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PHYSICAL MODELING OF TURBULENT THERMICS

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In order to investigate atmospheric convection processes and the development of safe methods of exploiting and storing explodable and toxic mixtures, and a number of ecological problems, it is necessary to study nonstationary convective flows that occur when a mass of light gas rises in a field of gravitational forces (thermics). Large-scale turbulent flows are of greatest interest from the practical viewpoint since the general complexity of studying them is due to the restricted possibility of obtaining direct experimental data. In this connection, a study of the modeling laws for turbulent thermics acquires special value.

At a certain time, let there be a free volume V_0 of gas with density ρ_0 different from the density ρ_a of the environment, in open space. The convective current that occurs is due to the action of the force $F = g(\rho_a - \rho_0)V_0$, the resultant of the Archimedes and gravity forces. For currents in an unstratified medium the quantity F is conserved in time: $F = g\int\limits_{V_\infty}(\rho_a - \rho(t))dV = g(\rho_a - \rho_0)V_0$, which is a result of the law of conservation of the excess quantity

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of heat for a thermic of thermal nature or a mass of light gas for concentration. From the dimensional quantities F (kg·m/sec²), ρ_a (kg/m³), V_0 (m³), σ (m²/sec), {χ, D} (m²/sec), x (m), r (m), t (sec), in the dynamics problem of the rise of a floating cloud (σ and {χ, D} are the kinematic viscosity and thermal diffusivity coefficient, x and r are the vertical and radial coordinates of some characteristic point of the cloud, t is the time), we can write according to the Π-theorem

$$x = \Pi_0^{1/4} t^{1/2} f_1\left(\frac{\sigma}{\Pi_0^{1/2}}, \frac{\{\chi, D\}}{\Pi_0^{1/2}}, \frac{V_0}{\Pi_0^{3/4} t^{3/2}}\right),$$

$$r = \Pi_0^{1/4} t^{1/2} f_2\left(\frac{\sigma}{\Pi_0^{1/2}}, \frac{\{\chi, D\}}{\Pi_0^{1/2}}, \frac{V_0}{\Pi_0^{3/4} t^{3/2}}\right), \quad \Pi_0 = \frac{F}{2\pi\rho_a}.$$

A certain time after the beginning of the motion, the thermic becomes much greater than its initial size beause of interaction with the surrounding medium, hence the parameter $V_0/(\Pi_0^{3/4} t^{3/2})$ can be omitted from consideration. Then for laminar convective rise of a gas with a density different from the surround medium and for sufficiently large times after the beginning of the motion

$$x = \Pi_0^{1/4} t^{1/2} f_1\left(\frac{\sigma}{\Pi_0^{1/2}}, \frac{\{\chi, D\}}{\Pi_0^{1/2}}\right),$$

$$r = \Pi_0^{1/4} t^{1/2} f_2\left(\frac{\sigma}{\Pi_0^{1/2}}, \frac{\{\chi, D\}}{\Pi_0^{1/2}}\right). \tag{1}$$

If the cloud rises in a turbulent regime, then the turbulent analogs should be used in place of the laminar transfer coefficients σ, χ, D since they are already independent of the physical properties of the medium and are governed by the current itself [2]: $E = \nu\Pi_0^{1/2}$, $E_T = Pr_T \nu \Pi_0^{1/2}$, $E_D = Sc_T \nu \Pi_0^{1/2}$. Then for turbulent thermics

$$x = a\Pi_0^{1/4} t^{1/2}, \quad r = b\Pi_0^{1/4} t^{1/2} \tag{2}$$

(the quantities a and b depend on the constants ν, Pr_T, Sc_T).

There results from (1) and (2) that the dimensionless rate of rise of the thermic $dx/dt/(\Pi_0^{1/4} t^{-1/2})$ is identical for different current scales in the turbulent regime and it depends on Π_0 in the laminar regime. The relationships presented describe the laws for the rise of a self-similar thermic that has infinitesimal size and is located at the point (x = 0, r = 0) for t = 0.

Two series of experiments were conducted. In the first series, the thermic was simulated by the combustion products of black powder. The powder charge was placed in a gauze sack on a thin rod and ignited. The rise of the quite visible cloud of heated combustion products was determined by using moving pictures. Under laboratory conditions the experiments were performed with 5, 10, and 20 g charges and ignition was by a heated spiral; under field conditions the charges were 3, 5, and 27 kg while ignition was by a system of deflagrators located symmetrically on the wire skeleton along the circumference of the charge.

The reserve buoyancy of the cloud of black powder combustion products n (kg) (under the assumption that all the energy of the powder charge goes over into heat) is $\Pi_0 = nQ_0 g\beta/(2\pi\rho_a c_p) \approx 12.2n$ (m⁴/sec²) (Q_0 = 2800 kJ/kg, β ≈ 1/300°K, g = 9.81 m/sec², ρ_a = 1.23 kg/m³, c_p = 1006 J/kg·deg).

A working graph was constructed in processing the experiments, a dependence of the coordinates of the upper edges of the cloud x_k on $t^{1/2}$. Extrapolation of the linear law (the self-similar stage of the rise) obtained at a certain time to t = 0 yields the location of the virtual source x_0. Finally, the dependence of $(x_k + x_0)/\Pi_0^{1/4}$ on $t^{1/2}$ was constructed. Data for the 3, 5, and 27 kg charges (points 1-3) are presented in Fig. 1. It is seen that the dynamics of the rise of thermics in these experiments is described by the relationship

$$x_e + x_0 \approx 4.35\,\Pi_0^{1/4} t^{1/2}, \tag{3}$$

which corresponds to (2) for a ≈ 4.35. The angle of cloud expansion because of the influence of the wind was determined successfully only in the a/b = 0.18-0.21 range.

Data on the dynamics of the rise of the upper edges of clouds from 20 kT and 1 MT intensity nuclear explosions [3, 4] (points 1 and 2) are represented in Fig. 2 and are described by the same dependence (3) ($\Pi_0 \approx 6.43 \cdot 10^6$W, m⁴/sec², where W is the total energy of the nuclear explosion in kilotons of a trotyl equivalent). Therefore, the relation (3) describes

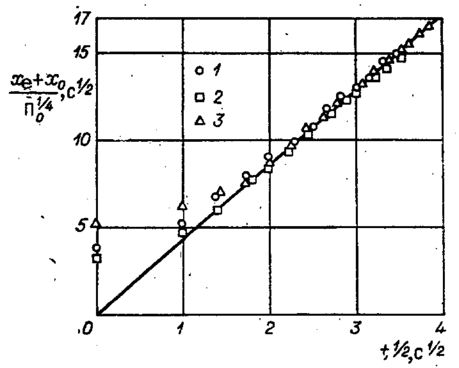

Fig. 1

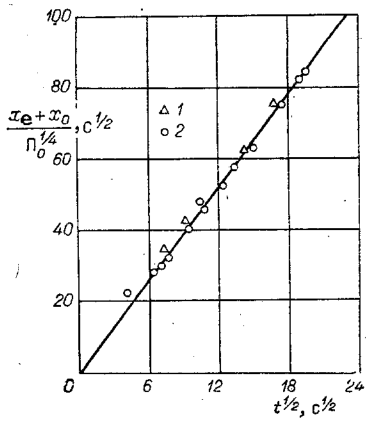

Fig. 2

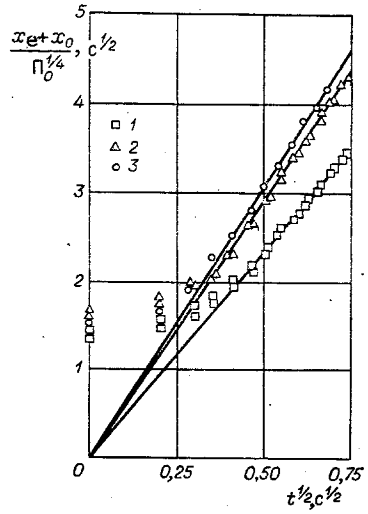

Fig. 3

the dynamics of the self-similar rise of a floating cloud in a developed turbulent flow regime.

The values of the quantity a were lower in the experiments with small batches of powder and had a substantial spread (a = 3.5-4.2) without visible regularity. This can be explained by the fact that the clouds being formed because of the combustion of a moderate batch of powder are substantially nonsymmetric. The effective value of the cloud buoyancy that governs the dynamics of the rise of its upper edges is only a part of the total reserve buoyancy in this case. Exaggeration of the quantity Π_0 in processing the experiment results in diminution of a. There was apparently an analogous situation in the tests in [6] where a = 3.8 is obtained on the average, and the data can also have a significant spread (the thermic was simulated by decanting portions of the heavy fluid into light).

The dynamics of motion of a thermic of concentration nature was studied in the second series of experiments. A soap bubble containing a light gas (helium or hydrogen at room temperature) was punched by a thin needle. Visualization of the convective current occurring here was by using the IAB-451 shadow device. The bubble dimensions varied between R_0 = 1-4 cm cm limits.

The data obtained on the dynamics of the rise of the upper edges of the thermics formed after puncturing of the differently sized soap bubbles with helium (R_0 = 14, 16, 17 mm; points 1-3) are presented in Fig. 3. It is seen that the self-similar rise mode holds with $x_k \sim t^{1/2}$ but the slope of the linear dependence for each initial bubble size is its own; therefore, the relationships (2) are not satisfied.

On the basis of a numerical simulation of thermics it is shown in [5] that for the laminar flow regime the function f_1 from (1) depends as follows on the parameters

$$f_1 \sim \left(\frac{\sigma\{\chi, D\}}{\Pi_0}\right)^{-1/4} = \mathrm{Ra}^{1/4} \tag{4}$$

($\mathrm{Ra} = \Pi_0/(\sigma\{\chi, D\}) = \Pi_0\{\mathrm{Pr}, \mathrm{Sc}\}/\sigma^2$ is the Rayleigh number).

The processed results of tests with soap bubbles are represented in Fig. 4. The values of the function $f_1 = (x_e + x_0)/(\Pi_0^{1/4}t^{1/2})$ were found for each experiment by means of the self-similar section of the rise of the thermic. The points 1 are He($\Delta\rho_0/\rho_a$ = 0.862, Sc = 1.7, σ = $1.06\cdot10^{-4}$ m²/sec), 2 are H_2($\Delta\rho_0/\rho_a$ = 0.93, Sc = 1.47, σ = $9.4\cdot10^{-5}$ m²/sec), and the solid line corresponds to (4).

Existing experimental results on the dependence of the self-similar coordinates of the upper edges of floating clouds on the Rayleigh number, for which the necessary parameters are known, are presented in Fig. 5. The left part of the graph corresponds to Fig. 4, where 1 are experiments with 5, 10, 20 g and 3, 5, 27 kg batches of powder (Pr = 0.72, σ = $1.33\cdot10^{-5}$ m²/sec); 2 are the averaged data of [6] (Sc = 10^5, σ = $1.05\cdot10^{-4}$ m²/sec, $\Pi_0 \approx 2.2\cdot10^{-4}$ m⁴/sec²), 3 are experiments with soap bubbles [7] ($R_0 \approx 4.75\cdot10^{-2}$ m, Sc = 1.1-1.7, Π_0 = (2-7)·10^{-4} m⁴/sec²), and 4 is the rise of clouds from nuclear explosions of 20 kT and 1 MT [3, 4] (Pr = 0.72, σ = $1.33\cdot10^{-5}$ m²/sec).

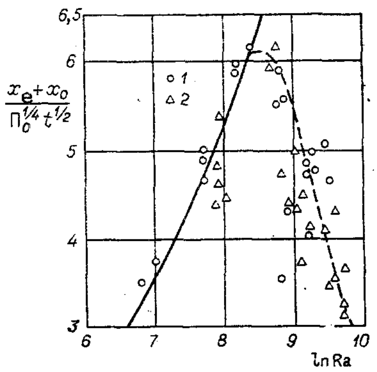

Fig. 4

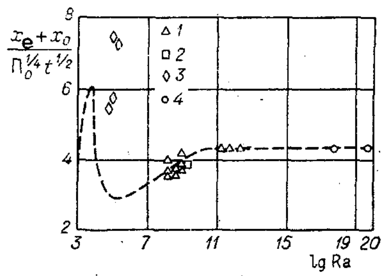

Fig. 5

Analysis of the results obtained permits making the deduction that the free convective motion of a finite volume of fluid or gas with density different from the surrounding medium occurs in the laminar regime for $Ra < 5\cdot10^3$ and in the turbulent regime for $Ra > 10^8$. The rate of cloud rise diminishes in the range $5\cdot10^3 < Ra < 3\cdot10^4$ as the buoyancy reserve Π_0 increases (Ra increases), which is apparently associated with the reconstruction of the flow characteristic for the transition regime. The self-similar section of the cloud rise was not isolated successfully in these experiments for $3\cdot10^4 < Ra < 10^5$ consequently these points are missing here. Poor repeatability of the tests and an abrupt change in the flow structure as the initial parameters change are characteristic for the transition flow regime. This fact is also noted in [7], where three observable flow variants are described. Separation of the points 4 from the regularity obtained can be explained by the special carefulness of the set-up and execution of the tests (sealing of the chamber, automation of the experiment), whereupon the authors succeeded in extending the domain of the laminar flow regime.

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