EFFECT OF DISPERSED IMPURITIES ON THE RISE OF A DUSTY THERMAL

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A rising cloud of heated gas (thermal) is capable of carrying to considerable distances various aerosol impurities that are present in the ground layer of the atmosphere (dust, soot). Transfer of large amounts of finely dispersed particles to the upper atmospheric layers can have consequences of a global character [1], and, therefore, mathematical simulation of such processes acquires great importance.

The basic stages in the evolution of a floating cloud have been studied fairly thoroughly by using numerical integration. Thus, the formation of a thermal and the subsequent development of a vortex structure as a result of a point explosion in a compressible atmosphere were considered in [2]. A numerical solution of the equations of an incompressible medium in the Boussinesq approximation was obtained in [3, 4], while the initial and the self-similar parts of the motion, as well as the hovering stage, were calculated separately. The turbulent character of the flow was taken into account by introducing the constant effective transport coefficients, the values of which were determined from the correspondence between the theoretical integral characteristics – the self-similar coordinate of the upper edge and the expansion angle of the cloud – and their experimental values [3, 5]. Many problems were solved on the basis of the relationships derived in [3, 4], in particular, the problem of transfer to the stratosphere of passively transported (without influence on the gas motion) impurities.

Comparison between theoretical and experimental data on the law of ascent of the upper edge of a thermal was then used in [6-8] for determining the turbulent exchange coefficients in the case of a compressible medium, where the atmospheric density changes greatly with altitude due to the gravimetric compressibility of air. It was demonstrated in [6, 7] that the rise dynamics is described by two parameters – the Rayleigh (or Grashof) number and the initial height of the thermal. The relationships derived made it possible to perform a complete calculation of all stages in the evolution of thermal in the nonuniform, compressible atmosphere [6, 8].

The model of a compressible medium was used in [9] for investigating the transfer to the stratosphere of aerosol particles, initially located in a cylindrical ground layer, by a hot thermal. Data on the degree of capture of particles from the ground region and the percentage of impurities reaching the stratosphere were obtained, and the results were compared with the estimates given in [1]. In describing the dispersed phase, its active influence on the gas due to its weight and thermal characteristics was taken into account. Such an impurity does not have its own pressure and, generally, cannot be considered as an additional gas component.

The present paper examines in detail the vertical transfer of an active impurity by an initially dusty, supernatant thermal. The gravimetric and energy mechanisms of interaction between phases and their relative effect on the rise of a floating cloud are analyzed for various fill factors characterizing the degree to which a thermal is filled with the impurity. The scope of applicability of the one-velocity model is discussed, and the characteristics of motion of a thermal with a high initial fill factor are considered. The limits of validity of the passive impurity approximation are examined on the basis of the results obtained.

1. Assume that, at the initial instant of time, a stationary spherical cloud of hot gas containing finely dispersed particles which are distributed throughout its volume is located above a flat horizontal surface. The continual approach is used for describing the carrier and the dispersed phases. Moreover, the particles are considered to be sufficiently small for the characteristic times of velocity and temperature relaxation to be much shorter than the time of convection development $(R_0/g)^{1/2}$ (R_0 is the initial radius of the thermal, and g is the acceleration due to gravity). Within the framework of Stokes' law of resistance, the

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time of velocity relaxation for a single particle is of the order of $d^2/18\nu\varepsilon$ (d is the particle diameter, ν is the gas viscosity, and $\varepsilon=\rho_{10}/\rho_2^0$ is the ratio of the actual densities of the gas and the impurity), which is comparable to the time of convection development for $d\sim d_*=(18\nu\varepsilon\sqrt{R_0/g})^{1/2}$. For $R_0 \sim 10^3$ m, $\nu = 0.15$ cm²/sec, and $\varepsilon = 10^{-3}$, we have $d_* \sim 1$ mm. The time of temperature relaxation of particles is equal to $d^2/4\varkappa\varepsilon$ ($\varkappa$ is the thermal diffusivity of the gas); its order of magnitude is equal to that of the equalization time of phase velocities. For particles whose dimensions are considerably smaller than d_* ($d \lesssim$ 10-100 μm), we can use the instantaneous relaxation hypothesis [10].

We introduce dimensionless variables, using, for the measuring scales of pressure, density, and temperature, the values of these parameters in the unperturbed atmosphere at the base surface, P_0, ρ_{10}, and T_0 ($P_0=\rho_{10}R^0T_0$, and R^0 is the gas constant). Moreover, as in [6, 7], we choose a fixed linear scale L of the order of the characteristic cloud radius (the velocity and time scales are $(Lg)^{1/2}$ and $(L/g)^{1/2}$, respectively), and we reduce all the final results to a form independent of a specific L value. The transient axisymmetric motion of the two-phase system is considered in a cylindrical coordinate system (r, z), the origin of which is located at the base surface under the center of the thermal. The carrier medium is described by the equations of a viscous, compressible gas, while the dispersed impurity is described by the convective diffusion equation

$$\frac{d\rho}{dt}=-\rho\operatorname{div}\mathbf{U},\quad P=\rho_1T,\quad \rho=\rho_1+\rho_2; \tag{1.1}$$

$$\rho\frac{d\mathbf{U}}{dt}=-\frac{1}{\gamma M^2}\nabla P+\frac{1}{\mathrm{Re}}\left[\Delta\mathbf{U}+\frac{1}{3}\nabla(\operatorname{div}\mathbf{U})\right]+\rho\mathbf{g}; \tag{1.2}$$

$$(\rho_1+\gamma_1\rho_2)\frac{dT}{dt}=-(\gamma-1)P\operatorname{div}\mathbf{U}+\frac{\gamma}{\mathrm{Re\,Pr}}\Delta T; \tag{1.3}$$

$$\frac{\partial\rho c}{\partial t}+\operatorname{div}(\rho c\mathbf{U})=\frac{1}{\mathrm{Re\,Sc}}\Delta c,\quad c=\rho_2/\rho, \tag{1.4}$$

$$\mathbf{U}=(u,v),\quad \mathbf{g}=(0,-1),\quad \frac{d}{dt}=\frac{\partial}{\partial t}+(\mathbf{U}\nabla),\quad \Delta=\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}.$$

Here, the subscript 1 pertains to the gas, subscript 2 pertains to the impurity, $\gamma_1=c_2/c_v$ is the ratio of the specific heat values of the phases, while the other symbols involve the commonly used notation (see [9]). The turbulent character of the flow is accounted for by introducing the constant effective coefficients of dynamic viscosity and thermal conductivity, the choice of which is substantiated below. The heat transfer equation (1.3) indicates that the volumetric specific heat of the entire mixture increases due to the presence of particles in comparison with that of a pure gas (the term $\gamma_1\rho_2$ is added).

The initial and the boundary conditions are assigned as follows:

$$\begin{gathered} t=0\colon \mathbf{U}=0,\ T=T_a+\theta_0\exp[-(r^2+(z-H)^2)/R^2],\\ P=P_a,\ \rho_2=M_{21}\exp[-(r^2+(z-H)^2)/R^2],\ \rho_1=P/T,\ \rho=\rho_1+\rho_2; \end{gathered} \tag{1.5}$$

$$r=0\colon u=0,\ \partial\varphi/\partial r=0,\ \varphi=\{v,P,T,c\}; \tag{1.6}$$

$$z=0\colon \mathbf{U}=0,\ \partial T/\partial z=0,\ \partial c/\partial z=0; \tag{1.7}$$

$$r^2+z^2\to\infty\colon \mathbf{U}=0,\ T=T_a,\ P=P_a,\ c=0, \tag{1.8}$$

and R and H are the initial values of the radius and the height of the thermal; the quantity M_{21} characterizes the degree to which the cloud is filled with the impurity; as in [9], the following relationships are used for the parameters of the unperturbed atmosphere:

$$\frac{1}{T_a}\left(\frac{dT_a}{dz}+(\gamma-1)M^2\right)=k,\quad \frac{dP_a}{dz}=-\gamma M^2\rho_a\quad(\rho_a=P_a/T_a),$$

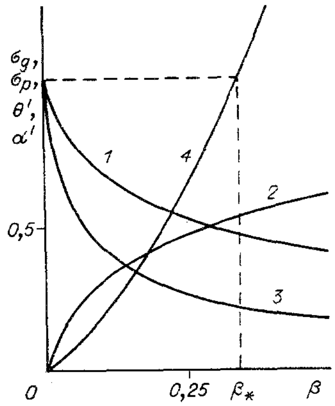

Fig. 1

which correspond to the international standard atmosphere (ρ_a is the atmospheric density, $k = N^2L/g$ is the stratification parameter, and $N^2 = \text{const} = 1.2 \cdot 10^{-4}$ sec^{-2} up to altitudes of 10-16 km).

The system of equations (1.1)-(1.8) was solved numerically by using the implicit three-layer scheme of coordinate splitting [6], which constitutes a modification of the method used in [11] and is characterized by superior conservative properties. Nonuniform, adjustable 40 × 50 grids were used, while the Courant number increased from 0.25-0.5 at the start of rise to 3.5-4 at the late stages of evolution of the thermal. All the results given below are obtained for $\gamma = 1.4$, $M = 0.3$, and $k = 1.22 \cdot 10^{-2}$, which correspond to the actual parameters of an unperturbed atmosphere for $L = 10^3$ m, $T_0 = 273$ K, and $P_0 = 1$ atm.

2. The initial conditions (1.5), along with the altitude of the cloud's center H, comprise the parameters R, θ_0, and M_{21}, which determine the initial state of the cloud. From results, we most often know only the integral characteristics of a thermal — the total heat energy Q_0 expended on its formation (which amounts to a certain percentage of the total explosion energy Q_Σ: $Q_0 = aQ_\Sigma$, $a \approx 1$ for powder charges, and $a \approx 0.35$ for nuclear explosions [1, 3, 5]) and the approximate total mass of the impurity M_Σ contained within the cloud volume, as well as the overheating ΔT_* at the center of the thermal. Therefore, it is advisable to use the dimensionless parameters $I_0 = Q_0/2\pi\rho_{10}c_p T_0 L^3$, $m = M_\Sigma/\rho_{10}L^3$, and $\theta_* = \Delta T_*/T_0$, that correspond to the characteristics as the determining parameters and express the R, θ_0, and M_{21} quantities in terms of the former in the following manner.

The radius of a pure-gas thermal with the stored heat I_0 can be found with respect to the initial temperature field (1.5) and the overheat (determined from experiments), assuming that $\theta_0 = \theta_*$ and solving numerically the following equation with respect to R:

$$I_0 = \int_0^\infty \int_0^\infty \rho_1 \theta r \, dr \, dz = \int_0^\infty \int_0^\infty \frac{P_a \theta}{T_a + \theta} r \, d r dz, \quad (2.1)$$

where $\theta = T - T_a = \theta_* \exp[-(r^2 + (z-H)^2)/R^2]$ is the overheat of the medium in the thermal. This approach was used in [6, 7], while the dimensions of the thermal obtained for different I_0 values corresponded fairly closely to the empirical relationships.

The presence of a dispersed impurity in a thermal causes a part of the heat to be expended on the heating of particles, and the energy I_0 is distributed between the gas and the impurity:

$$I_0 = I_g + I_p,$$
$$I_g = \int_0^\infty \int_0^\infty \rho_1 \theta r \, dr \, dz, \quad I_p = \frac{\gamma_1}{\gamma} \int_0^\infty \int_0^\infty \rho_2 \theta r \, dr \, dz. \quad (2.2)$$

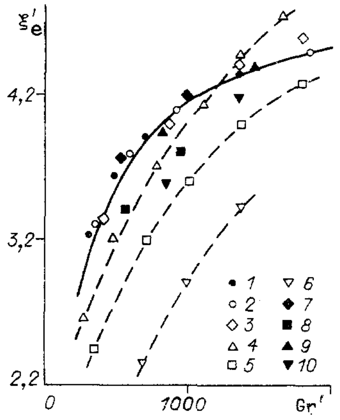

Fig. 2

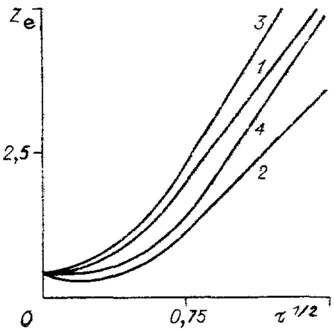

Fig. 3

Naturally, the dimensions and the temperature of a dusty thermal will differ from these values in a pure-gas cloud with the energy I_0. In order to determine these values, it is generally necessary to consider in detail the process whereby a dusty thermal is formed, which constitutes a complex problem. We assume here that the radii of a dusty and a pure-gas cloud are approximately equal, but the temperature of the thermal is reduced from θ_* to θ_0 due to the presence of the impurity. Therefore, the value of R is calculated, as before, by means of relationship (2.1) with respect to the stored heat I_0 and the characteristic overheat θ_* (the presence of the impurity is neglected). Using (1.5), we determine the parameter M_{21} with respect to the assigned total amount of the impurity m, and then, having solved numerically the integral equation (2.2), we determine the initial overheat θ_0. This procedure can readily be modified when the initial energy I_0 and the radius of the dusty thermal are known from experiments, but the overheat value θ_* is not known.

The calculation results pertaining to the initial state of the thermal can be conveniently interpreted by means of two additional parameters that characterize the heat balance in the thermal and the forces acting on it.

The capacity of the impurity to store a part of the heat released is described by the parameter $\beta = c_2 M_\Sigma T_0/Q_0 = \gamma_1 m/2\pi\gamma I_0$, which is the ratio of the heat absorbed by the total amount of impurity as its temperature increases by T_0 to the total heat energy of the thermal Q_0. Introduction of the parameter β makes it possible to describe uniquely the heat distribution between the phases. Figure 1 illustrates the calculation of the initial state of a thermal in a wide range of parameters, $0 \leqslant m \leqslant 10$; $0 \leqslant \gamma_1 \leqslant 10$; $0{,}1 \leqslant I_0 \leqslant 2{,}7$, for H = 1.56 and $\theta_* = 21$ (at T_0 = 273 K, this value corresponds to the experimentally determined temperature in the thermal [1]) in the form of the percentages of energy stored by the gas $\sigma_g = I_g/I_0$ and by particles $\sigma_p = I_p/I_0$ as functions of β (curves 1 and 2). This figure also provides the ratio of the temperature of a dusty thermal to the temperature of a pure-gas thermal $\theta' = \theta_0/\theta_*$ (curve 3).

Let us now consider the forces acting on the gas and on the impurity. We distinguish between the total weight of particles F_- and the boundary F_+, which is equal to the difference between the Archimedes' force and the gas weight. In terms of dimensionless variables, F_- = m, and

$$F_+ = \int (\rho_a - \rho_1)\, dV = \int \frac{P_a}{T_a}\left(1 - \frac{T_a}{T}\right) dV = \int \frac{1}{T_a} \rho_1 (T - T_a)\, dV. \quad (2.3)$$

If the initial height of the thermal is not excessive, we assume that $T_a \approx 1$ (for the largest height value used in the calculations, H = 6, the error entailed by this approximation did not exceed 15%), and we find $F_+ = 2\pi I_g = 2\pi I_0 \sigma_g(\beta)$.

The gravimetric action of the impurity is characterized by the parameter α, which is equal to the ratio of the weight of particles to the buoyancy:

$$\alpha = F_-/F_+ = m/2\pi I_g = m/2\pi I_0 \sigma_g.$$

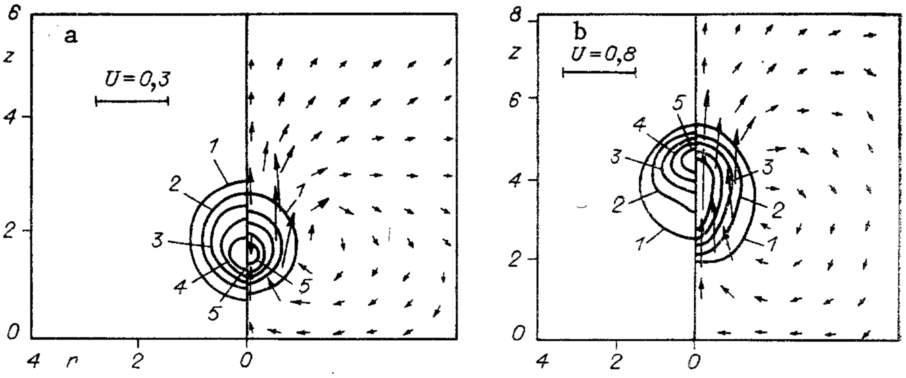

Fig. 4

The relationship between α and β is given by $\alpha\gamma_1 = \gamma\beta/\sigma_g(\beta)$. Figure 1 shows the dependences of the function $\alpha' = \alpha\gamma_1$ on the parameter β (curve 4). An increase in the impurity fill factor of the cloud (an increase in β) causes a reduction of the buoyancy F_+ due to the smaller amount of heat stored by the gas and the simultaneous increase in the weight of particles. For a sufficiently large fill factor, the forces F_+ and F_- are equalized, which corresponds to zero initial buoyancy and the critical value $\alpha_* = 1$. The critical value of the parameter $\beta = \beta_*$ is determined by solving the equation $\gamma_1 = \gamma\beta_*/\sigma_g(\beta_*)$. Thus, for $\gamma_1 = 1$, we have $\beta_* \approx 0.34$. It should be noted that, if the particles did not affect the force F_+ as a result of removal of some of the heat from the gas, the critical value β_* would be equal to $\beta_* = \gamma^{-1} = 0{,}71$. Consequently, the thermal action of the impurity reduces the critical fill factor by roughly one-half.

3. As was mentioned above, a relationship has been established in [6, 7] which makes it possible to describe uniquely the self-similar coordinate of the upper edge ξ_e of a gas thermal rising in an atmosphere which has variable density and transports a passive impurity. It has the form $\xi_e(H', \mathrm{Gr}) = F(H')G(\mathrm{Gr})$, where $\xi_e = (dz_e/dt^{1/2})I_0^{-1/4}$, and $\mathrm{Gr} = \mathrm{Re}^2 I_0$, while the functions F and G assign the dependence of ξ_e on the dimensionless initial height and the Grashof number. It would be of interest to compare this relationship with the velocity of self-similar motion of a dusty thermal.

If the aerosol impurity in a dusty thermal does not affect the gas motion and the cloud rise (passive impurity), the above relationship between ξ_e and Gr holds. The dimensionless variables ξ_e and Gr should be determined with respect to the amount of the heat energy stored only by the gas

$$\xi_e'(H', \mathrm{Gr}') = F(H')\,G(\mathrm{Gr}'); \tag{3.1}$$

$$\xi_e' = (dz_e/dt^{1/2})\,I_g^{-1/4}, \quad \mathrm{Gr}' = \mathrm{Re}^2 I_g. \tag{3.2}$$

Comparing the coordinate of the upper edge for a thermal transporting an active impurity (see (1.1)-(1.8)) with the value of ξ_e' calculated by means of (3.1), we can form an idea of the interaction between the gaseous and the dispersed phases during the rise. Figure 2 shows the results of calculations of the motion of a dusty thermal in the form of a $\xi_e'(\mathrm{Gr}')$ relationship. The thermal is initially located at the altitude H = 1.56 (the value of H' appearing in (3.1) is equal to $H' = \gamma M^2 H = 0{,}2$): The ratio of the specific heat values of the phase was assumed to be $\gamma_1 = 1$, since the specific heat of many solid substances (dust, soot, or sand) is close to the specific heat of air under normal conditions. Moreover, it was assumed that Pr = Sc = 1. The solid curve in Fig. 2 corresponds to the rise of a gas thermal (see [6, 7]) and is described by relationship (3.1). The points 1-6 were obtained for a dusty thermal with the energy $I_0 = 0.68$ for α = 0.1; 0.2; 0.3; 0.5; 0.7; 0.95, respectively. In the case of a low impurity fill factor of the cloud, when the value of α does not exceed $\alpha_0 \approx 0.4$, the self-similar coordinates of the upper edges of a dusty and a gas thermal coincide with a high degree of accuracy in the $250 \leqslant \mathrm{Gr}' \leqslant 2000$ range: The points 1-3 lie on the solid curve. A further increase in the amount of impurity ($\alpha > \alpha_c$) causes the cloud ascent to slow down due to the increase in the impurity weight (points

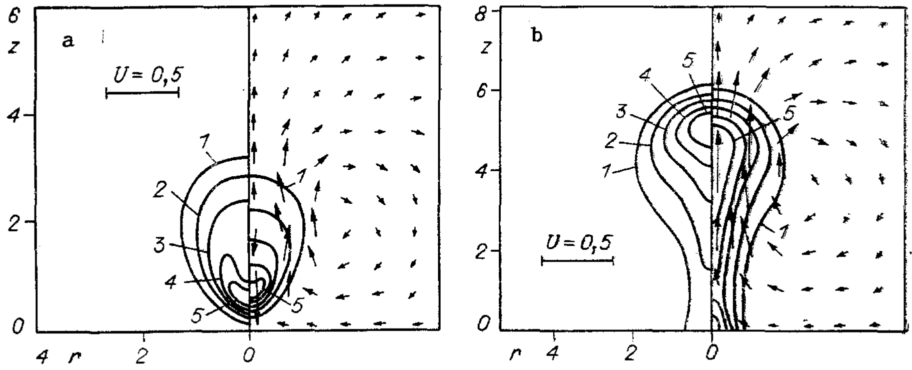

Fig. 5

4-6). Similar results are obtained for fill factors $\alpha = 0.2$ and 0.5 and other values of the initially stored heat I_0: Points 7 and 8 correspond to $I_0 = 0.34$, while points 9 and 10 correspond to $I_0 = 2.7$.

Let us now investigate in detail the mechanism whereby an impurity affects the gas motion during the rise of a dusty thermal. We shall use $\xi_e'(Gr')$ as the basic relationship for a cloud with $I_0 = 0.68$, $\gamma_1 = 1$, $H' = 0.2$, and $\alpha = 0.5$ (in this, $\beta = 0.2$, $\sigma_g = 0.57$, and $I_g = 0.39$ — see points 4 in Fig. 2) and compare it with similar relationships, derived for different variations of the parameters determining the interaction between phases. In the basic variant, the fill factor of the thermal is close to α_0, and deviations from (3.1) only begin to manifest themselves. For small values of Gr', the thermal rises more slowly than a pure-gas thermal, while it rises faster for large values of Gr' (compare in Fig. 2 the solid curve with the dashed curve passing through points 4).

The results of calculations of the motion of gas and dusty thermals are given in Fig. 3 for the basic variant at Gr' = 1650 with subsequent allowances for the gravimetric and thermic interaction between phases. The coordinates $\tau^{1/2} = (t/t_s)^{1/2}$ and $Z_e = (z_e - H)/I_g^{1/4}t_s^{1/2}$ ($t_s = k^{-1/2}$ is the characteristic rise time of the thermal), which do not depend on the linear scale, are used. The dynamics of the rise of a pure-gas thermal with the energy I_g containing a passive impurity (it is assumed that $\rho_2 = 0$ in the equations of motion and transport) is represented by curve 1. The slope of the rectilinear segment of the curve is equal to the self-similar coordinate ξ_e', amounting to 4.45 in this case.

In order to take into account only the gravimetric effect of an active impurity, we consider a cloud whose initial parameters correspond to the basic variant, but in calculating its evolution, we consider that the specific heat of particles is equal to zero ($\gamma_1 = 0$ in (1.3)). It can be said that the dispersed phase is passive in the sense of heat transfer, but active with regard to its gravimetric action. The dynamics of the rise of such a thermal is represented in Fig. 3 by curve 2; $\xi_e' = 3.40$.

Curve 3 was obtained by calculations based on the parameters of the basic variant, involving, however, a small initial amount of the impurity ($\alpha = 3.3 \cdot 10^{-2}$) and a large specific heat of particles ($\gamma_1 = 15$). The gravimetric effect of the impurity is insignificant, but the initial, effective specific heat of the medium remains unchanged due to the special choice of the γ_1 value that ensures the same value of the parameter $\beta \sim \gamma_1\alpha$, as that in the basic variant. Thus, the impurity is active with regard to its thermal effect, but it does not exert gravimetric action: For curve 3, $\xi_e' = 5.10$.

Finally, the results of calculations of the basic variants, where particles exert both gravimetric and thermal action, are described by curve 4 for $\xi_e' = 4.75$ (the top point 4 in Fig. 2).

By comparing curves 1-4 in Fig. 3, we can draw conclusions concerning the relative contribution of various mechanisms of interaction between phases that determine the trends in the rise of a thermal. At the initial stage of motion, the impurity is concentrated at the cloud center; its concentration is high, which delays the stage of acceleration of a dusty thermal (curves 2 and 4) in comparison with a pure-gas thermal (1). At the self-similar stage, the impurity not engaged in heat exchange with the gas retards considerably the rise (2), while faster ascending flow (3) occurs in the presence of particles that store heat but do not possess weight. These factors influence the rise of a thermal in opposite ways: On the one hand, the impurity increases the weight of the cloud and slows down its motion, and, on the other, as it transfers heat to the gas, it hinders its cooling and promotes its rise. The velocity of a dusty thermal depends on these factors. In the case of a small fill factor ($\alpha < \alpha_0$), they are mutually compensated, which explains the fact that points 1-3 coincide with the solid curve in Fig. 2. With an increase in the fill factor ($\alpha > \alpha_0$), the heat action of the impurity is no longer sufficient to compensate for its gravimetric effect, and the cloud slows down (points 5 and 6 in Fig. 2). In the transitional region ($\alpha \sim \alpha_0$; see points 4 in Fig. 2), the predominance of the gravimetric or the heat mechanism of action depends on the convection intensity, which is characterized by the Grashof number. If, for $Gr' = 1650$, the ascent velocity of a dusty thermal along the self-similar segment is higher than that of a pure-gas thermal (compare the slopes of curves 1 and 4 in Fig. 3), then, a reverse pattern is observed: The mechanisms of interaction between phases, $\xi_e' = 3.55$, 2.20, 4.05, 3.20, "kick in" successively in the above case. This means that the effects connected with heat transfer from the impurity to the carrier gas at the self-similar stage of rise of the thermal are more strongly pronounced with an increase in Gr'.

4. The coefficients of turbulent transport introduced in (1.2)-(1.4) are determined not only by the characteristics of the medium (as in the laminar case), but also by the character of the flow and, therefore, additional data must be used for determining the values of these characteristics. As was shown in [3]-[5], the coefficients can be found by matching the theoretical law of ascent of the upper edge with the experimental relationships in the case of a pure-gas thermal. The difficulty in extending this approach to the case of a dusty thermal is due to a lack of necessary experimental data on the effect of the impurity on the motion dynamics.

For the results given in paragraph 3, it is clear that, for fill factors that are not excessive, the ascent dynamics of a dusty thermal in a nonuniform, compressible medium is described by relationship (3.1), obtined earlier for pure-gas thermals. It would seem natural to use (3.1) also for determining the turbulent transport coefficient for a thermal containing particles. Thus, the energy stored in the gas is to be determined with respect to the known total heat energy of the cloud I_0, the mass of the impurity contained in the cloud, and the specific heat of the impurity. If we know the initial height H of the cloud center, we can find the value of Gr' corresponding to ξ_e', using the functions F and G from [6, 7] that appear in (3.1). We borrowed the experimental value $\xi_e' = \zeta_* \approx 4.35$ given in [3, 5]. If more complete experimental data are available, the procedure of determining the transport coefficient can be refined by comparing the experimental value of ξ_e' with the relationships in Fig. 2; the values of Pr and Sc are assumed to be equal to unity, which is justified for a well-developed turbulent flow.

5. The ascent of a dusty thermal for $\alpha < \alpha_0$ is similar to that investigated in [6, 7] for a thermal cloud carrying a passive impurity. At the initial stage, a toroidal vortex flow is formed, and the thermal assumes the characteristic mushroom shape. A multivortex configuration developes at the hovering stage, and the thermal performs oscillations, which are damped in time, about the stabilization level.

For $\alpha_0 < \alpha < \alpha_*$, the presence of an active impurity produces certain peculiarities in the thermal ascent process. Thus, for $\alpha = 0.56$ ($I_0 = 0.68$, $H = 1.56$, $\gamma_1 = 1$), the concentration of particles at the center of the thermal is rather high at the initial stage, the heavy core hinders the gas rise, and there is virtually no convection in this region. A toroidal, vortex flow is formed at the periphery of the thermal, where there are few particles, so that the heated gas rises. The three-dimensional distributions of excess for $t = 1.6$ (the isotherms $\theta = \text{const}$ are on the left, and the velocity field and the $\rho_2 = \text{const}$ lines are on the right); here and elsewhere, the isolines 1-5 are plotted at intervals of 1/6 of the maximum value, $\theta_m = 2.2$ and $\rho_{2m} = 0.73$ (1/6, 2/6, etc., respectively). In time, convection and diffusion transport reduce the impurity concentration at the core, the ascending gas flow involves the entire axial region, and the subsequent evolution of the vortex structure is similar to that of a gas cloud. At the rise stage (Fig. 4b: $t = 6.7$, $\theta_m = 0.8$, $\rho_{2m} = 0.16$), the form of the isolines differs for some time from that obtained in [6, 8] for a non-dusty thermal: The isolines are more stretched in the vertical direction. These differences are then smoothed out, and the concentration of particles is so low at the hovering stage that it does not exert an appreciable effect on the process.

The effect of the impurity becomes even greater for a cloud fill factor close to its critical value. The structure of the thermal for $\alpha = 0.95$ ($I_0 = 0.68$, $H = 1.56$, $\gamma_1 = 1$) is shown in Fig. 5a ($t = 3.9$, $\theta_m = 1$, and $\rho_{2m} = 0.68$). In this case, the weight of particles in the cloud core is so great that the central part of the thermal descends to the surface. The ascending flow in the case of such fill factor cannot prevent the descending motion of the impurity and its accumulation at the surface. After the settling process has ended, the toroidal, vortex motion gradually draws upward particles from the surface zone and carries the impurity to higher altitudes (Fig. 5b: $t = 12.8$, $\theta_m = 0.26$, $\rho_{2m} = 0.1$). It should be mentioned that the results obtained for $\alpha \sim \alpha_*$ are qualitative in character, since the interaction between the impurity and the surface during precipitation (for instance, nonelastic impact of particles on a flat surface) must be considered on the basis of the more complete two-velocity model of the medium (as was done, for instance, in [12]). Moreover, if the opposing forces acting on the medium are balanced, and convection occurs more slowly, the single-velocity model can be used only for very fine particles (since the condition of its applicability stipulates low terminal velocity of a single particle in comparison with the convective velocity of the gas).

Thus, in the case of a low impurity fill factor in the thermal ($\alpha < \alpha_0$), the rise of a dusty cloud occurs in the same way as that of a thermal which has the stored heat $I_g < I_0$ and transports a passive impurity. In other words, the passive impurity approximation holds if the total impurity weight does not exceed 40% of the buoyancy force acting on the gas. During the rise of a dusty thermal with a large fill factor, the characteristics that manifest themselves are related to the weight of particles (cloud deformation, stretching of the initial stage, and precipitation of impurity particles on the ground surface and their thermic characteristics (changes in the effective specific heat of the medium and slower cooling of the thermal).

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