Simulation of impact assessment of crown forest fires on boundary layer of atmosphere using software PHOENICS

Elina E. Soprunenko[a], Valeriy Perminov[a], Vladimir V. Reino[b], Egor L. Loboda[c]
[a]National Research Tomsk Polytechnic University, [b]V.E. Zuev Institute of Atmospheric Optics SB RAS (IAO SB RAS); [c]National Research Tomsk State University

ABSTRACT

Mathematical model of heat and mass transfer of crown forest fire is used in this paper, which is developed on the base of experimental research data and laws and methods of mechanics of reacting media. The numerical calculation carried out using software PHOENICS for non stationary three dimensional case. *K-ε* model of turbulence is taken into account. It is studied the influence of temperature and wind velocity in boundary layer of atmosphere on the turbulent kinematic viscosity coefficient value and distribution of temperature above the crown forest fire front.

Keywords: forest fire, boundary layer of the atmosphere, turbulence, pollution, convection column

1. INTRODUCTION

Forest fires are the one of the main source of environmental pollution. Every year in Russia there is more than 18000 of forest fires [1]. The most dangerous kind of forest fires are the crown forest fires. They account for most of the area burned. Recently, in connection with the assessment of the environmental and climatic consequences of severe fires a question about the impact of these processes on the state of the boundary layer of the atmosphere [2]. The most promising is the use of mathematical modeling of forest fires [2]. The aim of this paper is to study the influence of external factors (temperature, operating systems, wind speed) at crown forest fires on changing of the chemical and thermal pollution of the atmospheric boundary layer using software PHOENICS [3]. The use of a mathematical model of forest fire, we have to get vertical profiles of temperature and kinematic viscosity over the source of fire at different wind speeds. The distribution of these data in the boundary layer of the atmosphere up to 50 m under different external conditions above the source of fire will allow us to assess and predict changes in time of chemical and thermal pollution of the atmospheric boundary layer. Software-computing system PHOENICS [3] - is a multifunctional software that allows you to solve one-dimensional, two-dimensional and three-dimensional problems with the heat and mass transfer and chemical reactions [3]. In the propagation of wildfire flow pyrolysis and combustion products, mainly takes place in the atmosphere. The air enters the emissions of air pollutants (carbon monoxide, carbon dioxide, nitrogen oxide, soot and smoke, methane, various hydrocarbons, ozone) and heat in the form of convective currents directed. Range spread of pollutants and thermal pollution from fires in many respects depends on the parameters of wind and turbulent characteristics above the fire, knowing that we can anticipate changes in the chemical composition of the time and temperature in the surface layer of the atmosphere. In the physics of atmospheric processes on the earth's surface the most important phenomena is micrometeorology - turbulence [4].

2. THE SETTING OF PROBLEM

The basic assumptions adopted during the deduction of equations, and boundary and initial conditions: 1) the forest represents a multi-phase, multistoried, spatially heterogeneous medium; 2) in the fire zone the forest is a porous-dispersed, two-temperature, single-velocity, reactive medium; 3) the forest canopy is supposed to be non - deformed medium (trunks, large branches, small twigs and needles), which affects only the magnitude of the force of resistance in the equation of conservation of momentum in the gas phase, i.e., the medium is assumed to be quasi-solid (almost non-deformable during wind gusts); 4) let there be a so-called “ventilated” forest massif, in which the volume of fractions of

21st International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics,
edited by G. G. Matvienko, O. A. Romanovskii, Proc. of SPIE Vol. 9680, 96805Y
 · doi: 10.1117/12.2205474

condensed forest fuel phases, consisting of dry organic matter, water in liquid state, solid pyrolysis products, and ash, can be neglected compared to the volume fraction of gas phase (components of air and gaseous pyrolysis products); 5) the flow has a developed turbulent nature and molecular transfer is neglected; 6) gaseous phase density doesn't depend on the pressure because of the low velocities of the flow in comparison with the velocity of the sound. Heat and mass transfer model for the crown forest fire was obtained by analyzing the data and using the concepts and methods of reacting media mechanics [2, 5]. The set area measuring 100 × 100 × 50 m was given an artificial fireplace combustion Wildfire circuit at any time in the fixed coordinate system is described by an ellipse with a size of 10 × 10 × 2 m. Let the coordinate reference point *x, y , z*= 0 be situated at the centre of the surface forest fire source at the height of the roughness level, axis *0x* directed parallel to the Earth's surface to the right in the direction of the unperturbed wind speed, axis *0y* directed perpendicular to *0x* and axis 0*z* directed upward (Fig. 1).

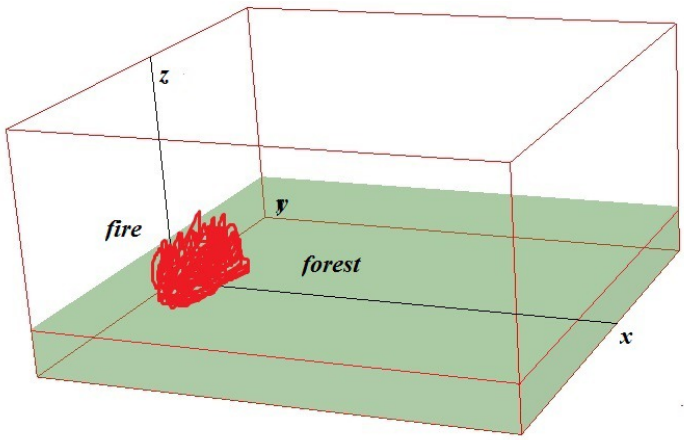

Figure 1.

Mathematically this problem is reduced to the solution of the next boundary value problem:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho v_j)=0,\ \ j=1,2,3; \tag{1}$$

$$\rho\frac{dv_i}{dt}=-\frac{\partial p}{\partial x_j}+\frac{\partial}{\partial x_j}(-\rho\overline{v_i'v_j'})-\rho s c_d v_i\,|\vec{v}\,|-\rho g_i,\ i=1,2,3; \tag{2}$$

$$\rho c_p\frac{dT}{dt}=\frac{\partial}{\partial x_j}(-\rho c_p\overline{v_j'T'})+k(cU_R-4\sigma T^4); \tag{3}$$

$$\rho\frac{dc_\alpha}{dt}=\frac{\partial}{\partial x_j}(-\rho\overline{v_j'c_\alpha'}),\ \alpha=1,3; \tag{4}$$

$$\rho\frac{dk}{dt}=\frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\Pr_t}\frac{\partial k}{\partial x_i}\right)+\rho(P_k+G_B-\varepsilon); \tag{5}$$

$$\rho\frac{\partial\varepsilon}{\partial t}=\frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\Pr_t}\frac{\partial\varepsilon}{\partial x_i}\right)+\rho\varepsilon/k(C_1P_k+C_3G_B-C_2\varepsilon); \tag{6}$$

$$\frac{\partial}{\partial x_j}\left(\frac{c}{3k}\frac{\partial U_R}{\partial x_j}\right)-kcU_R+4\sigma kT^4=0; \tag{7}$$

$$\sum_{\alpha=1}^{3} c_\alpha = 1, P_e = \rho RT \sum_{\alpha=1}^{3} \frac{c_\alpha}{M_\alpha}, \vec{v} = (v_1, v_2, v_3),\ \vec{g} = (0,0,g). \quad (8)$$

The system of equations (1)–(8) must be solved taking into account the initial and boundary conditions:

$$t = 0 : v_1 = 0, v_2 = 0, v_3 = 0, T = T_e, c_\alpha = c_{\alpha e}, ; \quad (9)$$

$$x_1 = 0 : v_1 = V, v_2 = 0, v_3 = 0, T = T_e, c_\alpha = c_{\alpha e},\ k = k_{air}, \varepsilon = \varepsilon_{air}, -\frac{c}{3k}\frac{\partial U_R}{\partial x_1} + \frac{c}{2}U_R = 0; \quad (10)$$

$$x_1 = x_{1e} : \frac{\partial v_1}{\partial x_1} = 0, \frac{\partial v_2}{\partial x_1} = 0, \frac{\partial v_3}{\partial x_1} = 0, \frac{\partial T}{\partial x_1} = 0,\ \frac{\partial c_\alpha}{\partial x_1} = 0, \frac{\partial k}{\partial x_1} = 0, \frac{\partial \varepsilon}{\partial x_1} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_1} + \frac{c}{2}U_R = 0; \quad (11)$$

$$x_2 = -x_{2e} : \frac{\partial v_1}{\partial x_2} = 0, \frac{\partial v_2}{\partial x_2} = 0, \frac{\partial v_3}{\partial x_2} = 0, \frac{\partial T}{\partial x_2} = 0,\ \frac{\partial c_\alpha}{\partial x_2} = 0, \frac{\partial k}{\partial x_2} = 0, \frac{\partial \varepsilon}{\partial x_2} = 0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_2} + \frac{c}{2}U_R = 0; \quad (12)$$

$$x_2 = x_{2e} : \frac{\partial v_1}{\partial x_2} = 0, \frac{\partial v_2}{\partial x_2} = 0, \frac{\partial v_3}{\partial x_2} = 0, \frac{\partial T}{\partial x_2} = 0,\ \frac{\partial c_\alpha}{\partial x_2} = 0,\ \frac{\partial k}{\partial x_2} = 0, \frac{\partial \varepsilon}{\partial x_2} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_2} + \frac{c}{2}U_R = 0; \quad (13)$$

$$\begin{aligned} x_3 = 0 :\ & v_1 = 0, v_2 = 0, \frac{\partial c_\alpha}{\partial x_3} = 0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_3} + \frac{c}{2}U_R = 0,\ k = k_{jet}, \varepsilon = \varepsilon_{jet}, \\ & \rho v_3 = \rho_0 \omega_0, T = T_0, |x_1| \le x_0, |x_2| \le x_0, \\ & \rho v_3 = 0, T = T_e, |x_1| > x_0, |x_2| > x_0; \end{aligned} \quad (14)$$

$$x_3 = x_{3e} : \frac{\partial v_1}{\partial x_3} = 0, \frac{\partial v_2}{\partial x_3} = 0, \frac{\partial v_3}{\partial x_3} = 0, \frac{\partial T}{\partial x_3} = 0,\ \frac{\partial c_\alpha}{\partial x_3} = 0, \frac{\partial k}{\partial x_3} = 0, \frac{\partial \varepsilon}{\partial x_3} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_3} + \frac{c}{2}U_R = 0. \quad (15)$$

Here and above $\frac{\mathrm{d}}{\mathrm{d}t}$ is the symbol of the total (substantial) derivative; α_V is the coefficient of phase exchange; ρ - density of gas – dispersed phase, t is time; v_i - the velocity components; T - temperatures of gas phase, U_R - density of radiation energy, k - coefficient of radiation attenuation, P - pressure; c_p – constant pressure specific heat of the gas phase; T_e - the ambient temperature; c_α - mass concentrations of α - component of gas - dispersed medium, index α=1,2,3, where 1 corresponds to the density of oxygen, 2 - to carbon monoxide CO, 3 - to carbon dioxide and inert components of air; R – universal gas constant; M_α , M_C, and M molecular mass of α -components of the gas phase, carbon and air mixture; g is the gravity acceleration; c_d is an empirical coefficient of the resistance of the vegetation, s is the specific surface of the forest fuel in the given forest stratum. It is supposed that the optical properties of a medium are independent of radiation wavelength (the assumption that the medium is "grey"), and the so-called diffusion approximation for radiation flux density were used for a mathematical description of radiation transport during forest fires. To close the system (1)–(8), the components of the tensor of turbulent stresses, and the turbulent heat and mass fluxes are determined using data of paper (Grishin, [2]). The system of equations (1)–(8) contains terms associated with turbulent diffusion, thermal conduction, and convection, and needs to be closed. The components of the tensor of turbulent stresses $\rho\overline{v_i' v_j'}$, as well as the turbulent fluxes of heat and mass $\overline{\rho v_j' c_p T'}$, $\overline{\rho v_j' c_\alpha'}$ are written in terms of the gradients of the average flow properties using the formulas:

$$- \rho\overline{v_i v_j} = \mu_t\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_i}{\partial x_i}\right) - \frac{2}{3}K\delta_{ij}, -\rho\overline{v_j\, c_p\, T'} = \lambda_t \frac{\partial T}{\partial x_j},\ -\rho\overline{v_j\, c_\alpha'} = \rho D_t \frac{\partial c_\alpha}{\partial x_j},$$
$$\lambda_t = \mu_t c_p / \mathrm{Pr}_t, \rho D_t = \mu_t / Sc_t, \mu_t = c_\mu \rho K^2 / \varepsilon,$$

where μ_t, λ_t, D_t are the coefficients of turbulent viscosity, thermal conductivity, and diffusion, respectively; Pr_t, Sc_t are the turbulent Prandtl and Schmidt numbers, which were assumed to be equal to 1. In dimensional form, the coefficient of dynamic turbulent viscosity is determined using model of turbulence [2]. The thermodynamic, thermophysical and structural characteristics correspond to the forest fuels in the canopy of a different (for example pine [2]) type of forest.

3. NUMERICAL SOLUTION AND RESULTS

The boundary-value problem (1)–(15) is solved numerically using software PHOENICS [3]. A discrete analogue was obtained by means of the control volume method using the SIMPLE like algorithm (Patankar [13]). Fields of temperature, velocity, concentrations of gas phase and turbulent characteristics were obtained numerically.

It has been studied the behavior of the boundary layer of the atmosphere at an altitude of 40-50 meters in the modeled area above the crown forest fire, depending on the given external environmental parameters (wind speed, air temperature, turbulent intensity). As a result of mathematical modeling using PHOENICS stationary distributions were obtained: three-dimensional fields of temperature (Fig. 2) and kinematic viscosity (Fig. 3) in the atmospheric boundary layer for different wind speeds.

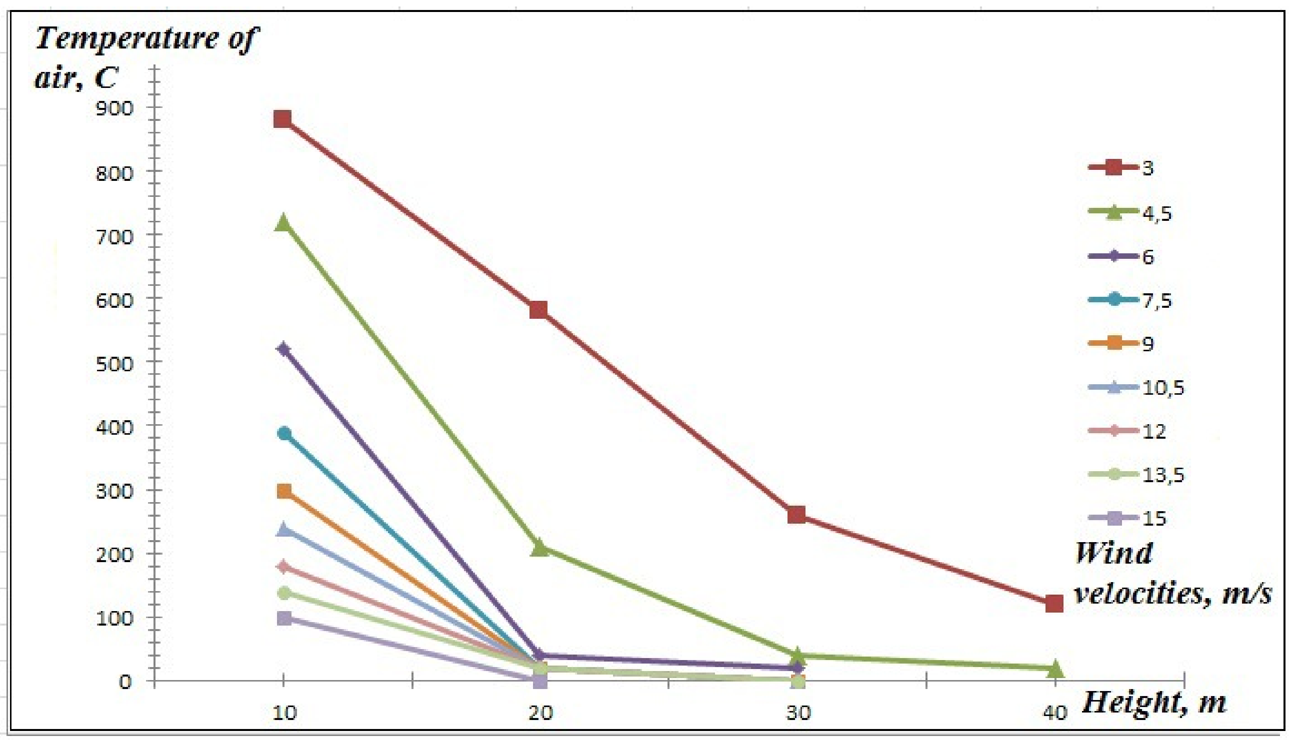

Figure 2. The temperature distribution with height above the fireplace crown forest fire for different wind speeds (3-15 m/s).

Above the fireplace there is a forest fire air flow (convection heater) caused the rise of the heated products of pyrolysis and combustion of forest fuel. The convective heater is the main source of heat and particulate matter from the fire area to the atmosphere. Large vertical and horizontal temperature gradients lead to the development of turbulent flow in the convective column. It should be noted that the characteristics of the turbulent flow is practically not explored [6].

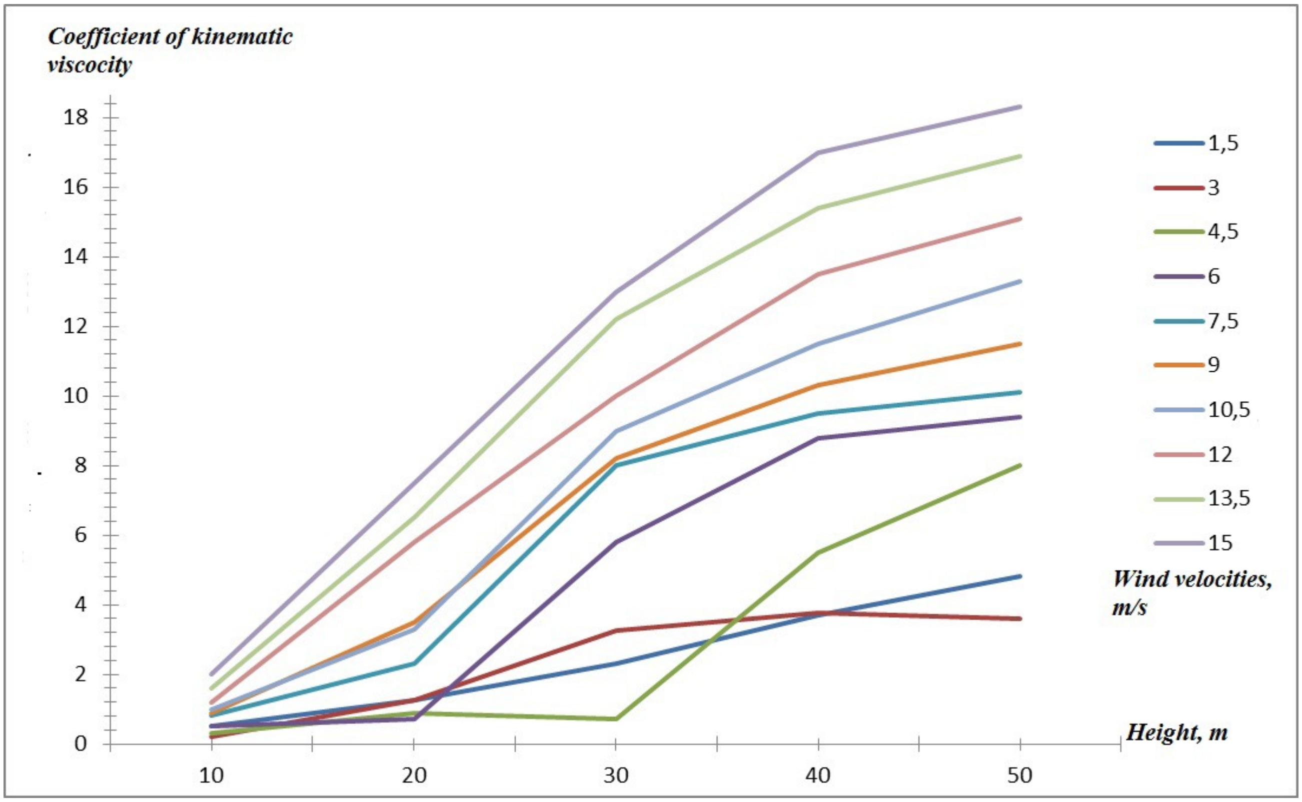

Figure 3. The distribution coefficient of kinematic viscosity at 50 m height above the fireplace grassroots wildfire for different wind speed (1.5-15 m/s).

During the creation of the our model in PHOENICS software [3], we used *K-ε* model: KEMODL (two classical equations for high Reynolds number). *K-ε* model - gradient turbulence model, the most developed and is often used for the calculation of heat and mass transfer in a fire. [7] Vertical turbulent viscosity characterizes the pulsating mass transfer vortices in the vertical direction is generated, according to the researchers mainly wind waves and wind currents, in turn, depend on the wind speed [8].

The obtained image data (Figures 2-3) shows the influence of wind speed distribution of temperature and turbulence parameters in the computational domain. Also designed models can be traced back angle change convective columns for different wind speeds (Figure 4).

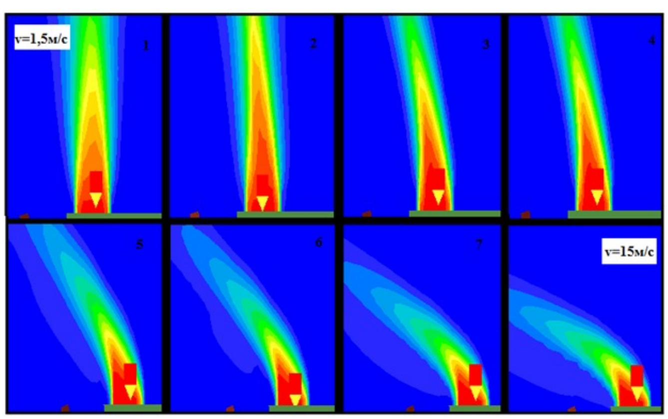

Figure. 4. The temperature distribution (h = 50 m) and the change in the angle of the convective column over the fire crown forest fire for different wind speed (1.5-15 m/s).

As a result of this work we studied the effect of turbulence on the rate of dissipation characteristics of thermal and chemical pollution of the surface layer of the atmosphere from forest fires. Research using PHOENICS [3] to better understand the fundamental physical processes that accompany the development of forest fires, their distribution and impact on the environment, particularly in the surface layer of the atmosphere. Verification of the data obtained experimentally, for example, the turbulent convection in a column appearing on the forest fires and the characteristics of turbulence in the boundary layer of the atmosphere above the forest fires may be investigated by means of optical methods and thermal imagers.

This work was supported by the "Science Foundation. D.I. Mendeleev Tomsk State University "in 2015 (the project № 8.1.27.2015).

REFERENCES

[1] Federal forest agency [electronic resource]/URL: http://www.rosleshoz.gov.ru (1.09.2014)

[2] Grishin, A.M., Mathematical Modeling Forest Fire and New Methods Fighting Them. Tomsk, Publishing House of Tomsk University, Russia. (1997).

[3] CHAM PHOENICS Your Gateway to CFD Success [Electronic resource], http://www.cham.co.uk/products.php (30.06.14).

[4] Valendik, E.N., Matveev, P.M, Sofronov, M .A., Large forest fires, Nauka, M . 198(1979).

[5] The methods of calculating the turbulent fluxes of sensible and latent heat in the surface layer of the atmosphere. [Electronic resource]/URL: http://shilin.pro/meteo/meth-calk-nest.htm(26.02.15).

[6] Grishin, A.M., Tsvyk, R..Sh., Experimental and t heoretical study of the effect of radi ation and combined heat on the e mergence and spread of grassroots forest fires. [Electronic resource] /URL: http://www.itmo.by/ru/conferences/mif_5/abstract/2-25.pdf(20.02.15).

[7] Belov, I.A., Isaev, S.A., Simulation of turbulent flows, Gidrometeoizdat, St. Petersburg, 108 (2001).

[8] Sudolsky, A.S., Dy namic effects in the aquatic environment, Gidrometeoizdat, Leningrad, 262 (1991).