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RADIATION AMPLIFICATION OF THE METEOTRON EFFECT

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The dynamics of an intense rising convective jet in the atmosphere has been investigated numerically and analytically. Primary consideration has been given to the interaction of the jet with stably stratified "retarding layers." The possible influence of radiation effects — heat release associated with the absorption of the short-wave solar radiation by the carbon black contained in the jet — on the jet dynamics has been considered. The above black is generated by the fuel combustion in the "meteotron," and can also be introduced additionally into the jet to intensify it. It has been shown that the radiation effects can, in principle, contribute greatly to the jet rise.

Keywords: *convective jets, atmosphere, meteotron, retarding layers, radiation effects, volume heat release.*

Introduction. To stimulate atmospheric convection, a few decades ago it was suggested to use artificial rising turbulent jets. Since that time, apart from theoretical studies, many large-scale natural experiments have been performed; a detailed review was given, e.g., in [1]. In the first experiments of this kind, free rising convective jets were created by intense combustion of petroleum products [1–3]. Then more effective technologies based on the application of used turbojet engines were proposed. This gave a triple effect: 1) more complete use of fuel, 2) reduction of atmospheric pollution, 3) intensification of the rising convective jet due to the additional "head" — source of the momentum in the jet engine.

Advances on these lines are relatively limited. While a fundamental possibility of artificial stimulation of the appearance and development of convective clouds was stated, at the same time it was concluded that the arising clouds were not intense enough for systematically obtaining additional precipitation. Therefore it was suggested to apply another strategy — acting on stratifying clouds, meaning artificial local transformation of such clouds into cumuli-nimbi [1]. However, these works did not lead to reliable practical results.

The present paper analyzes certain features of the dynamics of rising convective jets and points to the possible role of a factor that was not taken into account before — the radiation effects in situations where the jet noticeably absorbs the short-wave solar radiation.

Theoretical Model. Let us take as a basis the model of stationary turbulent jets used, for example, in [1] (it is also close to many other models considered in the literature, see, e.g., [4–6]). We assume that at a certain level $z = 0$ stationary heat and vertical momentum sources of power Q_θ and Q_w, respectively, localized in one and the same range of small sizes operate. The power of these sources is assumed to be high enough, so that over them a relatively thin turbulent axisymmetric rising jet is formed. Using the approximation of the boundary layer stretched along the jet axis and the hypothesis of similarity of the vertical velocity and temperature disturbance profiles in the jet, we derive for these disturbances the system of equations

$$\frac{d}{dz}(wR)^2 = \frac{a_2}{a_1}\alpha g \theta R^2 , \tag{1}$$

$$\frac{d}{dz}(w\theta R^2) = -\frac{a_4}{a_3}\Gamma w R^2 . \tag{2}$$

Here the jet radius $R(z)$ is determined by the intensity of involvement, and the values of dimensionless coefficients a_i are expressed in terms of the integrals of the assumed radial profiles of the vertical velocity w and the temperature

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deviation θ. In [1], from empirical data radial dependences of the type $\sqrt{1-(r/R(z))^2}$, for which $a_1 = a_3 = 1/4$, $a_2 = a_4 = 1/3$, were taken. The quantity (wR^2) is proportional to the vertical momentum of the jet elements, and the product $\alpha g\theta R^2$ is proportional to the work done by the buoyancy forces as the jet element rises. It is this work that leads to a change with height in the momentum. Likewise, the buoyancy of the jet element, as well as its heat content relative to the environment, are proportional to $w\theta R^2$ and change with height proportionally to $-\Gamma w$, since in the process of the jet element rise the temperature of its environment changes. The differential model under consideration differs slightly from the known integral models (e.g., [4]). Note that in deriving Eqs. (1), (2) we assumed that the jet was stretched vertically. Therefore, they may be violated significantly, e.g., in the region of the horizontal spread of the jet under the retarding layer, as well as directly over the source where a clearly defined jet has not yet been formed.

An equation analogous to (2) can also be derived for the impurity transfer. Below we consider the transfer of the fine (practically weightless) carbon black introduced into the jet which absorbs the short-wave solar radiation and thus influences the jet buoyancy. If the background stratification of the impurity is absent, then the analog of Eq. (2) for the impurity has the form

$$\frac{d}{dz}(w\mu R^2) = 0 . \qquad (3)$$

If the background profile of $\Gamma(z)$ is assumed to be known, then Eqs. (1), (2), generally speaking, represent a system of two equations with three unknowns w, θ, R (the additional inclusion of Eq. (3) adds one equation and one unknown). To close the system, additional information or hypotheses are used. One often uses the hypothesis of the involvement in the jet of the environment proportional to the jet cross-section perimeter (i.e., to the jet radius $R(z)$ and the vertical velocity [4]). In other words, the involvement is assumed to be proportional to the area of the lateral surface of the jet element $2\pi Rw$. Then one can write the third equation closing the system [4]. In [1], a simpler scheme was used: on the basis of theoretical considerations and experimental data it was assumed that the radius of the turbulent jet increases linearly with height

$$R(z) = \beta z , \quad \beta = 0.1\text{–}0.2 . \qquad (4)$$

Below exactly such a closing hypothesis will be used.

The consideration of the point sources at the lower level $z = 0$ entails certain difficulties for numerical modeling. They are largely formal since it is known that the dynamics of jets at a distance from local sources weakly depends on the geometric details of these sources — it is determined only by the integrated intensities of the heat and momentum sources. Therefore, the problem can be regularized by replacing point sources with sources of finite radius $R = R_s$ located at some small height $z = z_s$. In so doing, concrete values of z_s and R_s (related to each other by relation (4)) are often immaterial — with increasing height the jet soon "forgets" about these values and the solutions are practically independent of them. The momentum source (in other words, the upward force) and the heat source on which solutions really depend, according to [1], are equal, respectively, to

$$Q_w = 2\pi\rho a_1 w_s^2 R_s^2 , \quad Q_\theta = 2\pi\rho c_p a_3 w_s \theta_s R_s^2 . \qquad (5)$$

In monograph [1], much consideration was given to the analysis of the model and its comparison with available experimental data. A conclusion about the adequacy of the model was drawn. Equations (1) and (2) used in the present work coincide with the corresponding equations of [1]. For situations admitting comparison with the results of [1], such comparison has been made by us. The results confirm that the present numerical model is as adequate as that presented in [1].

Dynamics of the Jet in a Neutrally Stratified Medium under the Retarding Layer. The dynamics of rising jets depends on a whole number of factors — medium stratification, involvement, intensity of the heat and momentum sources, etc. Therefore, in spite of the large volume of calculations made earlier, some general laws, as we see it, remained unnoticed. A very important point is the ability (or inability) of jets to break through retarding (stably stratified) layers in the atmosphere. Such layers are often relatively thin but can strongly impede vertical convective motions. The calculation of the interaction of jets with retarding layers was given much consideration in [1]. To ana-

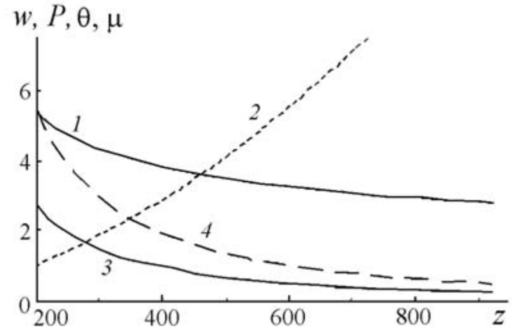

Fig. 1. Profiles of the vertical velocity on the jet axis w (1), vertical mass flow P in the jet (2), temperature deviation on the jet axis θ (3), and partial density of the passive impurity introduced into the origin of the jet μ (4) for the rising jet in a neutrally stratified environment.

lyze in more detail the influence of these layers on the jet rise, we shall consider an idealized situation where above and below the retarding layer the atmosphere is stratified neutrally so that the influence of such layers shows up in pure form.

Of interest is the rise of the jet in the neutrally stratified medium under the retarding layer. As was shown in [1], the momentum source Q_w plays an important part only in the lower hundreds of meters. The jet rises higher mainly due to the action of the heat source. Therefore, the asymptotics obtained as early as the 1930s by Zeldovich for convective turbulent jets

$$w \sim (Q_\theta / z)^{1/3}, \quad \theta \sim Q_\theta^{2/3} z^{-5/3} \tag{6}$$

is fulfilled approximately.

Figure 1 gives a numerically calculated example of profiles of the vertical velocity w, the vertical mass flow (the quantity $(2\pi/3 \cdot 10^4) w R^2$ was plotted), the temperature disturbance, and the partial density of passive impurity injected into the jet origin ($10^6 \mu$). Values of $\beta = 0.15$, $Q_w \approx 2.5 \cdot 10^4$ N, and $Q_\theta \approx 2 \cdot 10^7$ W were taken. Such intensity of the sources corresponds to the indices of the TF33-1 jet engine [1] in which about 1 liter of fuel is burned in 1 sec: $R_s = 0.25$ m, $w_s = 460$ m/sec, $\theta_s = 440^\circ$C.

The jet buoyancy (temperature deviation) decreases with height much faster than the velocity. At altitudes where retarding layers are often situated (of the order of 1 km or at least a few hundreds of meters), the jet temperature deviation, as is seen from Fig. 1, is already very small. Therefore, it may be expected that if a retarding layer is "pierced," this will be mainly due to the mechanical momentum of the jet alone.

Interaction of the Jet with a Retarding Layer. Figure 2a gives an example of vertical profiles for the same jet in the presence of a weak retarding layer. The potential temperature gradient in the latter is described by the expression

$$\Gamma(z) = \Gamma_0 \exp\left[-\left(\frac{z - z_1}{h}\right)^2\right]. \tag{7}$$

Figure 2a was plotted for values of $z_1 = 700$ m, the maximum potential temperature gradient $\Gamma_0 = 0.01$ K/m; $h = 50$ m (in addition to the quantities whose profiles were plotted in Fig. 1, curve 5 for the profile of the quantity 100Γ, K/m, is given). Thus, we speak of a very weak retarding layer situated at a height of 700 m with a maximum gradient corresponding to isothermality (the vertical background temperature gradient at $z = z_1$ reaches the maximum value equal to zero; in the atmosphere it is stable stratification) and a thickness of the order of 100 m. The potential temperature drop (stability index of the layer) in this layer is only about 1°. In the simplified model under consideration, the stratification over this layer is neutral again.

In the earlier literature (see, e.g., [1]), calculations of the "piercing" of retarding layers received much consideration. By default it is considered (and this seems to be obvious) that such a layer can be thought to be broken

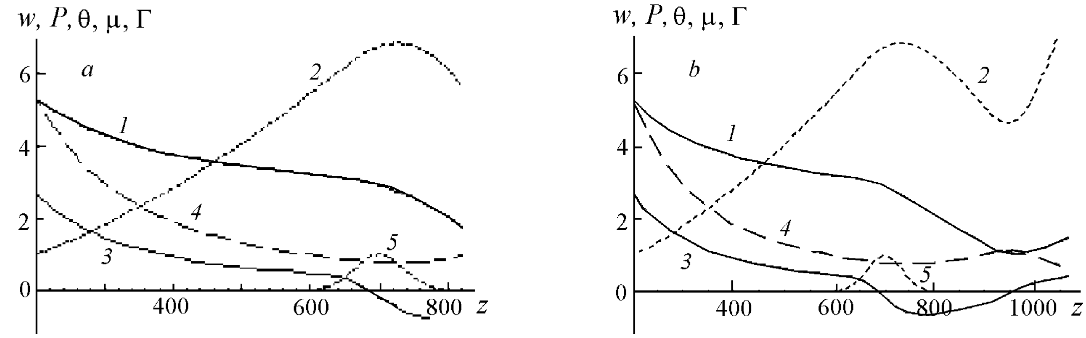

Fig. 2. Vertical profiles of w (1), P (2), θ (3), partial impurity density μ (4), and background temperature gradient Γ (5) in the presence of a retarding layer: a) in the case of passive impurity; b) with account for the radiation effects of impurity.

through if the convective elements reach its upper boundary. But, as is evident from Fig. 2a, in reality the situation is much more complicated. Formally, the jet in the considered example easily pierces the retarding layer and, in so doing, is even not very strongly retarded at first. But in the process of passing through this layer it acquires negative buoyancy, which with further rise leads to an increasingly faster retardation of the jet. The vertical mass flow in the jet begins to decrease markedly as soon as the retarding layer is practically passed.

This result is easy to understand from physical considerations: since the jet transfers upward the denser air from under the retarding layers, subsequently (above this layer) it turns out to be heavier than the environment and, naturally, is retarded. This can also be obtained formally from Eq. (2). If we integrate the latter for the height from some level z_0 to z, we obtain

$$w\theta R^2 = (w\theta R^2)\big|_{z=z_0} - \frac{a_4}{a_3}\int_{z_0}^{z} \Gamma(z')\, w(z')\, R^2(z')\, dz' .$$

This elementary result contradicts the intuitive notion that the motion of the convective element is determined by the medium stratification at the level where it is situated. From the latter formula it is seen that the buoyancy of the convective element (and, consequently, its dynamics) is not determined by the local value of stratification at the level at which it is situated at a given moment, but depends integrally on the stratification along the path covered by it. Usually it is thought to be obvious that convective elements are retarded exactly in the retarding layer, and from the above consideration it follows that they can be retarded to an even greater extent at higher levels where stable stratification is absent. This is due to the previously accumulated negative buoyancy of convective elements. Moreover, numerical experiments have shown that upon passing through the retarding layer the jet may decay with height even if unstable (e.g., unstable towards humidity) stratification over the layer is given.

From Fig. 2a it is seen that the presence of an even very weak retarding layer leads to a significant retardation of the jet as soon as this layer is left behind. Indeed, the air in the jet, which over this layer turned out to be colder than the environment by some value of θ_0, can (as seen from the elementary energy balance) rise by inertia only to a height of the order of $\Delta z \sim \frac{T_*}{\theta_0} w_0^2/g$. If $w_0 = 2$ m/sec and $\theta_0 = 1$ K, then Δz is only of the order of 100 m. The same result can be obtained more rigorously from the exact analytical solution for the stationary jet at neutral stratification of the environment given in [1] (formula (2.19.2)):

$$w(z) = \frac{1}{\beta z}\left[u_0 + \frac{\beta}{2} u_0' (z^2 - z_0^2)\right]^{1/3},$$

where

$$u_0 = \left(\frac{Q_w}{2\pi\rho a_1} \right)^{3/2} ; \quad u_0' = \frac{AQ_\theta}{2\pi\rho c_p a_4} ; \quad A = \frac{3}{2} \frac{g}{T_*} \frac{a_2 a_4}{a_1 a_3} .$$

The expression for $w(z)$, as far as we know, was not analyzed earlier in the special case where the momentum source was positive and the heat source was negative. Precisely this situation takes place over the retarding layer: the jet moves upwards by inertia but has a negative buoyancy thereby, since it carries upwards the denser air from under the above-mentioned layer. Therefore, there exists a limiting height of rise z_* which we find by equating $w(z)$ to zero. We obtain

$$z_* = \sqrt{z_0^2 - \frac{2}{\beta} \frac{u_0}{u_0'}} = z_0 \sqrt{1 - \frac{2}{\beta} \frac{u_0}{u_0' z_0^2}} \approx z_0 - \frac{1}{\beta} \frac{u_0}{u_0' z_0} .$$

The approximate equality here presupposes that the second term under the root is small compared to the first term, which corresponds, in particular, to not too low retarding layers (not too low z_0 values) and can easily be checked in a specific instance. In view of (4) and (5) it is easy to get from here

$$\Delta z = z_* - z_0 \approx - \frac{1}{\beta} \frac{u_0}{u_0' z_0} = \frac{T_* w_0^2}{2g\theta_0} ,$$

which agrees in order of magnitude with the above nonrigorous estimate.

Possible Role of the Radiation Effects. From the examples considered above it is seen that the positive buoyancy of the jet after a few hundreds of meters from the heat source decreases significantly, and the mechanical inertia alone is insufficient for effective breaking through even weak retarding layers. We can try to change this unfavorable condition by injecting into the jet an impurity absorbing the short-wave solar radiation and thus increasing the jet buoyancy. Actually, in the process of fuel combustion in the meteotron such an impurity (black) is released "automatically" and it would be expedient to take into account its possible effects. But to do this, it is necessary to know fairly well the optical properties of such an impurity depending on particular conditions of the fuel combustion, which is a subject of a separate investigation. Here we will dwell upon the case of an impurity with known properties. This is, for example, fairly fine (tens of fractions of a micron) carbon black; its application was proposed as far back as the 1970s for acting actively on some atmospheric processes [7–11].

Let the heat and momentum source in the meteotron be also a source of the above impurity. Below we will give the calculations for an impurity source of intensity M = 40 g/sec. The weight of such a quantity of carbon black makes no appreciable contribution to the jet buoyancy. The system of equations in this case should be completed with Eq. (3), whose integration gives

$$\mu(z) = \frac{2M}{\pi w(z) R^2(z)} , \tag{8}$$

where the integration constant was chosen from the normalization condition

$$2\pi \int_0^R \tilde{w}(r, z)\, \tilde{\mu}(r, z)\, r dr = M ,$$

in which a tilde denotes the vertical velocity and impurity concentration fields (unlike those used above and depending only on z values of these quantities on the jet axis).

With account for the solar radiation absorption in the jet there is an additional volume heat source whose intensity in the first approximation is assumed by us to be proportional to the impurity density $\tilde{\mu}$:

$$E = \kappa\tilde{\mu} \, . \tag{9}$$

The value of the proportionality coefficient κ depends, in particular, on the intensity and spectrum of the coming solar radiation and the optical properties of the impurity. For the situations considered in [7] (fine carbon dust in the boundary layer of the atmosphere in the tropical zone), $\kappa \sim 5{\cdot}10^3$ K·m^3/(sec·kg) [9, 10]. Note that relation (9) is, strictly speaking, applicable only in the case of an optically thin layer of the impurity where the "self-screening" of the impurity cloud (layer) can be neglected. This means a certain restriction on the quantity of the impurity along the sunbeam μL. According to the estimates of [9, 10], the product μL for the considered impurity should be much smaller than $3{\cdot}10^{-4}$ kg/m^2. Otherwise the cloud of impurity will be opaque, heat is released only at the edge of the cloud facing the Sun so that we cannot speak of a heat release proportional to the impurity density, the problem becomes much more complicated, and the impurity as a heat source is used ineffectively. As applied to such small-scale objects as jets (especially in their initial portions), the latter restriction, generally speaking, is very significant. Near the impurity source where its density is high this restriction is violated a fortiori. But in the initial portion of the jet, the heat associated with the impurity and the error in its estimation should not have a strong effect on the dynamics since there the influence of the main heat source in the meteotron predominates. And at a height of a few hundreds of meters where the jet radius reaches and exceeds 100 m, the impurity density strongly decreases, and when sunbeams are incident at an angle with the vertical the above transparency condition of the jet may be fulfilled as to the order of magnitude, so that the considered heat release model (9) may lead to correct tentative estimates. Equation (2) with account for the above additional volume heat release takes on the form

$$\frac{d}{dz}(w\theta R^2) = \frac{a_4}{a_3} R^2 (\kappa\mu - \Gamma w) \, . \tag{10}$$

Note that there exists a simple analytical solution of the system of equations (1), (8), (10) at a homogeneous stable stratification

$$\mu = \sqrt{\frac{2\Gamma M}{\pi\kappa}} \frac{1}{R(z)} = \sqrt{\frac{2\Gamma M}{\pi\kappa}} \frac{1}{\beta z} \, , \quad w = \frac{\kappa}{\Gamma}\mu = \sqrt{\frac{2\Gamma M}{\pi\kappa}} \frac{1}{\beta z} \, , \quad \theta = 0 \, .$$

This solution describes the "neutral-buoyancy conditions" whose existence for a number of problems of convection with a heat-releasing impurity at a stable stratification was noted earlier in [9, 10] and in some of the author's papers cited therein. The above-mentioned conditions have a clear physical meaning: the increase in the buoyancy due to the volume heat release in the environment is fully compensated by the decrease in the buoyancy due to the rising of convective elements into the denser layers of the environment. The buyoncy (temperature disturbance) therewith remains close to zero. But the jet can go to this regime only at a fair distance from the source since in the initial portion of the jet the buoyancy disturbances, on the contrary, are very significant.

Figure 2b gives an example of the numerical solution of the system of equations (1), (8), (10) at the same, as above, background stratification with a retarding layer (7). The intensity of the source of fine carbon dust M is assumed to be equal to 40 g/sec. To reduce the influence of the above-mentioned incorrectness of the model connected with the opacity of the jet in its initial portion, we assume that radiation heating in this example "started" beginning with the retarding layer, i.e., that the coefficient κ determining the "heating power" of the impurity is a function of the vertical coordinate z:

$$\kappa(z) = \kappa_0 \left[1 + \tanh\left(\frac{z - z_1}{h} \right) \right] .$$

Here the coefficient $\kappa_0 = 2.5{\cdot}10^3$ K·m^3/(sec·kg). It can easily be seen that below the retarding layer the coefficient κ is close to zero, and beginning with this layer it increases to the above value $\kappa = 5{\cdot}10^3$ K·m^3/(sec·kg). The quantity of impurity along the sunbeam intersecting the jet at levels of the order of 1 km in the considered example can exceed 10^{-4} kg/m^2, so that the given model gives only tentative estimates.

From Fig. 2b it is seen that owing to the radiation heating the negative buoyancy of the jet that arose upon passing through the retarding layer gradually decreases to zero. Accordingly, the jet ceases retarding and then begins to intensify.

The appreciable effect of the considered impurity source can be understood from the following estimate. At a height of 700 m, where the jet radius R is about 100 m, $w \sim 3$ m/sec and the volume of the jet element $W \sim \pi R^2 w \sim 10^5$ m^3. The partial impurity density in this volume at the considered intensity of its source $M = 40$ g/sec will be equal to $\mu \sim 0.4 \cdot 10^{-6}$ kg/m^3. This is about 6–7 times higher than the concentrations considered in [7] where the heating rate was estimated to be equal to 1 K/h. Such a jet can no longer be considered to be optically thin. The partial "self-screening" decreases the heat release, but in order of magnitude we can roughly estimate the characteristic heating rate at a favorable geometry (the altitude of the Sun above the horizon) to be equal to 5 K/h. Such a heating rate, as can easily be seen, is able to compensate for the buoyancy loss of the jet rising with a velocity $w \sim 1.5$ m/sec at a stable potential temperature gradient $\Gamma = 10^{-3}$ K/m. This is not a very strong effect, but in situations where the initial buoyancy of the jet with height has already ceased, it can play a noticeable role. Indeed, in the specially performed natural experiments [11] a noticeable "self-lofting" of smoke heated by solar radiation was registered.

Conclusions. The numerical and analytical investigation of the dynamics of the turbulent convective jet of the meteotron has led to a number of new results concerning mainly the interaction of the jet with retarding layers. The results presented above point to the importance of the following fact. The influence of stratification on the jet dynamics is not local but integral: the buoyancy force at any level may strongly depend on the "background" of the convective element — the stratification conditions on the path covered by it before. In particular, the influence of the stratified layer on the jet retardation is strong not only when the jet is breaking through it, but also higher, even in the absence of stable stratification of the air over this layer. We have considered the possible influence of the radiation effects on its dynamics — the heat release due to the short-wave solar radiation absorption by the carbon black contained in the jet. The above-mentioned carbon black is generated by the fuel combustion in the meteotron, and can also be additionally introduced into the jet to intensify it. It has been shown that the radiation effects can, in principle, noticeably promote the jet rise.

NOTATION

A, dimensional buoyancy parameter, m/(sec^2·K); a_i, dimensionless coefficients; c_p, heat capacity of air, J/(kg·K); E, intensity of volume heat release, K/sec; g, gravitational acceleration, m/sec^2; h, thickness scale of the retarding layer, m; L, characteristic size of the impurity cloud in the direction of sunbeams, m; M, intensity of the impurity source, g/sec; P, vertical mass flow in the jet referred to be medium density, m^3/sec; Q_w, intensity of the momentum source, N; Q_θ, intensity of the heat source, W; r, radial coordinate (distance from the jet axis), m; R, jet radius, m; T_*, average absolute temperature in the considered air layer, K; u_0, dimensional parameter introduced to shorten the writing of formulas, m^6/sec^3; u_0', dimensional parameter introduced to shorten the writing, m^4/sec^3; w, value of the vertical velocity component on the jet axis, m/sec; $\tilde{w}$, velocity component in the direction of the z axis, m/sec; w_0, vertical velocity upon leaving the retarding layer, m/sec; W, volume of the jet element, m^3; z, vertical coordinate (the z axis is directed upwards), m; z_s, level at which the source is situated, m; z_0, initial (counting-off) level, m; z_1, medium height of the retarding layer — the level at which the stable temperature gradient reaches its maximum, m; z_*, limiting jet altitude, m; z', integration variable, m; Δz, altitude of the convective element upon passing through the retarding layer, m; $\alpha = 1/T_*$, thermal expansion coefficient of the medium, K^{-1}; β, dimensionless coefficient; $\Gamma(z)$, vertical potential temperature gradient (difference of the vertical temperature gradient from the neutral one), K/m; Γ_0, maximum value of Γ in the retarding layer, K/m; κ, proportionality coefficient ("heating power" of the heat-releasing impurity), K·m^3/(sec·kg); κ_0, dimensional coefficient (characteristic value of κ), K·m^3/(sec·kg); $\tilde{\mu}$, partial impurity density, kg/m^3; μ, value of the partial impurity density on the jet axis, kg/m^3; ρ, average density of air, kg/m^3; θ, temperature deviation on the jet axis, K; θ_0, absolute value of the temperature deviation on the jet axis upon passing through the retarding layer, K. Subscripts: s, values of the quantities at z_s level (on the surface); i, dimensionless coefficient number in Eqs. (1) and (2).

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