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NUMERICAL SIMULATION OF A TURBULENT THERMAL

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Ascent of a large-scale thermal in a standard atmosphere is calculated with the use of the Reynolds equations and the k model of turbulence, which takes into account temperature inhomogeneity and vorticity of the flow, and the Euler equations. Results of numerical calculations of a flow examined experimentally are presented. Gas-dynamic and turbulent flow parameters obtained in calculations and experiments are compared.

Key words: *large-scale thermal, numerical simulation, fluctuating parameters of the flow.*

A large number of papers dealing with numerical simulation of the development of large-scale thermals in the atmosphere have been published. The Reynolds equations were used in [1–6] to describe flow evolution. Various models of turbulent transfer were used to take into account dissipative processes in the thermal: rather simple models, where the coefficients of turbulent viscosity and thermal conductivity were set with the help of effective Reynolds and Prandtl numbers constant over the flow field [1–4], and more complicated models, such as the standard (k–ε) model [5] and (k–ε) model with allowance for buoyancy forces and flow anisotropy in the thermal [6]. In [7], the flow was simulated using the Euler equations, but it was assumed that scheme viscosity allows for turbulent-transfer processes. The calculation results were compared with data for a cloud formed in the case of a strong explosion in the atmosphere (height of ascent, horizontal size).

Despite the versatile approaches to numerical simulation (see, e.g., [3, 4, 7–9]), the structural features of the flow in an ascending thermal, which allow its identification at the late stage of development as a floating vortex ring observed under real conditions, were not considered in [1–7]. The correctness of turbulence models used to describe this class of phenomena was not examined either, which can be done by numerically calculating the development of a thermal for which experimental data are available. The latter can be a thermal formed by detonation of a methane–oxygen mixture in the atmosphere, for which experimental data from averaged and spectral characteristics of turbulence were obtained in [10] as the thermal passed through a system of gauges.

Darintsev et al. [11], based on the analysis [12] of special features of turbulent transfer in a vortex, proposed to use the k model, which explicitly takes into account suppression of turbulent heat and momentum fluxes toward the center of gas rotation, to describe the structure of the buoyant thermal. From the physical viewpoint, suppression of turbulent flows in the vortex is caused by energy consumption for the work against centrifugal forces [12]. Data on the formation of a floating vortex ring [11] could be obtained as a result of a rather correct calculation of the early stage of formation of vortex motion due to the Bjerknes effect [13]. This stage was described by the Euler equations with the use of a numerical method with low scheme viscosity [14, 15]. At the stage of a developed vortex flow, the thermal was calculated on the basis of the k model of turbulence, and the numerical method proposed in [8] was used to solve the Reynolds equations.

The studies of [16, 17] showed that the governing factor in the description of ascent of heated gas volumes in the field of the gravity force is the correct allowance for the processes of generation and transfer of flow vorticity. Turbulence of the medium for this class of flows accompanied by the formation of a floating vortex ring is not a factor determining the character of motion. For this reason, it was proposed [16, 17] to describe the evolution of heated gas volumes in the atmosphere by the Euler equations with the use of the numerical method developed in [14, 15].

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The results presented in [11, 16] allow us to trace the process of transformation of the initially spherical thermals into a floating vortex ring. The formation of a vortex-flow core is shown, where the gas motion occurs in the same manner as that in a rotating solid body. The method proposed was used in [16] to describe the flow of detonation products of an oxygen–methane mixture. The flow parameters were written in the locally equilibrium approximation. The calculation results of external geometric characteristics of the thermal and turbulence parameters are in satisfactory agreement with experimental data. This method was used to calculate the development of clouds formed by strong explosions in the atmosphere in [17] and to calculate the development of vertical vortices in the atmosphere in [18]. At the same time, determination of turbulence parameters in buoyant thermals is of independent interest, since it is the necessary condition for solving a number of applied problems. This necessitates the improvement of the method proposed in [16, 17] to describe the development of heated gas volumes, in the aspect concerning the allowance for turbulent transfer.

Important features of the numerical method used in [11, 16, 17] are its high-order accuracy and monotonicity. Below, we consider the application of this method for the description of evolution of thermal structures in the atmosphere on the basis of solving the Reynolds equations; in the development of the method, the processes of generation and transfer of flow vorticity were described with the use of the model of turbulent transfer, which takes into account the special features of the vortex flow. To study the influence of turbulence on gas-dynamic parameters of the flow in the thermal, its structure was also analyzed using the solution of the Euler equations.

1. Formulation of the Problem. The turbulent flow in the thermal was calculated using the model of [11] with certain modifications considered below, which were introduced into equations and relations of the model to take into account the results of numerical simulation of the series of experiments [10].

The problem is solved in a cylindrical coordinate system with the z axis directed vertically. The Reynolds equations in this coordinate system take the form

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u) + \frac{\partial}{\partial z}(\rho v) = 0,$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u^2 + r\rho\langle u'^2\rangle) + \frac{\partial}{\partial z}(\rho uv + \rho\langle u'v'\rangle) + \frac{\rho}{r}\langle w'^2\rangle + \frac{\partial p}{\partial r} = 0,$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho uv + r\rho\langle u'v'\rangle) + \frac{\partial}{\partial z}(\rho v^2 + \rho\langle v'^2\rangle) + \rho g + \frac{\partial p}{\partial z} = 0, \qquad (1.1)$$

$$\frac{\partial}{\partial t}(\rho T) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho uT + r\rho\langle u'T'\rangle) + \frac{\partial}{\partial z}(\rho vT + \rho\langle v'T'\rangle) + \frac{p}{c_v}\operatorname{div}\boldsymbol{V} = 0.$$

Here ρ is the density, u, v, and w are the averaged components of velocity along the axes r and z and the angle, T is the temperature, $p = \rho RT$ is the pressure, R is the gas constant, t is the time, c_v is the heat capacity, u', v', w', and T' are the fluctuations of velocity components and temperature, and $\operatorname{div}\boldsymbol{V} = \partial u/\partial r + \partial v/\partial z + u/r$. Based on the Boussinesq hypothesis [19], the second-order moments in (1.1) are closed as follows:

$$\langle u'v'\rangle = \nu_t\Big[\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r}\Big], \qquad \langle u'^2\rangle = \frac{2}{3}k - 2\nu_t\Big[\frac{\partial u}{\partial z} - \frac{1}{3}\operatorname{div}\boldsymbol{V}\Big],$$

$$\langle v'^2\rangle = \frac{2}{3}k - 2\nu_t\Big[\frac{\partial v}{\partial z} - \frac{1}{3}\operatorname{div}\boldsymbol{V}\Big], \qquad \langle w'^2\rangle = \frac{2}{3}k - 2\nu_t\Big[\frac{u}{r} - \frac{1}{3}\operatorname{div}\boldsymbol{V}\Big], \qquad (1.2)$$

$$k = \frac{1}{2}(\langle u'^2\rangle + \langle v'^2\rangle + \langle w'^2\rangle), \quad \langle u'Q'\rangle = -\nu_Q\frac{\partial Q}{\partial r}, \quad \langle v'Q'\rangle = -\nu_Q\frac{\partial Q}{\partial z}.$$

Here k is the turbulent kinetic energy, Q' and Q are quantities that should be replaced by T', T'^2, or $k' = (u'^2 + v'^2 + w'^2)/2$ and T, $\langle T'^2\rangle$, or k, respectively.

In (1.2), we introduced coefficients of turbulent transfer of momentum ν_t and scalar quantities ν_Q:

$$\nu_t = BL_n k^{1/2}, \qquad \nu_Q = B_Q L_n k^{1/2}.$$

Here $B = 0.7$, $B_Q = B/\mathrm{Pr}_t$, $\mathrm{Pr}_t = 0.8$ is the turbulent Prandtl number [20], and L_n is the scale of turbulence. The value of k is calculated using the k model of turbulence.

To take into account anisotropy of turbulent transfer in the floating vortex ring, the scales L_n and L_s are determined at each point in the radial direction and in the direction tangential to the streamlines. In [11], in determining the relation between L_n and L_s, the results of [12] were used, which show that the expression for radial turbulent fluxes in the vortex core should be supplemented by the correction factor $1/f_0$:

$$f_0 = 1 + \beta_1 \tau^2 \frac{1}{T} \frac{\partial T}{\partial n} \frac{\partial p}{\partial r} + \beta_2 \tau^2 \frac{2V_s}{r} |\operatorname{rot} \boldsymbol{V}|.$$

Here $\tau = AL_s/k^{1/2}$ is the time scale of turbulence, r is the radius of curvature of the streamlines in the vortex, $|\operatorname{rot} \boldsymbol{V}| = |\partial u/\partial z - \partial v/\partial r|$, $\beta_1 = 0.5$, $\beta_2 = 0.5$, and V_s is the flow velocity tangential to the streamline in the vortex. It was assumed in [11] that $L_s/L_n = f_0$, and the scale L_s was set to be proportional to the vortex size.

The calculations with the use of this relation for scales showed that the choice of the value of the parameter τ as in [11] leads to unlimited suppression of turbulence in the floating vortex ring. Therefore, the parameter τ here is related to characteristic flow parameters. In accordance with [10], it is assumed that velocity fluctuations reach 20% of azimuthal velocity in the vortex. Then, we have $\tau = 0.05R/(0.2V_s)$, where $L_s = 0.05R$ (R is the radius of the floating vortex ring). The chosen value of L_s corresponds to the value used in [11] and to the experimental data of [10]. In addition, since the turbulent fluxes of heat and momentum are proportional to the squared mixing length [19, 21], we used $L_s/L_n = f_0^{1/2}$ in the present work.

The equations for the turbulent kinetic energy and temperature fluctuations have the form

$$\begin{gathered}\frac{\partial}{\partial t}(\rho k) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u k + r\rho\langle u'k'\rangle) + \frac{\partial}{\partial z}(\rho v k + \rho\langle u'k'\rangle) + \rho\varepsilon + \rho\Phi = 0,\\ \frac{\partial}{\partial t}(\rho\langle T'^2\rangle) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u\langle T'^2\rangle + r\rho\langle u'T'^2\rangle) + \frac{\partial}{\partial z}(\rho v\langle T'^2\rangle + \rho\langle v'T'^2\rangle) + \rho\varepsilon_\theta + \rho\Phi_\theta = 0.\end{gathered} \quad (1.3)$$

Here

$$\Phi = \frac{2}{3}k \operatorname{div} \boldsymbol{V} - \nu_t\Big\{2\Big[\Big(\frac{\partial u}{\partial r}\Big)^2 + \Big(\frac{\partial v}{\partial z}\Big)^2 + \Big(\frac{u}{r}\Big)^2\Big] + \Big(\frac{\partial v}{\partial r} + \frac{\partial u}{\partial z}\Big)^2 - \frac{2}{3}(\operatorname{div} \boldsymbol{V})^2\Big\}$$

is the generation of turbulent kinetic energy, $\varepsilon = B_D k^{3/2}/L_s$ is the dissipation rate of turbulent kinetic energy, $\Phi_\theta = \nu_Q(\partial T/\partial r)^2 + \nu_Q(\partial T/\partial z)^2$ is the generation of temperature fluctuations, and $\varepsilon_\theta = SB_D k^{1/2}\langle T'^2\rangle/L_s$ is the dissipation rate of temperature fluctuations ($S = 1$ and $B_D = 0.225$ [20]).

The initial conditions for the thermal are set as follows: $T(r,z) = T_0$ for $(r^2 + z^2)^{1/2} \leqslant R_0$ (R_0 and T_0 are the initial radius and temperature of the thermal), $T(r,z) = T_a(z)$ for $(r^2 + z^2)^{1/2} > R_0$ (T_a is the temperature of the standard atmosphere at a height z), $P(r,z) = P_a(z)$ (P_a is the pressure of the standard atmosphere at a height z), and $u = v = 0$ in the entire computational domain. The initial values for the turbulent kinetic energy k_0 and intensity of temperature fluctuations $\langle T'^2\rangle_0$ were assumed to be equal to low background values. Some arbitrariness in setting k_0 and $\langle T'^2\rangle_0$ is explained by the extremely weak dependence of the solutions of Eqs. (1.3) on these values, which was verified in test calculations.

At the axis of symmetry of the flow, we impose the boundary conditions

$$u = 0, \qquad \frac{\partial\rho}{\partial r} = \frac{\partial v}{\partial r} = \frac{\partial T}{\partial r} = \frac{\partial k}{\partial r} = \frac{\partial\langle T'^2\rangle}{\partial r} = 0,$$

and at the external boundaries of the computational domain, we set the conditions

$$u = v = 0, \qquad \rho = \rho_a, \qquad T = T_a,$$

where ρ_a and T_a are the density and temperature of the standard atmosphere at the corresponding height.

2. Numerical Implementation of the Mathematical Model. Since the formation of the flow structure in the thermal and in the explosion cloud, as is shown in [11, 16, 17], is primarily determined by the processes of generation and transfer of vorticity, the method of the numerical solution of the Reynolds equations should take into account these processes. This requirement is satisfied, in particular, by the method of splitting in terms of physical processes [22]. This means that different methods will be used in flow simulation in the thermal to take into account convective transfer (generation and transfer of vorticity), viscous dissipation, and thermal conductivity caused by turbulence, and also generation and dissipation of turbulence.

Convective transfer can be most accurately calculated by explicit numerical methods, since they admit nonlinear approximation of high-order accuracy, which cannot be reached in implicit methods based on linear approximation. In the present work, like in [11, 16, 17], convective transfer is simulated by the FCT method [14, 15].

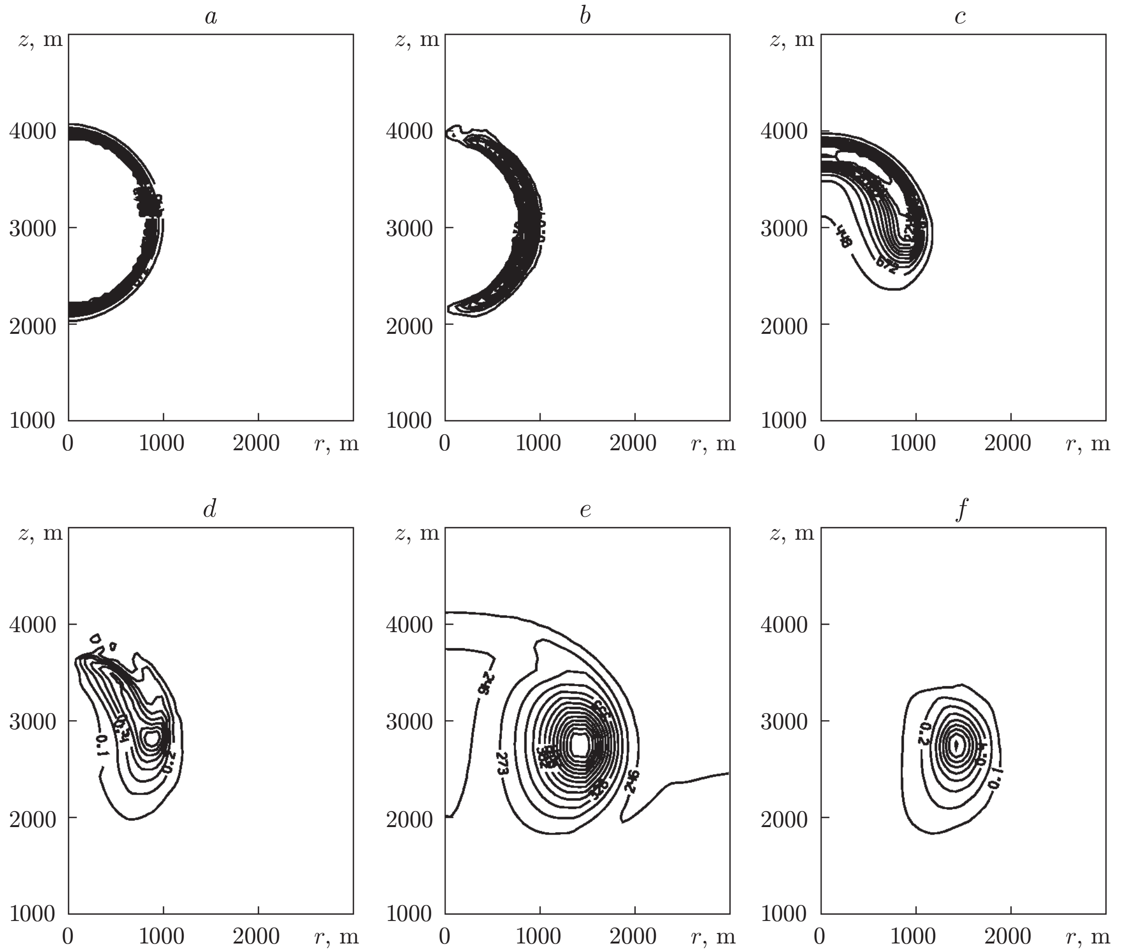

Fig. 1. Fields of temperature (a, b, and c) and vorticity (d, e, and f) (calculation with allowance for turbulence) for $t = 2$ (a and d), 15 (b and e), and 50 sec (c and f).

In modeling diffusion processes, the explicit scheme of [23] is supposed to be used, since the restriction on the Courant number in calculating diffusion processes in the thermal is not too stringent for the currently used grids. Within the framework of the method of splitting in terms of physical processes, generation and dissipation of turbulent parameters are described by ordinary differential equations admitting analytical solutions. Thus, a simple and effective method for calculating the turbulent flow in the thermal is proposed.

3. Calculation Results for a Large-Scale Thermal. The initial radius of the thermal was $R_0 = 1000$ m, the height was $H_0 = 3000$ m, and the temperature was $T_0 = 3000$ K. The calculations were performed on a uniform grid 100×200, which moved so that the buoyant thermal was located in the center of the computational domain; the initial size of the latter was four times the thermal size.

The experimental data for flows that are rather good approximations for thermals show that an important feature of such flows is the formation of a floating vortex ring from the initially spherical volume of the hot gas [24]. Therefore, we propose to analyze the of numerical simulation of thermals and also the possible effect of turbulence on the flow primarily by studying the time-space structure of the vortex ring. According to the definition proposed in [24], the vortex ring of the thermal is a toroidal region in which the hottest air is located and the velocity distribution is similar to that observed in rotation of a solid body. This definition will be justified below.

Let us consider the process of formation of the floating vortex ring by the example of a calculation with the use of the Reynolds equations. When the thermal floats up, a vortex sheet is formed at its boundary; according to the Bjerknes theorem, this vortex sheet arises because of nonparallel gradients of density and pressure at the thermal–atmosphere boundary. Initially, the vortex sheet has a spherical shape, which is seen from Fig. 1d, which shows the vorticity field for $t = 2$ sec. The corresponding temperature field is shown in Fig. 1a. Later on, the vortex sheet is transformed into the vortex ring. Figure 1b and e shows the flow pattern for $t = 15$ sec, when the

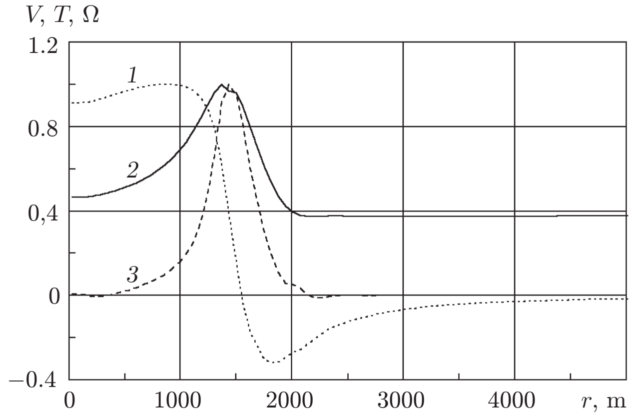

Fig. 2. Distribution of vertical velocity, temperature, and vorticity along the horizontal straight line passing through the center of the floating vortex ring: curves 1, 2 and 3 refer to $V/V_{\max}$, $T/T_{\max}$, and $\Omega/\Omega_{\max}$, respectively.

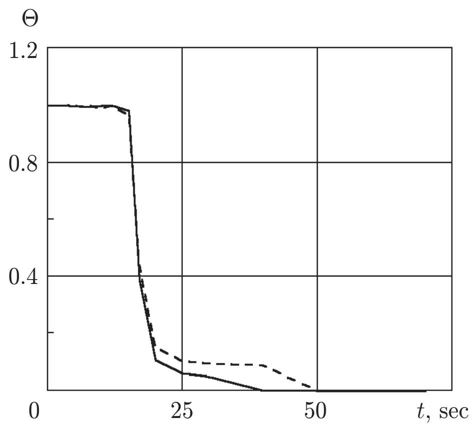

Fig. 3

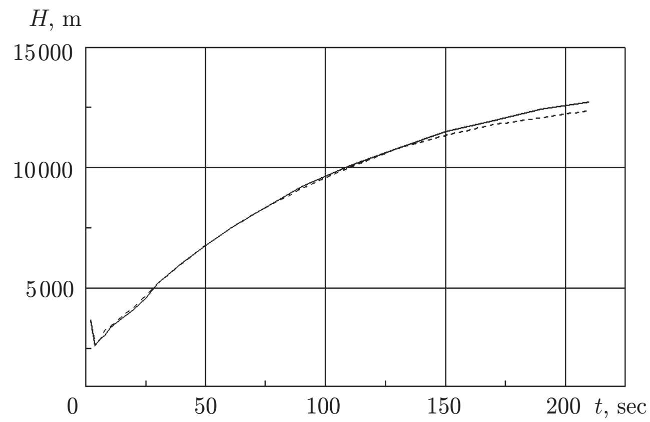

Fig. 4

Fig. 3. Dependence of $\Theta(t)$: the solid and dashed curves refer to the gas-dynamic calculation and calculation with allowance for turbulence, respectively.

Fig. 4. Height of thermal ascent versus time: the solid and dashed curves refer to the gas-dynamic calculation and calculation with allowance for turbulence, respectively.

transformation mentioned above is not yet completed. By the time $t = 50$ sec (Fig. 1c and f), the floating vortex ring is formed, since the regions of hot air and intense vortex motion become congruent and acquire a circular form.

We consider the ring structure in more detail. Figure 2 shows the profiles of temperature, vertical velocity, and vorticity along the horizontal straight line passing through the point (r_0, z_0) with the maximum value of vorticity, which are normalized to the corresponding maximum values at the time $t = 50$ sec. It is assumed that the point (r_0, z_0) is the center of the core of the floating vortex ring. It follows from Fig. 2 that the above-given definition of the floating vortex ring of the thermal is justified. We determine the radius of the vortex ring as

$$R = (r_{\min} + r_{\max})/2,$$

where $r_{\min}$ and $r_{\max}$ are the horizontal coordinates of flow points where the vertical component of velocity reaches the minimum and maximum values, respectively. It is convenient to use the quantity R to specify the scale of turbulence L_s in the k model of turbulence.

The time of vortex-ring formation is a qualitative characteristic to a certain extent. We assume that the vortex ring is formed when the temperature at the flow centerline at the height where the hottest air is located equals the atmospheric value. To qualitatively evaluate the time of formation of the vortex ring, we introduce the parameter $\Theta(t)$:

$$\Theta(t) = (T_0 - T_a)/(T_{\max} - T_a).$$

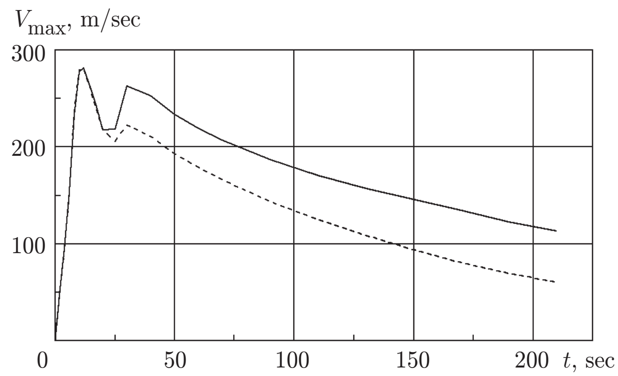

Fig. 5

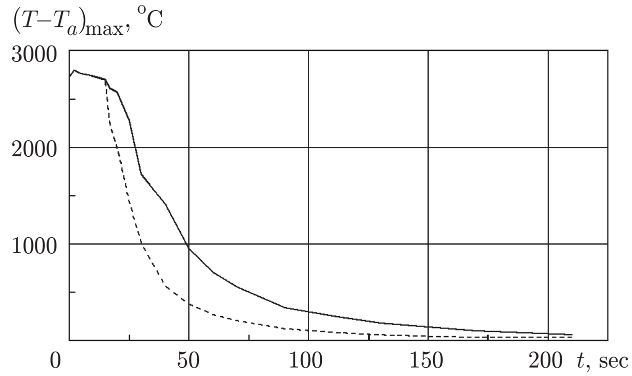

Fig. 6

Fig. 5. Maximum flow velocity versus time: the solid and dashed curves refer to the gas-dynamic calculation and calculation with allowance for turbulence, respectively.

Fig. 6. Maximum difference in temperature in the thermal and atmosphere versus time: the solid and dashed curves refer to the gas-dynamic calculation and calculation with allowance for turbulence, respectively.

Here T_{max} is the maximum temperature in the computational domain and T_a and T_0 are the atmospheric temperature and the temperature at the axis of symmetry at the height where $T = T_{max}$. In this case, vanishing of $\Theta(t)$ characterizes the time of vortex-ring formation, which, according to [11, 16], equals $4\sqrt{R_0/g}$. This estimate, however, is obtained on the basis of the Euler equations. Figure 3 shows the dependences $\Theta(t)$ calculated by the Euler and Reynolds equations. The quantity $\Theta(t)$ vanishes at $t \approx 40$ sec in the first case and at $t \approx 50$ sec in the second case. This difference can be assumed to be insignificant; hence, the quantity $4\sqrt{R_0/g}$ allows a rather exact estimate of the time of vortex-ring formation.

The possible effect of turbulence on the height of thermal ascent can be evaluated using the data in Fig. 4. The height of thermal ascent was assumed to be the vertical coordinate of the point z_0 with the maximum vorticity. It follows from Fig. 4 that the allowance for turbulence leads to an insignificant decrease in the height of thermal ascent. It is of interest to compare the calculated heights of thermal ascent with the data obtained by other authors for flows of the same class. This comparison is difficult because it is not clear what is understood as the "upper edge of the thermal" [5]; nevertheless, the agreement of the data in the present work and those in [5] for the geometric parameters of the thermal seems to be satisfactory.

It follows from Figs. 5 and 6 that the allowance for turbulence leads to a significant decrease in the maximum values of velocity and temperature in the flow field, especially at later times, though their decrease in the flow as a whole can be less significant. The maximum values of velocity and temperature fluctuations reach 30–40% of the corresponding averaged values, which does not contradict the experimental data on turbulent flows available in the literature [25].

The above-given data on the geometric parameters of the thermal, which were obtained by the Reynolds equations and turbulence model and by the Euler equations, are rather close, which is caused by using a scheme with low numerical viscosity in calculating the convection processes and the model of turbulence taking into account its suppression in the vortex ring. Nevertheless, the allowance for turbulence is necessary, since it leads to significant variation of local gas-dynamic parameters of the flow.

4. Calculation Results for Conditions of the Model Experiment. To verify that the model of turbulence is adequate to the class of atmospheric flows considered, we solved the problem of the development of a small-scale thermal, for which we used the data of [10] obtained in a series of full-scale experiments.

The test conditions were as follows. The experiments were performed at a height of 1890 m above the sea level. A stoichiometric oxygen–methane mixture was enclosed into a thin Mylar envelope of radius of 5 m and was placed at a height of 39.6 km above the ground level. A cable was placed at a distance of 20 m from the center of the envelope. A frame with gauges that allowed obtaining the mean and turbulent parameters of the flow was attached to the cable. The explosion was initiated by a detonating device at the center of the envelope. The explosion cloud formed as a result of detonation passed through the gauges, which registered random variations of

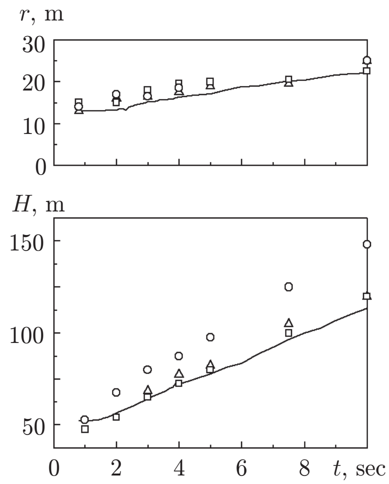

Fig. 7

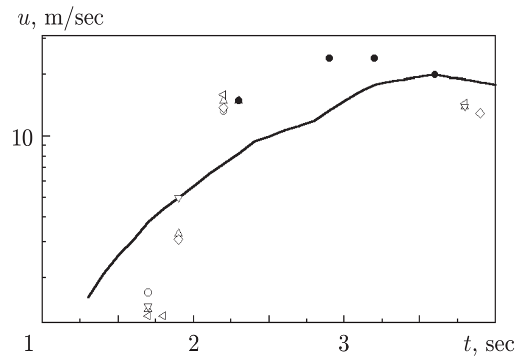

Fig. 8

Fig. 7. Geometric size of the thermal formed due to combustion of the oxygen–methane mixture: the solid curves show the calculated data, and the points refer to the first, second, and fourth experiments of [10].

Fig. 8. Convective flow velocity as the thermal passes along the gauges: the solid curve shows the calculated data, and the points refer to the experimental data for various gauges in the third experiment of [10].

instantaneous values of temperature and velocity. Subsequent processing of experimental data allowed us to obtain the mean velocity and temperature in the cloud, the value of temperature fluctuations and their spectrum, and the micro- and macroscales of turbulence according to Taylor. Thus, the experimental data of [10] allow testing various models of turbulence.

In numerical simulation of the experiments of [10], in addition to convection processes, which occur during the ascent of the explosion cloud in the atmosphere, one should take into account the processes of detonation and shock-wave propagation in the atmosphere. In the present work, we propose a simplified approach, where the latter processes are not considered, and the result is assumed to be the formation of a thermal — uniformly heated spherical volume where there is no motion and the pressure equals the atmospheric value. According to [10], pressure equalization in the region disturbed by the explosion and, hence, thermal formation occur in 1 sec after the time of ignition of the mixture. In the present work, the time of thermal formation is assumed to equal 0.8 sec. According to the data of optical measurements, the initial radius of the thermal is 13 m and its temperature is 1370 K.

The geometric parameters (radius and height) of the ascending explosion cloud were determined from the data of optical measurements. The following procedure was used to calculate them. At the initial time, special markers were uniformly distributed over the entire volume of the hot sphere. The markers were weightless particles whose velocity at subsequent times coincided with flow velocity at points where the markers were located. The maximum and minimum values of the vertical coordinates of the markers were assumed to equal the heights of the upper and lower edges of the cloud; the horizontal coordinates coincided with the cloud radius. The solid curve in Fig. 7 and others shows the variation of the calculated geometric parameters of the cloud, and the points refer to the experimental data of [10]. The agreement of the calculated and experimental data is quite satisfactory.

Figure 8 shows the calculated and experimental data for the convective flow velocity as the cloud passes along the gauges in the third experiment of [10]. The calculated velocity maximum is lower than that in the experiment. In addition, for $t \leqslant 2.5$ sec, the calculated and experimental data are in qualitative agreement only, which can be explained by the following reasons. First, in setting the initial data for the cloud of the detonating mixture, we used the thermal approximation, i.e., ignored the detonation processes. Second, the equation of state for an ideal gas was used for the oxygen–methane mixture.

Variation of the mean temperature T, its fluctuations $\langle T'^2 \rangle$, and their ratio $\langle T'^2 \rangle / T$ is shown in Fig. 9. It is possible to distinguish the core of the cloud and its wake. The temperature fluctuations inside the cloud are several times lower than those at the cloud edges, since the turbulence inside the cloud is suppressed due to the centrifugal

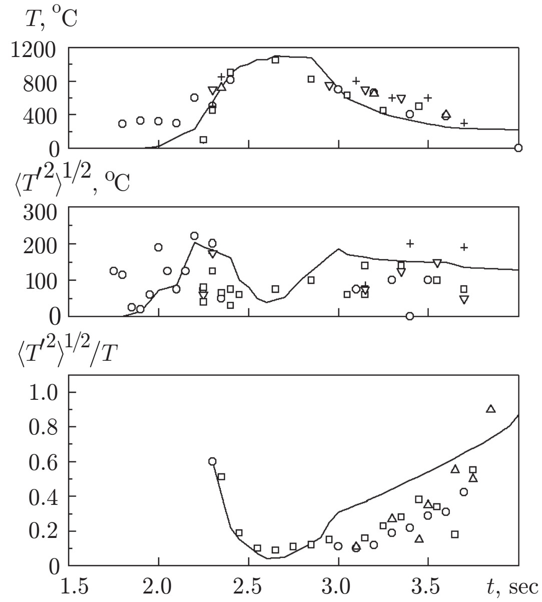

Fig. 9

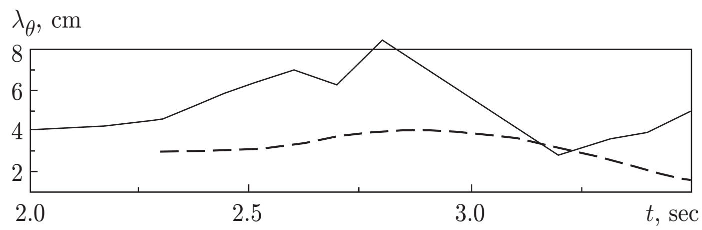

Fig. 10

Fig. 9. Temperature, intensity of temperature fluctuations, and ratio of intensity fluctuations to temperature as the thermal passes along the gauges: the solid curves refer to the calculation, and the points refer to the experimental data for various gauges in the third experiment of [10].

Fig. 10. Taylor microscale of temperature fluctuations as the thermal passes through the gauges: the solid and dashed curves refer to the calculation and experiment of [10], respectively.

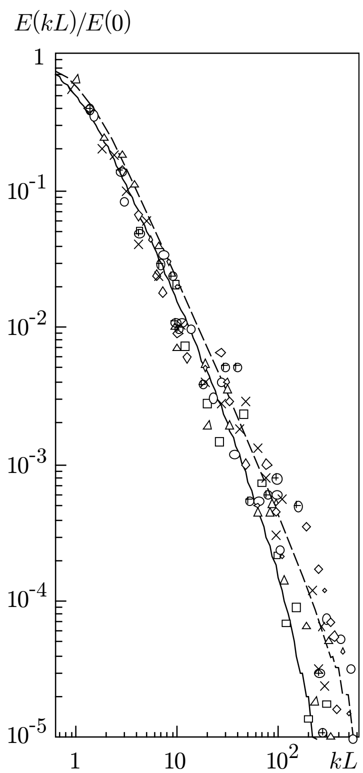

Fig. 11. Normalized one-dimensional spectrum of temperature fluctuations: the solid and dashed curves refer to the calculated data for $t = 2.8$ and 3.6 sec, respectively; the points refer to the experimental data for various gauges in the third experiment of [10].

forces and temperature gradient. It should be noted that the calculated intensity of temperature fluctuations as a whole are in good agreement with the experimental data.

In the experiments, we also determined the Taylor microscale of turbulence λ_θ. First, we measured the time microscale of turbulence according to Taylor τ; then, in accordance with Taylor's hypothesis, we determined the spatial microscale $\lambda_\theta = u\tau$ (u is the convective flow velocity). The dependence $\lambda_\theta(t)$ obtained, like in [16], with the use of results of the theory of isotropic turbulence and then averaged over all gauges is plotted in Fig. 10 (the calculated values of λ_θ are slightly higher than the experimental ones [10]).

It is also of interest to study the spectrum of temperature fluctuations, which can be obtained knowing the averaged parameters of turbulence. In the present paper, we used the method for spectrum construction, which was described in [16].

The spectra of temperature fluctuations averaged over all gauges at the times $t = 2.8$ and 3.6 sec are shown in Fig. 11. Using the relations of [16], we can evaluate the integral scale of turbulence for temperature fluctuations Λ_θ. As the thermal passes along the gauges at the times mentioned, we have $\Lambda_\theta = 1$ and 0.8 m. At the same time, the estimate for Λ_θ obtained in [10] are within the interval of 0.9–1.1 m. This agreement can be considered as satisfactory.

Thus, the calculations yield rather realistic values of parameters of flow turbulence in the thermal. As is indicated in [16], acceptable values of turbulence parameters can also be obtained using the locally equilibrium approximation, but the influence of turbulence on gas-dynamic flow parameters is ignored here.

The proposed method for solving the Reynolds equations, which is based on splitting in terms of physical processes and the use of a scheme with low numerical viscosity in calculating convection processes, and the model of turbulence, which takes into account suppression of turbulent flows in the vortex ring, allow one to correctly describe the processes of vorticity generation and transfer and obtain acceptable values of parameters of flow turbulence in the thermal.

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