Фізика аеродисперсних систем. – 2018. – № 55. – С.104-111

УДК 539.328

Sofronkov A. N., Khetselius O. Yu., Glushkov A. V., Buyadzhi V. V., Romanova A. V., Ignatenko A. V.

Odessa State Environmental University, Odessa
E-mail: a_sofronkov@ukr.net, okhetsel@gmail.com

New geophysical complex-field approach to modelling dynamics of heat-mass-transfer and ventilation in atmosphere of the industrial region

New generalized approach, including an improved theory of atmospheric circulation in combination with the hydrodynamic model (with correct account of turbulence in atmosphere of the urban area) and the Arakawa-Schubert method of calculation of cloud convection and theory of complex geophysical field is applied to the simulation of heat and air transfer in atmosphere of industrial region. The modelling ventilation data (mesocirculation) parameters over territory of Odessa, as well as the area of the Fukushima power plant after 2011 accident are presented.

Introduction. Studying energy-, heat-, mass-transfer in continuous environments such as atmosphere or other geospheres, remains one of the most actual, complicated and important problems of the modern physics of aerodispersed systems, atmosphere, climate and environment physics etc. The most difficult aspect of the problem is modelling processes of energy-heat, air mass- transport, dissipative and relaxation, self-cleaning, particles (for example, radioactive) deposition etc. [1-16]. At present time there is a number of different simplified models that allow to estimate the temporal and spatial structure of air ventilation in an atmosphere, and as a rule, these models are based on the laws of molecular diffusion, as well as a system of regression equations [1-5]. The most of these models have a number of disadvantages; for example, the known flare model or molecular diffusion models do not work if the atmosphere contains elements of convective instability. Moreover, the majority of the models are relatively simple and do not take into account the transience wind field, the mutual influence of the many sources of pollution etc. More sophisticated approaches such as different versions of the Lagrangian Particle Dispersion Models, model of the European Center for Medium-Range Weather Forecasts (ECMWF) and others [1-17] and Refs. therein) provide significantly more accurate results, however, such approaches require very complicated simulation and very correct input parameters data. Going on our studies [6,9,18-22], here we present an advanced approach to the simulation of heat and air ventilation in atmosphere of an industrial region (so called local scale atmospheric circulation complex-field (LACCF) approach). It includes an improved theory of atmospheric circulation in combination with the hydrodynamic forecast model (with quantitatively correct account of turbulence in the atmosphere at local scales) and the Arakawa-Schubert model of cloud convection.

Mathematical modelling an atmospheric ventilation. Our generalized approach is based on the Arakawa-Schubert model, modified to calculate the current involvement of the ensemble of clouds [3,18-22]. To calculate the involving streams

 DOI: http://dx.doi.org/10.18524/0367-1631.2018.55.149998

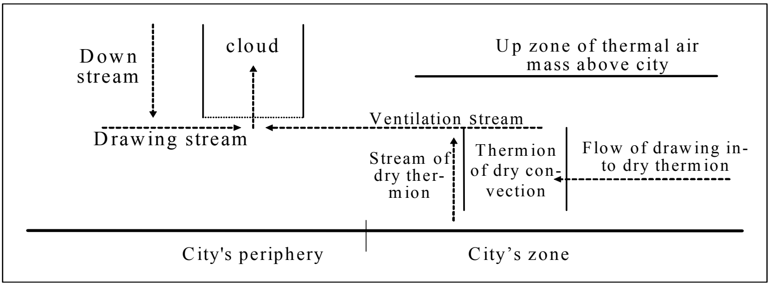

Fig 1. Flowchart of air mass transfer between the city and its periphery

(the real involving masses effect is created due to misbalance of vertical and down-running streams), the Arakawa-Schubert equations system for humidity and warm flow equations are solved [3,6]. Flowchart of the ventilation over the urban region territory by air flows in a presence of the cloud's convection is presented in Figure 1 and explains the key physical processes in a system.

Let us remind that the known effect of creation of the mesojets which are formed in the ventilation currents as the Couette flows. If square of a cloud base is smaller than a square of cross-section of the dry thermal top, than the ventilation current can not be appeared due to a lack of power of a cloud in the formation of the involvement meso-jets. 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 compensate a mass-balance current by an involvement current from the periphery of the city. A signal of the destruction of the thermal air mass over the city is the appearance of convective cloudiness over the city territory. Basically convective clouds that move to the city territory, are formed by ridges on the secondary fronts or in the lines of convective instability arising in the real synoptic processes. On top of the thermal mass of the city there is no restriction in the air exchange in the absence of a closed circulation there, "bordering" heat "hat" of the city. However, an extract of the lower layer of air from the air basin of the city should take place through a vertical convection current in a dry thermal. Indeed there is a complex picture of the anisotropic flow vortex structure over the urban region. The turbulent eddies over the urban area must be in the interaction resonant contact with the turbulent eddies of cloud-based arrays in order to obtain a successful air ventilation. In fact the currents of the front convection must coincide with currents of thermal convection of the city in the phase setting. The physical features of air ventilation predetermine the necessary modification of the well-known Arakawa-Schubert model. The model includes the budget equations for mass, moist static energy, total water content plus the equations of motion [3,6]:

$$E - D - \frac{\partial M_c}{\partial z} = 0, \qquad (1a)$$

$$E\,\tilde{s} - D\,s_c - \frac{\partial M_c s_c}{\partial z} + pLc = 0, \qquad (1b)$$

$$E\,\tilde{q} - D\,q_c - \frac{\partial M_c q_c}{\partial z} + pc = 0\,, \qquad (1c)$$

where E is an inflow, D is an outflow, $M_c = \sum p\omega_i\sigma_i = p\omega_c\sigma$ – vertical mass flow of air in the cloud; w_i is an average (on the cross-section) speed in the i-th cloud, c – horizontal cross-section square for the i-th cloud; ω_c, $s_c = c_pT + gz$, q_c – weighted average values of vertical speed, statistical energy and the ratio of the mixture of water vapor; $\tilde{s}$, $\tilde{q}$ – average statistical energy and the ratio of the mixture of water vapor in the ambient air, p – air density; c is an amount of the condensed moisture. If e is an amount of evaporated moisture, L – specific heat of phase transitions, then the equation of heat and moisture influx will be as follows [3,6]:

$$\frac{\partial\overline{ps}}{\partial t} + v\overline{ps\vec{v}} + \frac{\partial\overline{(p\omega s)}}{\partial z} + pL(c-e) - \frac{\partial\overline{(p\omega)'s'}}{\partial z}, \qquad (2a)$$

$$\frac{\partial\overline{pq}}{\partial t} + v\overline{pq\vec{v}} + \frac{\partial\overline{(p\omega q)}}{\partial z} + p(c-e) - \frac{\partial\overline{(p\omega)'q'}}{\partial z}. \qquad (2b)$$

The spectral representations in ensemble of clouds:

$$E(\mathrm{z}) = \int \varepsilon(z,\lambda) m_B(\lambda)\, d\lambda\,, \qquad (3a)$$

$$D(\mathrm{z}) = \int d(z,\lambda) m_B(\lambda)\, d\lambda\,. \qquad (3b)$$

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

$$dA/dt = dA/dt_{conv} + dA/dt_{downstr}\,, dA/dt_{downstr} = \int_0^{\lambda_{\max}} m_B(\lambda')K(\lambda,\lambda')d\lambda'\,, \qquad (4)$$

Here λ is a speed of involvement, $m_B(\lambda)$ is an air mass flux, $K(\lambda,\ \lambda')$ is the Arakawa-Schubert integral equation kernel [3], which determines the dynamical interaction between the neighbours clouds. In the case of air ventilation emergence, mass balance equation in the convective thermals is as follows [6]:

$$m_B(\lambda) = F(\lambda) + \beta\int_0^{\lambda_{\max}} m_B(\lambda')K(\lambda,\lambda')d\lambda'\,. \qquad (5)$$

Here β 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 Eq. (2) with accounting for air stream superposition of synoptic processes can be determined by a resolvent method:

$$m_B(\lambda) = F(\lambda) + \beta\int_0^{\lambda_{\max}} F(s)\Gamma(\lambda,s;\beta)ds, \quad \Gamma(\lambda,s;\beta) = \sum_{i=1}^{\infty}\beta^{i-1}\cdot K_i(\lambda,s)\,. \qquad (6)$$

The key idea [6,18-20] is to determine the resolvent as an expansion to the Laurent series 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. The Laurent representation for resolvent is provided by the standard expansion:

$$\Gamma=\sum_{n=-\infty}^{\infty} c_n(\zeta-a)^n\,,\quad c_n=\frac{1}{2\pi i}\oint_{|\zeta|=1}\frac{\Gamma(\zeta)d\zeta}{(\zeta-a)^{n+1}}=\frac{1}{2\pi i}\int_0^{2\pi}\Gamma(e^{it})e^{-int}dt\,,\qquad (7)$$

where a is center of the Laurent series convergence ring.

The method for calculating a turbulence spectra inside the urban zone should be based on solving the system of equations for the Reynolds tensions, moments of connection of the speed pulsations with entropy ones and the corresponding closure equations [19, 22]. 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 (with physical explanations of any term):

$$\frac{\partial b}{\partial t}+\frac{\partial u_k b^2}{\partial x_k}+\frac{\partial}{\partial x_k}\left(\overline{u_k' u_i' u_j'}+2\overline{u_k' p'}\right)=-2\overline{u_k' u_i'}\frac{\partial u_i}{\partial x_k}-2\frac{g}{\theta_0}\overline{w'\theta'}\,.\qquad (8)$$

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, θ_0 is the equilibrium potential temperature, θ', p' are departures from equilibrium values. The speed components, say, v_x, v_y, of an air flux can be determined in an approximation of "shallow water" [6]. In contrast to the standard difference methods of solution, here we use the spectral expansion algorithm [24,25]. 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, a air flux speed over a city's periphery in a case of convective instability can be found by method of plane complex field theory (in analogy with the Karman vortices chain model) [6,19]:

$$v_x-iv_y=\frac{df}{d\xi}=\frac{\Gamma}{2\pi i}\left[\frac{1}{\zeta-\zeta_0}+\sum_{k=1}^{\infty}\left(\frac{1}{\zeta-\zeta_0-kl}+\frac{1}{\zeta-\zeta_0+kl}\right)\right]+\frac{d}{d\zeta}\left[\sum_{k=1}^{n}\Gamma_k\ln\left(\zeta-b_k\right)\right].\ (9)$$

Here Γ_k –circulation on the vortex elements, created by clouds, b_k – co-ordinates of these elements, Γ – circulation on the standard Karman chain vortices of, l – distance between standard vortices of the Karman chain, ζ – co-ordinate of the convective perturbations line (or front divider) centre, $\zeta_0 - kl$ – co-ordinate of beginning of the convective perturbation line, ζ_0+kl – co-ordinate of end of this line. The indicated parameters are the input model ones.

Equating the speed components determined in the shallow water model and model (9), one can find 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. Let us underline that using this procedure allows significantly to simplify a solving the whole problem. 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 functionψ, to express the rotational part, and a velocity potential χ, to express the divergent part. Namely these parameters are of a great interest in applied analysis of an air ventila-

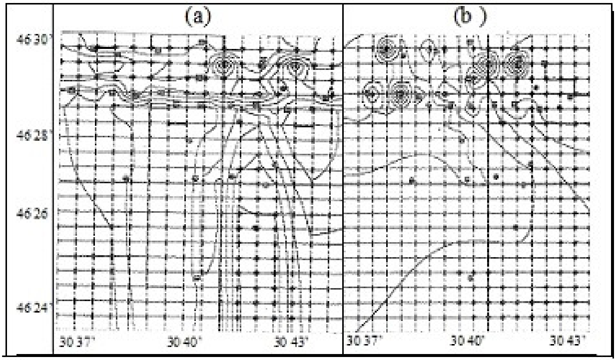

Fig. 2. (a) The potential of ventilation, (b) The current function (see text)

tion in the urban zone. Below we present the results of test computing the air ventilation parameters for some complicated synoptic situations in the Odessa city.

Some results and conclusion. The modelling has been fulfilled with using natural and model data on a cloudiness and convection and the "Geomath" PC code [6,18-23] has been used. The data of modelling an air flux parameters over the territory of Odessa (model synoptic situation), as well as the area of the Fukushima power plant after accident are presented. The corresponding model situation on cloudiness is absolutely real. Basically, it was assumed that the clouds (designed as black squares) run from the sea by two lines of convective disturbances and penetrate deep into the Gulf of Odessa. The distance between the convective clouds was assumed to be 300 to 700 meters. The figure is oriented so that the sea is in the right part, the borders of a figure are corresponding to the borders of Odessa city. Approximately one can assume that the contours of complex potential reflect the variation in time of the speed field, namely 0.5 m/s for an hour. Density of current lines is adequate to the flows speed, about 1 m/s to 0.5 cm of gradient in Figure. Analysis of the potential function gives the following: if $v_x > 0$, the speed rate increases in the direction of positive foci (and similarly on y).

This means that the potential function draws flow in positive foci. The direction of flow is obtained from the definition of the current function, i.e ., $v_x > 0$, if $\partial\varphi/\partial y > 0$. It means an availability of positive foci of the current function from a flow direction. The isolines in Figure 2 are not signed, as modular values depend on many factors, notably than intensity of convection, which determines the involvement currents power and density of cloud arrays. In whole, ventilation is manifested in the focal point from the sea side. The field of the current function in Fig.2b in this case is consistent with the field of the ventilation potential.

Another application the LACCF approach is studying the air mass ventilation in the region of the Fukushima nuclear power plant (FNPP) after accident of Marc 2011. We have carried put calculation of the ventilation potential and the current function at FNPP analogously to the previous ones and compare the obtained data with the similar theoretical ECMWF model data and observed ones (see [26-27]).

The detailed analysis will be presented in the separate paper. Here we only note that the ECMWF modeled air transfer speed is often higher than the observed values, which is consistent with the difference in heights between observations [27]. While the LACCF1 our data (model parameters, taken according to methodics [6]) are not in good agreement with the observed data, on the contrary, LACCF2 our data (calibrated parameters are corresponding to real meteodata) are quite realistic in agreement with the observed ones. That is significantly provided by using the real input parameters values. During March 15, the LACCF 2 data indicate the realistic (north-north-west) air mass (plume) travel direction, whereas the ECMWF modeled direction is mostly west. Obviously, the approach presented can be effectively used in quantitative studying a local scale atmospheric ventilation (air mass transfer), however, as minimum, its further development requires an improvement of the input parameters values choice, possibly using more correct approximation of the "shallow water" model, atmospheric turbulence modelling, region orography accounting etc.

References:

1. *A J Cimorelli, S G Perry, A Venkatram, J C Weil, R J Paine, R B Wilson, R F Lee, W D Peters and R W Brode* AERMOD: A dispersion model for industrial source applications Part I: General model formulation and boundary layer characterization// J. Appl. Meteor. – 2005. – Vol 44. – P. 682-693.
2. *S G Perry, A J Cimorelli, R J Paine, R W Brode, J C Weil, A Venkatram, R B Wilson, R F Lee and W D Peters* AERMOD: A dispersion model for industrial source applications Part II: Model performance against seventeen field-study databases//J. Appl. Meteor. – 2005. –Vol. 44. – P. 694-708.
3. *Arakava A., Shubert W.H.* Interaction of cumulus cloud ensemble with the lerge-scale environment//Journ. of Atm. Sci. – 1974. – Vol.31. – P.674-701.
4. *C D Argyropoulos, G M Sideris, M N Christolis, Z Nivolianitou , N C Markatos* Modelling pollutants dispersion and plume rise from large hydrocarbon tank fires in neutrally stratified atmosphere//Atmospheric Environment. – 2010. – Vol.44 (6). – P.803-813.
5. *G M Stavrakakis, P L Zervas, H Sarimveis, N C Markatos* Development of a computational tool to quantify architectural-design effects on thermal comfort in naturally ventilated rural houses//Building and Environment. – 2010. – Vol.45(1). – P.65-80.
6. *Bunyakova Yu., Glushkov A.* Analysis and forecast of the impact of anthropogenic factors on air basein of an industrial city. – Odessa, Ecology, 2010.
7. *Bunyakova Yu., Glushkov A., Khetselius O., Ignatenko A., Bykowszczenko N., Buyadzhi V.* New approach and microsystem technology of advanced analysis and forecasting the air pollutant concentration temporal dynamics in atmosphere of the industrial cities// Sensor Electr. and Microsyst.Techn. – 2017. – Vol.14, №3. – P. 65-78.
8. *Khetselius O.* Hyperfine structure of radium// Photoelectr. – 2005. – №14. – P.83-85.
9. *Gubanova E., Glushkov A., Khetselius O., Bunyakova Yu., Buyadzhi V., Pavlenko*

E. New methods in analysis and project management of environmental activity: Electronic and radioactive waste.– Kharkiv: FOP. – 2017. – 120p.

10. Lu *J., Araya S.P., Snyder W.H., Jr. Lawson R.E.* A Laboratory Study of the Urban Heat Island in a Calm and Stably Stratified Environment. Part I: Temperature Field; Part II: Velocity Field // Journal of Applied Meteorology. – 1997. – Vol.36. – P.1377-1402.
11. *Brandstater A., Swinney H.* Strange attractors in weakly turbulent Couette-Taylor flow//Phys. Rev. A. – 1987. – Vol. 35. – P. 2207–2220.
12. *Ghil M., Kimoto M., Neelin J.D.* Nonlinear dynamics and predictability in the atmospheric sciences//Rev.Geophys. – 1991. – Vol.29. – P.46–55.
13. *Voss R. and Mikolajewicz U.* Long-term climate changes due to increased CO2 concentration in the coupled atmosphere-ocean general circulation model ECHAM3/LSG// Climate Dynamics. – 2001. – Vol.17. – P.45–60
14. *Kang I., Lau K.* Principal modes of atmospheric circulation anomalies associated with global angular momentum fluctuations//J.Atm.Sci. – 1994. – Vol.51. – P.1194.
15. *Wang, C.* ENSO, climate variability, and the Walker and Hadley circulations. The Hadley Circulation: Present, Past, and Future (Springer). – 2004.
16. *Boer G.J., Sargent N.E.* Vertically integrated budgets of mass and energy for the globe // J. Atmos. Sci. – 1985. – Vol. 42. – P.1592-1613.
17. *Trenberth K.E., Stepaniak D.P., Caron J.M.* Interannual variations in the atmospheric heat budget // J. Geophys. Res. – 2002. – Vol.107. – P.4.1-4.15
18. *Glushkov A.V., Buyadzhi V.V., Ponomarenko E.L.* Geometry of Chaos: Advanced approach to treating chaotic dynamics in some nature systems// Proc. Intern. Geom. Center. – 2014. – Vol.7(1). – P.24-30.
19. *A V Glushkov, O Yu Khetselius, E V Agayar, V V Buyadzhi, A V Romanova, V F Mansarliysky* Modelling dynamics of atmosphere ventilation and industrial city’s air pollution analysis: New approach//IOP Conf. Ser.: Earth Environ. Sci. – 2017. – Vol.92. – P.012014.
20. *BunyakovaYu.Ya., Khetselius O.Yu.* Non-linear prediction statistical method in forecast of atmospheric pollutants// Proc. of the 8th International Carbon Dioxide Conference. – 2009. – P.T2-098.
21. *Khetselius O.Yu.* Forecasting evolutionary dynamics of chaotic systems using advanced non-linear prediction method// Dynamical Systems – Theory, Eds. J. Awrejcewicz, M. Kazmierczak, P. Olejnik, J.Mrozowski. – 2013. – Vol.1. – P.145-152.
22. *Glushkov A., Khetselius O., Ambrosov S., Bunyakova Yu., Mansarliysky V.* The use of microsystems technology "Geomath" to modeling the balance of the angular momentum of the Earth, atmospheric processes and parameters of radio waveguides: III. Nonstationary theory//Sensor Electr. and Microsyst. Techn.- 2013. – Vol.10, №1 – P.22-28.
23. *Glushkov A.V., Kuzakon V., Ternovsky V.B., Buyadzhi V.V.* Dynamics of laser systems with absorbing cell and backward-wave tubes with elements of a chaos// Dynamical Systems Theory, eds. J. Awrejcewicz, M. Kazmierczak, P. Olejnik, and J. Mrozowski (Lodz). – 2013. – Vol.T1. – P.461-466

24. *Glushkov A.V.* Relativistic Quantum Theory. Quantum mechanics of Atomic Systems. – Odessa: Astroprint, 2008.
25. *Khetselius O.Yu.* Hyperfine structure of atomic spectra. – Odessa: Astroprint, 2008.
26. *Glushkov A., Safranov T., Khetselius O., Ignatenko A., Buyadzhi V., Svinarenko A.* Analysis and forecast of the environmental radioactivity dynamics based on methods of chaos theory: General conceptions//Environm. Problems. – 2016. – Vol.1, №2. – P.115-120.
27. *Korsakissok I., Mathieu A., Didier D.* Atmospheric dispersion and ground deposition induced by the Fukushima Nuclear Power Plant accident: A local-scale simulation and sensitivity study// Atm.Env. – 2013. – Vol.70. – P.267-279.

Софронков О.Н., Хецеліус О.Ю., Глушков О.В., Буяджи В.В., Романова Г.В., Ігнатенко Г.В.

Новий геофізичний комплексно-польовий підхід до моделювання динаміки тепло-масо-переносу та вентиляції в атмосфері промислового регіону

АНОТАЦІЯ

Новий узагальнений підхід, що включає вдосконалену теорію атмосферної вентиляції в поєднанні з моделлю гідродинамічного прогнозу (з кількісним урахуванням турбулентності в атмосфері міської території) і методами теорії комплексного геофізичного поля та Аракави-Шуберта розрахунку кучкової конвекції застосовано до моделювання тепло-масо-переносу та повітряної вентиляції в атмосфері промислового міста (регіону). Представлені результати моделювання параметрів повітряної вентиляції (мезоциркуляції) над територією м. Одеси, а також районом атомної електростанції Фукусіма.

Софронков А.Н., Хецелиус О.Ю., Глушков А.В., Буяджи В.В., Романова А.В., Игнатенко А.В.

Новый геофизический комплексно-полевой подход к моделированию динамики тепло- массо-переноса и вентиляции в атмосфере промышленного региона

АНОТАЦИЯ

Новый обобщенный подход, включающий усовершенствованную теорию атмосферной циркуляции в сочетании с моделью гидродинамического прогноза (с количественно корректным учетом турбулентности в атмосфере городской территории), теорией плоского комплексного геофизического поля и методом Аракава-Шуберта расчета облачной конвекции применен к моделированию тепло- массо- переноса и воздушной вентиляции в атмосфере промышленного города (региона). Представлены результаты моделирования параметров воздушной вентиляции (мезоциркуляции) над территорией м. Одессы, а также районом атомной электростанции Фукусима.