IOP Conference Series: Earth and Environmental Science

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To cite this article: A V Glushkov *et al* 2017 *IOP Conf. Ser.: Earth Environ. Sci.* **92** 012014

# Modelling dynamics of atmosphere ventilation and industrial city's air pollution analysis: New approach

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**Abstract**. We present a new effective approach to analysis and modelling the natural air ventilation in an atmosphere of the industrial city, which is based on the Arakawa-Schubert and Glushkov models, modified to calculate the current involvement of the ensemble of clouds, and advanced mathematical methods of modelling an unsteady turbulence in the urban area. For the first time the methods of a plane complex field and spectral expansion algorithms are applied to calculate the air circulation for the cloud layer arrays, penetrating into the territory of the industrial city. We have also taken into account for the mechanisms of transformation of the cloud system advection over the territory of the urban area. The results of test computing the air ventilation characteristics are presented for the Odessa city. All above cited methods and models together with the standard monitoring and management systems can be considered as a basis for comprehensive "Green City" construction technology.

## 1. Introduction

The aim to ensure a steady pace of economic development, which has the known organizational forms of the globalization and industrialization, cannot be realized except through an increase in the already excessive burden on the environment with the further increasing atmospheric pollution. Although the development of global industrial, transport and communication systems rules out the possibility of localization of human influence on the environment, the large industrial cities are in the most difficult situation. As a rule, the indicated systems are the main source of environmental (atmospheric) pollution [1-3]. The composition of atmosphere in the industrial city is influenced by many factors such as an effect of pollution sources, climatic, meteorological factors, the city's topography, the energy and transport factors, processes of dissipation, relaxation, self-cleaning, regeneration etc [1]. At present time a number of different models is carried out to estimate the temporal and spatial structure of the atmosphere pollution [1-12]. As a rule, these models base on the simplified molecular diffusion or statistical regression equations algorithms (see [1-25] and Refs. therein). It is worth also to mention the known computational fluid dynamics models such as "Weather Research & Forecasting–Chem" and others [5-7]. Now it is clear that the most of models especially for urban zones should be advanced. The known torch-like model of molecular diffusion does not work if the atmosphere contains elements of convective instability and a vortices diffusion plays the dominant role.

The aim of our research is to develop a new "Green City" construction technology that includes as monitoring, management measures as a group of the physical, chemical, ecological blocks which allow to provide quantitative reliable modelling an atmospheric ventilation dynamics and precise analysis of the city air pollution. In this paper we briefly present a new generalized approach to an atmospheric turbulence and natural air ventilation for the industrial city. It is based on the Arakawa-

Schubert and Glushkov models [12,13], modified to calculate the current involvement of the ensemble of clouds. For the first time methods of a plane complex field theory and spectral expansion algorithms are applied to calculate the air circulation characteristics for the cloud layer arrays, penetrating into the territory of the city. Some numerical test data are listed for the Odessa city.

## 2. Models of atmospheric turbulence and air ventilation for the industrial city

Here we briefly consider generalized models of atmospheric turbulence and air ventilation for the industrial city, modified to calculate the current involvement of the ensemble of clouds. To calculate the involving streams (*the real involving mass effect is emerged due to a disbalance of vertical and down-running streams*), reaching the territory of city, the modified Arakawa-Schubert equations system is solved [1,12,13]. Sketch for air ventilation between a city and its periphery in a presence of the atmosphere clouds convection is presented in figure 1.

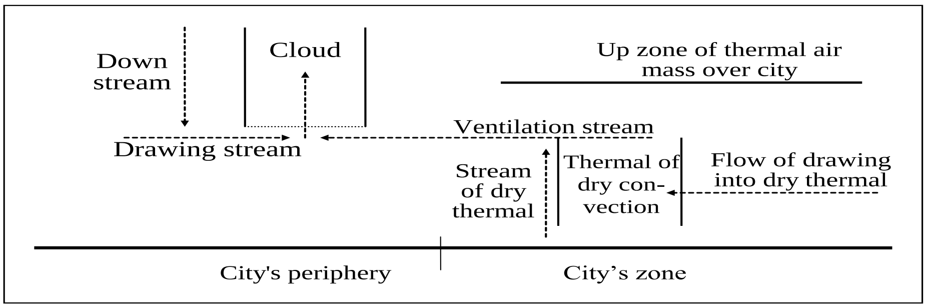

**Figure 1.** Sketch for the air ventilation between a city and its periphery.

It is important to note that 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. A signal of the destruction of thermal air mass over a city is an appearance of the convective cloudiness over the city's periphery. The corresponding convective clouds are usually formed 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 any method in its pure form is possible only to a flat surface. Indeed, the air flows in the city area are far from isotropic picture. The horizontal turbulent vortices within the city are involving the circulation currents. More consistent description of city's turbulence should reflect a complex picture of the anisotropic vortex flow structures. *The turbulent vortices over the urban area must be in the resonant interaction contact with the turbulent vortices of the cloud-based arrays in order to obtain an effective air ventilation.* It is possible if the front convection currents coincide with currents of the thermal convection over the city zone in the phase setting. The antiphase state of the urban convective vertical currents with the cloud convection currents would mean mutual compensating the two mechanisms. These physical features of air ventilation predetermine the necessary modification of the well-known Arakawa-Schubert model. The model (equation (1)) includes the budget equations for mass, moist static energy, total water content plus the equations of motion (look details in [12]). In [12] it is also defined a cloud work function which is an integral measure of the buoyancy force in the clouds. 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 a cloud:

$$dA/dt = d\,A/dt_{conv} + dA/dt_{downstr},\, dA/dt_{downstr} = \int_0^{\lambda_{\max}} m_B(\lambda')K(\lambda,\lambda')d\lambda', \tag{1}$$

Here $\lambda$ is a velocity of involvement, $m_B(\lambda)$ is an air mass flux, $K(\lambda, \lambda')$ is the Arakawa-Schubert integral equation kernel, which determines the dynamical interaction between the neighbours clouds. The actual form of $K(\lambda, \lambda')$ and $F(\lambda)$ as well as their derivations are given in Appendix B [12]. In the case of air ventilation emergence, mass balance equation (2) in the convective thermals is as follows [13]:

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

Here $\beta$ is parameter which determines disbalance of cloud work due to the return of part of the cloud energy to the organization of a wind field in their vicinity, and balance regulating its contribution to the synoptic processes. The solution of the equation (2) with accounting for air stream superposition of synoptic processes can be determined by a resolvent method (equation (3)):

$$m_B(\lambda) = F(\lambda) + \beta \int_0^{\lambda_{\max}} F(s)\Gamma(\lambda,s;\beta)ds, \;\; \Gamma(\lambda,s;\beta) = \sum_{i=1}^{\infty} \beta^{i-1} \cdot K_i(\lambda,s) \tag{3}$$

The key idea [13] is to determine the resolvent as an expansion to the Laurent series in a complex plane $\zeta$. 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. The Laurent representation for resolvent is provided by the standard expansion (see equation (4)):

$$\Gamma = \sum_{n=-\infty}^{\infty} c_n(\zeta - a)^n, \;\; c_n = \frac{1}{2\pi i} \oint_{|\zeta|=1} \frac{\Gamma(\zeta)d\zeta}{(\zeta - a)^{n+1}} = \frac{1}{2\pi i}\int_0^{2\pi} \Gamma(e^{it})e^{-int}dt, \tag{4}$$

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

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 [1,11]). As usually, it is convenient to partition velocity $\boldsymbol{u}(v_x,v_y,w)$, pressure $p$, temperature $\theta$ etc into equilibrium and departures from equilibrium values (for example: $p=p_0+p'$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 important parameter of the turbulent processes is the kinetic energy of turbulent vortices $b^2 = \overline{u'_k u'_k}$, which can be found from the equation (5) (with physical explanations of any term):

$$\frac{\partial b}{\partial t} + \frac{\partial u_k b^2}{\partial x_k} + \frac{\partial}{\partial x_k}\left(\overline{u'_k u'_i u'_j} + 2\overline{u'_k p'}\right) = -2\overline{u'_k u'_i}\frac{\partial u_i}{\partial x_k} - 2\frac{g}{\theta_0}\overline{w'\theta'} \tag{5}$$

| | | | | |
|---|---|---|---|---|
| Advection | Turbulent diffusion | Effect of forces of the tension | Interaction: Reynolds tension-averaged motion | Accounting for swimming forces |

Here $g$ is the magnitude of the acceleration vector due to the planet's gravity, $\theta_0$ is the equilibrium potential temperature, $\theta'$, $p'$ are departures from equilibrium values.

The velocity components, say, $v_x$,$v_y$, 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 [1,27]. The necessary solution, for example, for the $v_x$-$iv_y$ 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 (equation (6)) [10,11]:

$$v_x - iv_y = \frac{df}{d\xi} = \frac{\Gamma}{2\pi i}\left[\frac{1}{\zeta - \zeta_0} + \sum_{k=1}^{\infty}\left(\frac{1}{\zeta - \zeta_0 - kl} + \frac{1}{\zeta - \zeta_0 + kl}\right)\right] + \frac{d}{d\zeta}\left[\sum_{k=1}^{n}\Gamma_k \ln(\zeta - b_k)\right] \tag{6}$$

Here $\Gamma_k$ –circulation on the vortex elements, created by clouds, $b_k$ – co-ordinates of these elements, $\Gamma$ – circulation on the standard Karman chain vortices of, $l$ – distance between standard vortices of the Karman chain, $\zeta$ - co-ordinate of the convective perturbations line (or front divider) centre, $\zeta_0$ - $kl$ – co-ordinate of beginning of the convective perturbation line, $\zeta_0+kl$ – co-ordinate of end of this line.

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. It is also worth to remind that any vector field $u$ can be separated into rotational and divergent parts, i.e., $u = \nabla\psi + u_\chi$ (the Helmholtz's theorem). If the vector field is a horizontal wind, one can define a current function $\psi$, to express the rotational part, and a velocity potential $\chi$, to express the divergent part. Namely these parameters are of a great interest in applied analysis of an air ventilation in the urban zone. Below we present the results of test computing the air ventilation parameters for a few synoptic situations in the Odessa city. All calculations are performed with using of the "Geomath" (blocks of numerical differentiation and integration, solution of the "shallow water" equations etc) and "Quantum Chaos" (blocks of expansion of the Reynolds tensions into series on the vector-tensor spherical functions, velocity components into the Bessel functions series etc) PC codes [1,13-20,27-34].

## 3. The numerical test results for air ventilation in the Odessa city and conclusions

The test computing is performed with using natural and model data on a cloudiness, convection intensities, the Odessa city topography parameters, including the parameters in (4),(6) etc (all data are taken from Refs. [1,8,13]). Basically, it is assumed that the clouds masses are coming to the city by lines of convective instability. The distance between the convective clouds is assumed to be 300-700 m. In figure 2a (left part) the Odessa city area (Google Map) is presented. In figures 2b and 2c we list the data on ventilation potential (b) (it is equivalent to a field of potential in the complex velocity potential function) and a current function (c). Figure 2b shows the results for the synoptic situation in Odessa, when the clouds run from the sea by two lines of convective disturbances and penetrate deeply into the Gulf of Odessa and city respectively. The clouds are marked as the black squares. The contours of a complex potential reflect time variation of the velocity field, namely 0.5 m/s per hour.

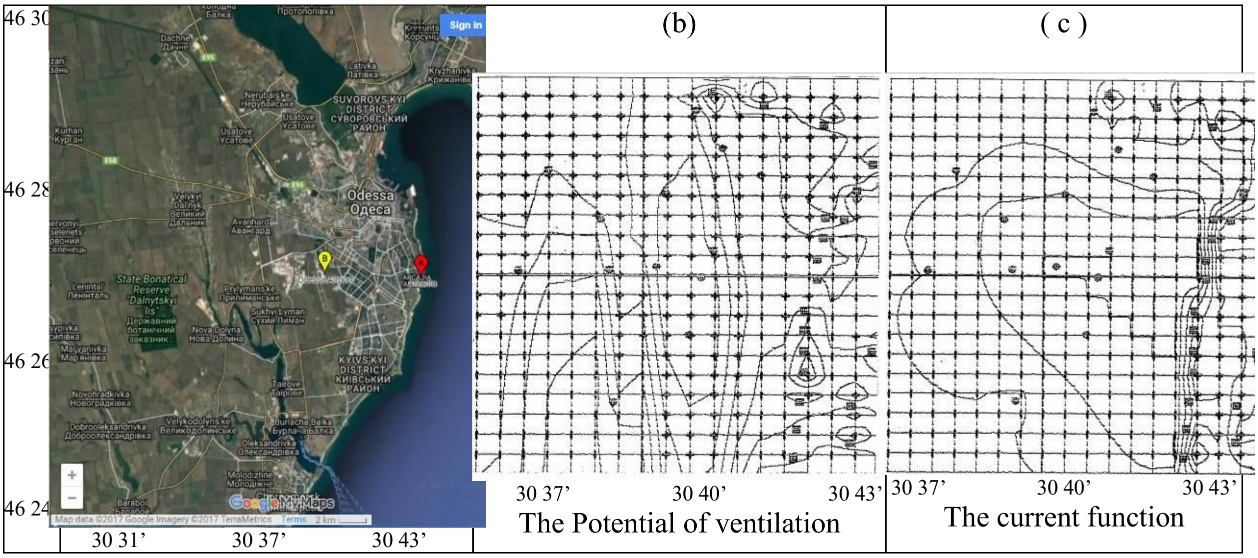

**Figure 2**. (a) Odessa city area map, (b) Potential of ventilation, (c) Current function for the situation b.

Density of current lines is adequate to ventilation flow speed, ~ 1 m/s to 0.5 cm of gradient in Fig 2. If $\nu_x>0$, the velocity increases in the direction of positive foci (and similarly on y). This means that the potential function draws flow in positive foci. Compression of the current function isolines means increasing a velocity. The direction of flow is obtained from the definition of the current function, i.e., $\nu_x>0$, if $\partial\varphi/\partial y$. 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 figure 2) are located in the city area. They create their involvement currents and increase the intensity of the annular heat circulation. The picture in figure 2b of the air ventilation is typical for most of the city. However, in the current function field (figure 2c) penetration of air ventilation is expressed more weakly. To conclude, we present a new approach to modelling an air ventilation and turbulence in the urban area and list the test data on air ventilation for the typical synoptic situation in the Odessa area.

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