the turbulent eddies of the cloud-based arrays. It means that so called currents of the front convection must coincide with currents of thermal convection of the city in the phase setting.

If A is a work of the convective cloud then it consists of the convection work and work of down falling streams in the neighbourhood of cloud [12, 13]:

$$\frac{dA}{dt} = 0 = \frac{dA}{dt}_{conv} + \frac{dA}{dt}_{downstr.},$$

$$\frac{dA}{dt}_{downstr.} = \int_0^{\lambda_{\max}} m_B(\lambda')K(\lambda,\lambda')d\lambda', \quad (1a)$$

Here $m_B(\lambda)$ is an air mass, drawn into a cloud with velocity of drawing λ; if

$$\frac{dA}{dt}_{downstr.} = F(\lambda),$$

$$\int_0^{\lambda_{\max}} K(\lambda,\lambda')m_B(\lambda')d\lambda' + F(\lambda) = 0 \quad (1b)$$

is an mass balance equation in the convective thermals and $K(\lambda, \lambda')$ is a nucleus of integral equation (1a), which determines the dynamical interaction between the neighbour clouds:

$$\beta\int_0^{\lambda_{\max}} K(\lambda,\lambda')m_B(\lambda')d\lambda' + F(\lambda) = m_B(\lambda) \quad (2)$$

The solution of this equation with accounting for air streams superposition of synoptic processes is:

$$m_B(\lambda) = F(\lambda) + \beta\int_0^{\lambda_{\max}} F(s)\Gamma(\lambda, s{:}\beta)ds, \quad (3a)$$

where Γ (x, s; β) is an resolvent of the integral eq.(2):

$$\Gamma(\lambda, s{:}\beta) = \sum_{m=1}^{\infty}\beta^{m-1}K_m(\lambda, s) \quad (3b)$$

The key idea [14] is to determine the resolvent as an expansion to the Laurent set cycle in a complex plane ζ. Its centre coincides with the centre of the city's "heating" island and the internal cycle with the city's periphery. The external cycle can be moved beyond limits of the urban recreation zone. In result one could obtain a representation for resolvent by the following Fourier expansion:

$$\Gamma = \sum_{n=-\infty}^{\infty} c_n(z-a)^n,$$

$$c_n = \frac{1}{2pi}\oint_{|z|=1}\frac{f(z)dz}{(z-a)^{n+1}} \quad (4)$$

where a is center of convergence ring of the Laurent series.

The method for calculating a turbulence spectra inside the urban zone should be based on the standard tensor equations of turbulent tensions (look details in [1,14]). As usually, it is convenient to partition velocity $u(u,v,w)$, pressure p, temperature q etc into equilibrium and departures from equilibrium values (for example: $p=p_o+p'$etc). One could write the system of equations for the Reynolds tensions, moments of connection of the velocity pulsations with entropy ones and the corresponding closure equations. The Reynolds equation have the standard form:

$$\frac{\partial\bar{u_j}}{\partial t} + \frac{\partial}{\partial x_k}(\bar{u_k}\bar{u_j} + \overline{u_k'u_j'}) = -\frac{\partial\bar{p}}{\partial x_j} - \delta_{j3}\frac{g\bar{\theta}}{\theta_0} \quad (5)$$

and if the index in a monomial expression is repeated twice, this means a summation of 1 to 3. We add the equation of the first law of thermodynamics:

$$\frac{\partial\bar{\theta}}{\partial t}+\frac{\partial}{\partial x_k}(\bar{u_k}\bar{\theta}+\overline{u_k'\theta'})=0 \qquad (6)$$

Usually the Reynolds tensions in the turbulent motion are parametrized as follows:

$$\frac{\partial}{\partial x_k}(\overline{u_k'u_j'})=k\Delta\bar{u}_j;$$
$$\frac{\partial}{\partial x_k}(\overline{u_k'\theta'})=k\Delta\bar{\theta}; \qquad (7)$$

where k – coefficient of turbulence, which is significantly different in magnitude for turbulent horizontal vortices, horizontally vertical and purely vertical ones. Parametrization with the help of the turbulence coefficient with a very high degree of approximation is applied in the models of the surface layer, where the concept of isotropy of the vortex motion in all three directions of space is used. But in our case, where the turbulent vortices in the horizontal direction in scale do not differ much from the vertical ones, such an approximation is completely unacceptable.

Therefore, it is necessary to apply equations for the prediction of the Reynolds stresses, which are the main closure models for nonlinear processes [12–14].

The derivation of these equations is carried out on the basis of equations (1) according to the following rule:

$$\frac{\partial u_j'}{\partial t}+\frac{\partial}{\partial x_k}(\bar{u_j}u_k'+\bar{u_k}u_k'+u_j'u_k'-\overline{u_j'u_k'})=$$
$$=\frac{\partial p'}{\partial x_j}-\sigma_{j3}\frac{g\theta'}{\theta_0};$$
$$\frac{\partial\theta'}{\partial t}+\frac{\partial}{\partial x_k}(\bar{\theta}u_k'+\overline{u_k}\theta'+u_k'\theta'-\overline{u_k'\theta'})=0. \qquad (8)$$

The system of closure equations can be written in the form [13]. As a result, there are 16 equations regarding the Reynolds stresses and the moments of connection of the velocity pulsations with the entropy pulsations, since

$$dS=c_p\cdot d\cdot ln\theta, \qquad (9)$$

where S is an entropy, c_p is is a heat capacity of the isobarical process.

Then $b^2=\overline{u_k'u_k'}$ is a kinetical energy of fluctuations; θ'^2 is a measure pof a process which is associated with the dispersion of entropy S; $\overline{u_i'\theta'}$ is a measure of coupling the dynamical deformations with an activity of a process. All unknown quantities can be united into 4-tenzor

$$\begin{vmatrix}\overline{u_1'^2} & \overline{u_1'u_2'} & \overline{u_1'u_3'} & \overline{u_1'\theta'}\\ \overline{u_2'u_1'} & \overline{u_2'^2} & \overline{u_2'u_3'} & \overline{u_2'\theta'}\\ \overline{u_3'u_1'} & \overline{u_3'u_2'} & \overline{u_3'^2} & \overline{u_3'\theta'}\\ \overline{\theta'u_1'} & \overline{\theta'u_2'} & \overline{\theta'u_3'} & \overline{\theta'^2}\end{vmatrix} \qquad (10)$$

On order to solve a system of the corresponding equations one should know the method of computing the quantities:

$$\overline{u_i'u_j'u_k'};\ \overline{u_k'u_j'\theta'};\ \overline{p'\left(\frac{\partial u_i'}{\partial x_j}+\frac{\partial u_j'}{\partial x_i}\right)};\ \overline{p'\frac{\partial\theta'}{\partial x_i}}. \qquad (11)$$

These quantities are represented as a definite linear combinations of a tenzor (10) and the parameter b^2, which can be found from the equation (the physical explanations of any term are in Ref. [13]):

$$\frac{\partial b}{\partial t}+\frac{\partial u_k b^2}{\partial x_k}+\frac{\partial}{\partial x_k}\left(\overline{u_k'u_i'u_j'}+2\overline{u_k'p'}\right)=$$
$$=-2\overline{u_k'u_i'}\frac{\partial u_i}{\partial x_k}-2\frac{g}{\theta_0}\overline{w'\theta'} \qquad (12)$$

Here g is the magnitude of the acceleration vector due to the planet's gravity, q_0 is the equilibrium potential temperature, q', p' are departures from equilibrium values. The velocity components, say, u,v, of an air flux over the city area are determined in an approximation of "shallow water" [3, 11].

In contrast to the standard difference methods of solution, here we use the spectral expansion algorithm (look all details in [46–63]. The necessary solution, for example, for the *u-iv* component for the city's heat island has the form of expansion into series on the Bessel functions. From the other side, the velocity of an air flux over the city's periphery in a case of convective instability can be found by method of a plane complex field theory in a full analogy with the known Karman vortices chain model [12, 13].

Equating the velocity components determined in the shallow water model and model (6), we find the spectral matching between the wave numbers that define the functional elements in the Fourier-Bessel series with the source element of a plane field theory. All calculations below are performed with using "Geomath" and "Quantum Chaos" computational codes [1, 12–14, 64–94].

Illustrative results and conclusions

We carried out test modelling air ventilation for a few synoptic situations for a number of cities, namely, Odessa (Ukraine), Trieste (Italy), Aleppo (Syria). The computing is performed with using natural and model data on a cloudiness and convection intensities (all data are taken from Ref. [1]). Basically, it was assumed that the cloud masses coming to the city by lines of convective instability. The distance between the convective clouds was assumed to be 300 to 700 meters.

In Fig. 1 the Odessa Ciry area (from Google Map) is presented. In Fig. 2 the calculated field of the ventilation potential is given, which is equivalent to the potential field as a function of the complex velocity potential. The clouds are marked as the black squares.

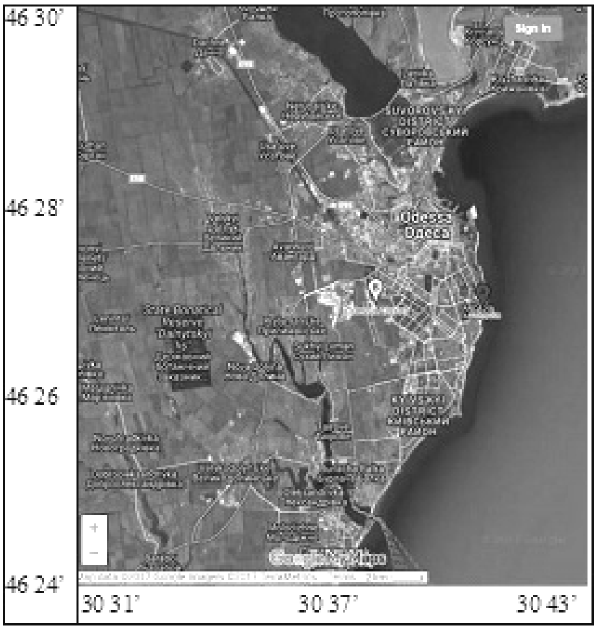

Fig. 1. The Odessa city area map

The contours of a complex potential reflect time variation of the velocity field, namely 0.5 m/s per hour.

Density of current lines is adequate to ventilation flow speed, ~ 1 m/s to 0.5 cm of gradient in Figure 2.

If $n_x>0$, the velocity increases in the direction of positive foci (and similarly on y). This means that the potential function draws flow in positive foci. Compaction of the current function isolines means increasing a velocity. The direction of flow is obtained from the definition of the current function, i.e., $n_x>0$, if $\partial j/\partial y$.

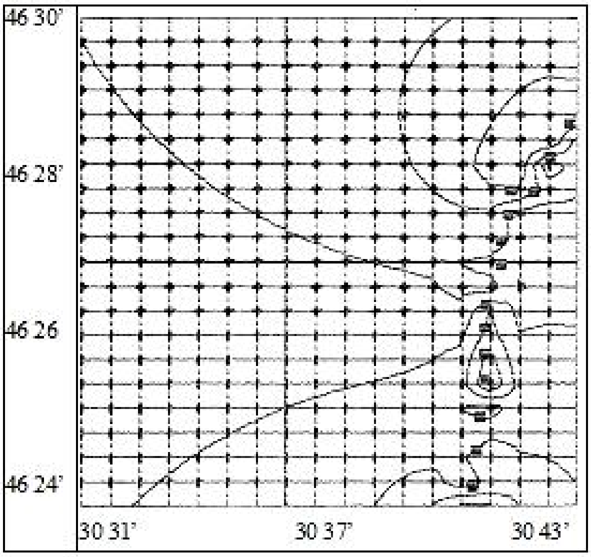

Fig. 2. Potential of ventilation

The isolines are not signed, because modular values depend on many factors, notably intensity of convection, which determines the involvement currents power and density of the cloud arrays. The dry thermals (marked by black circles in Fig. 2) are located in the city area and create their involvement currents and increase the intensity of the annular heat circulation. From Fig. 2 it is clear that if the clouds are located just above the sea at the city's border, the direction of ventilation strives to cover the northern urban areas, while the southern territories of the city are not on the contrary ventilated. The current function in Fig. 3 confirms the fact established in Fig. 2.

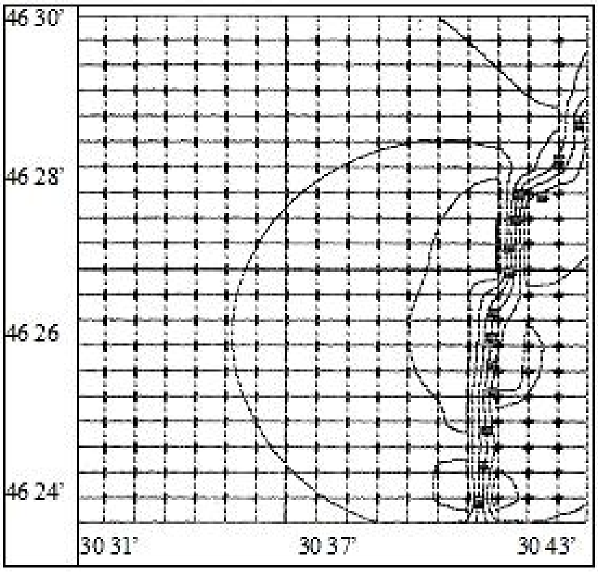

Fig. 3. Current function for the situation Fig. 2

If the clouds are just above the sea, then the ventilation of the urban area is practically non-existent. The clouds from the sea can not enter the thermal ring of the city, i.e. they can not break through the ring of heat circulation. However, Fig. 3 shows that there is a tendency to the ventilation of the city from the side of Hadzhibeevsky estuary. To conclude, we present the elements of a new approach to modelling air ventilation and unsteady turbulence in the urban area)industrial city) with using plane complex geophysical field method and list test data on air ventilation for the simple typical situation in the Odessa area. More complex sinoptical situations will be studied in the separate paper.

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