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ON THE INTERACTION OF MULTIPLE CONTACT THERMICS NEAR AN UNDERLYING SURFACE

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The motion of single thermics (free buoyant objects) occurring in high-altitude and contact explosions has been studied in detail (see [1–7]). Some aspects of the motion of multiple thermics were considered in [8–10]. When several neighboring thermics appear over a short period of time at or near an underlying surface, they interact to produce an inhomogeneous cloud of a buoyant gas. The goal of this paper is to study the dynamics of thermics and the motion of a gas near the underlying surface.

Let at time t_i a number of thermics having volume V_i and density ρ_i appear at points with coordinates x_i at various heights H_i from a surface $F = F(x)$ in a medium with given density ρ_0 in a field with gravity g. Furthermore, some thermics are adjacent to the surface F (contact thermics) at time t_i. It is necessary to determine the motion in the space above the surface F.

A single contact thermic is initially a homogeneous cloud of a buoyant gas of definite shape which is adjacent to the underlying surface. Similar cylindrical and hemispherical clouds have been studied previously [7]. The rise of such thermics is followed by the transformation of the initial cloud to a toroidal vortex ring. A salient feature of these motions is a convergent, radial, surface flow which cuts off the thermic from the underlying surface. In this case, the laws of motion of the leading point of ambient-medium flow are slightly different for cylindrical and hemispherical thermics. For a cylindrical thermic, the law of motion for this point has the form [7]

$$r^0 = R_0^0 \quad \text{for} \quad t^0 < t^0_{\text{ini}}, \qquad R_0^0 - r^0 = \sqrt{2}\left(t^0 - t^0_{\text{ini}}\right) \quad \text{for} \quad t^0 \geqslant t^0_{\text{ini}}, \tag{1}$$

where

$$r^0 = r/h, \qquad R_0^0 = R_0/h, \qquad t^0 = t\,(\xi g/h)^{1/2}; \tag{2}$$

h and R_0 are the height and radius of the cylindrical-thermic base; r is the radius vector of the leading point of the radial flow; t is time; $\xi = (\rho_0 - \rho)/\rho_0$ is the relative thermic density; ρ_0 is the atmospheric density; and ρ is the density of thermic gas.

For a hemispherical thermic, the law of motion of the leading point is also given by formula (1), but

$$r^0 = r/h_{\text{eff}}, \qquad R_0^0 = R_0/h_{\text{eff}}, \qquad t^0 = t\,(\xi g/h_{\text{eff}})^{1/2}. \tag{3}$$

Unlike (2), here instead of the height h for a cylindrical thermic, we use the effective height of a hemispherical thermic h_{eff}, which is assumed to be the height h of a cylindrical thermic that has the same base area and the same volume as the hemispherical thermic. In this case, we have $h_{\text{eff}} = (2/3)R_0$.

Figure 1 compares the measurement and calculation results at $t^0_{\text{ini}} = 0.7$ for a cylindrical thermic and 0.2 for a hemispherical thermic.

For axisymmetric flows (not only a single thermic near the surface but also two or several thermics whose centers are located on the same vertical axis), we can readily determine the time dependence of the

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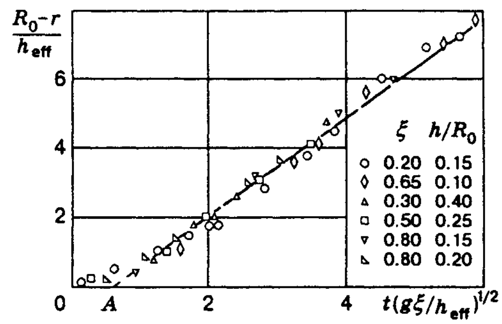

Fig. 1

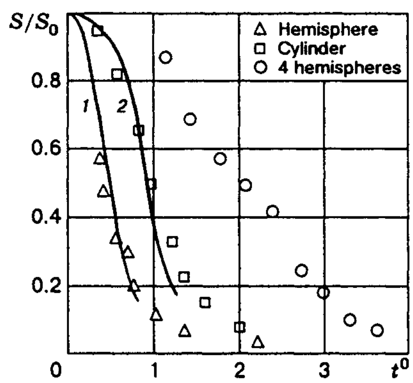

Fig. 2

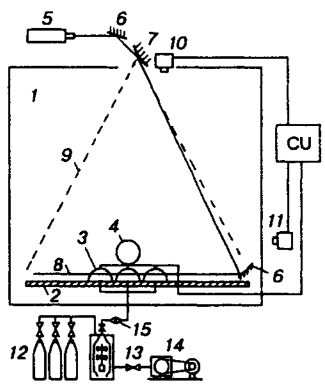

Fig. 3

area $S = S(t)$ covered by a buoyant gas [we call it the gas-laden zone; $S^0(t^0)$ is the relative size of this zone] if we know values of $r = r(t)$. Indeed, according to (1), for cylindrical and hemispherical thermics, we have

$$S^0 = S(t)/S_0 = (1 - \sqrt{2}(t^0 - t^0_{\text{ini}})/R^0_0)^2. \tag{4}$$

Figure 2 shows fair agreement between the results of calculation by formulas (1)–(4) (curve 1 corresponds to a hemispherical thermic and curve 2 corresponds to a cylindrical thermic) and measurement data. In all cases, the flow is axisymmetric and $S(t)$ is a circle.

For multiple thermics that arise simultaneously, the pattern becomes spatial, and the flow structure changes drastically. The rise of four and six thermics was studied experimentally on a setup shown in Fig. 3, where 1 is the working chamber, 2 is the underlying surface, 3 are contact hemispherical thermics, 4 are spherical thermics, 5 is the laser, 6 and 7 are systems of mirrors, 10 is the upper chamber, 11 is the side chamber, 12 are cylinders with oxygen, helium, and nitrogen, 13 is the mixer, 14 is the vacuum pump, 15 is the smoke generator, and CU is the control unit.

In our studies, we photographed vortex flows which were colored by smoke and visualized by a light-system.

The measuring equipment includes cameras and light-systems consisting of light (laser) knives 8 and 9. The light knife is a powerful LG-106M laser beam which is fan spread using cylindrical mirror 7. Photography can be performed simultaneously from above (through the aperture in the cover) and from the side (through the transparent chamber wall). In this case, horizontal 8 and vertical 9 knives are used.

With the progress of motion, the configuration of the volume which contains the initial gas of the thermics changes continuously under the Archimedean force and the interactions of thermics with each other and with the underlying surface. The concentration of this gas also changes as a consequence of mixing with atmospheric air. These changes are taken down by frame recording using cameras 10 and 11. The degree of

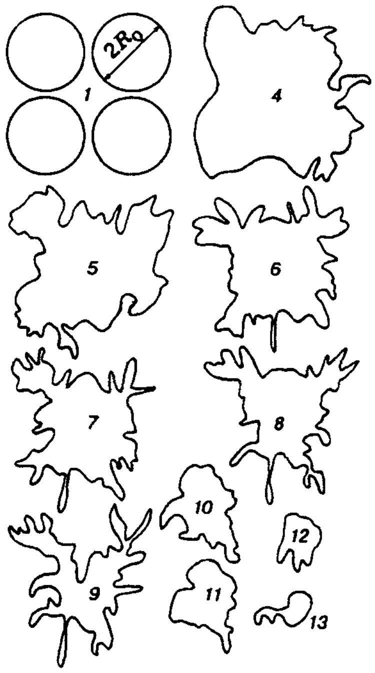

Fig. 4

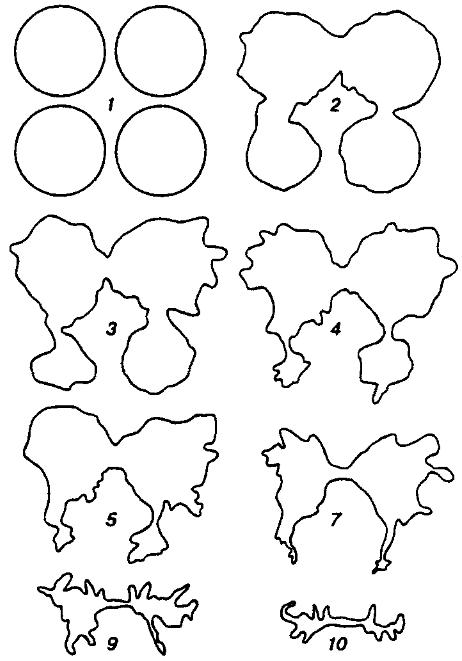

Fig. 5

decrease in the gas-particle brightness in the knife plane gives a measure of decrease in the concentration of the gas that initially fills a thermic (a measure of decrease in gas content of the layer).

Figure 4 shows the evolution of the gas-laden zone during the rise of four hemispherical thermics (each with radius R_0) that occurred simultaneously. The centers of these thermics are located in a plane at the vertices of a square with side $2R_0$. The contours of the gas-laden zone are taken from the records of the rise of the thermics (the numbers in Fig. 4 correspond to the frame number; the shooting frequency was 33 frames/sec).

Under "ideal" conditions (simultaneous initiation and the same size and composition of thermics), all four thermics give rise to a common nonconcentrated vortex. In most experiments, however, the vortex rings that formed in the initial step decompose upon interaction. In this case, the velocity of the cloud rise decreases drastically. The "legs" that are formed under each buoyant thermic move to the center (the tendency to merging is evident) and curl thereby (the formation of four tornados is possible). It is probable that the total circulation of the "legs" remains zero (two vortices rotate in one direction, and the two other rotate in the opposite direction).

We determined the dynamics of "folding" of the regions near the surface which entrap the gas that was initially present in the thermic. The area of these regions $S(t)$ was estimated using records obtained by means of camera 10 located in the upper section of the chamber. The laser knife was moved from the vertical to the horizontal position by a system of mirrors at a height of 2–3 mm from the underlying surface. The knife lased the smoke-colored gas in a thin cross section (the thickness of the knife was 5 mm).

The variation in the gas-laden surface area $S^0(t^0) = S(t)/S_0$ with time for four thermics is shown in Fig. 2, where $S_0 = 4\pi R_0^2$. Evidently, the degassing time of the underlying surface for multiple thermics increases considerably.

Figure 5 shows the variation in the contours of the gas-laden zone with time for the rise of six thermics, of which four are surface thermics (such as those in the previous case) and the two others are spherical thermics whose centers are located at a height of $2R_0$ above two neighboring thermics near the surface (the shooting frequency was 16 frames/sec). The pattern repeats qualitatively all phases of the motion considered above, but it develops much more slowly. It is evident that at any time, the area which contains the gas filling thermics

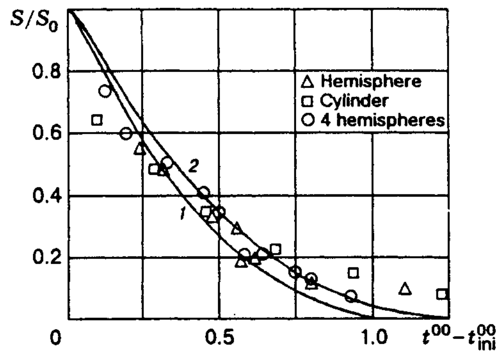

Fig. 6

under paired objects is much larger than that under single thermics. With time this difference only increases.

For all motions considered above, an approximate general law of degassing of the region near the surface can be established from the following considerations. A simultaneous release of all interacting multiple thermics causes a weight deficit, which, in turn, stimulates the rise of gas mass due to the Archimedean force. The gas mass contains not only the gas of thermics but also the volume of the ambient medium. This volume must primarily include the gas that fills the space among the thermics. In this case, because of the constant weight deficit, the mean relative difference in density of the buoyant gas ξ_m must decrease with respect to the initial value of ξ in the thermics in the proportion

$$\xi_m/\xi = V/V_{ent}, \quad (5)$$

where V is the total volume of all thermics and V_{ent} is the volume of the entire buoyant mass. As V_{ent}, we can use a cylinder whose base is a circle with radius R_{ent} which is tangent (inside) to the contours of thermics near the surface at $t = 0$ and whose height h_{ent} is equal to that of the upper point of the group of thermics considered. In this case, we have

$$\tau = (1/(\xi g)(3V_{all}/4\pi)^{1/3})^{1/2}, \qquad t^{00} = t/\tau. \quad (6)$$

Relations (6) are based on the model of motion of a cylindrical thermic with height h for $h < R_0$ [see (1), (2), and (4)]. When $h > R_0$, a more adequate model of the general motion of group thermics is a "density-averaged" hemispherical thermic [Eqs. (3) and (4)]. In this case, the mean radius R_{m1} is given by the relation $R_{m1} = (3V_{all}/(4\pi))^{1/3}$. Thus, we have

$$\tau_1 = (R_{m1}/(\xi_m g))^{1/2}, \qquad t^{00} = t/\tau_1. \quad (7)$$

In the real time scale, the law of degassing has the form

$$S/S_0 = \left(1 - \sqrt{2}(\xi g V)^{1/2}(4\pi/3)^{1/6}(t - t_{ini})/V_{ent}^{2/3}\right)^2. \quad (8)$$

In Fig. 6, the $S^0(t^0)$ dependences shown in Fig. 2 are reconstructed in S^0, t^{00} coordinates. All the curves obtained in various situations (single, paired, and multiple thermics) are grouped along the same curve which is determined by the relations that follow from (5)–(8).

Note that using (8), we can determine the time of separation τ_s of the gas filling the thermic from the underlying surface from the relation $S/S_0 = \left(1 - \sqrt{2}(\tau_s - t_{ini})/\tau\right)^2 = 0$. Hence, $\tau_s = \tau/\sqrt{2} + t^0_{ini}\tau$.

The wall flow which pushes the light gas away from the underlying surface is caused by the difference in hydrostatic pressure between the thermic axis and beyond the thermic. As is shown above, this flow is always directed toward the center.

Example. In an explosion of a gas, $\xi \sim 0.7$–0.8. If the explosion products occupy a region with a height $h = 100$ m, the flow velocity near the underlying surface $v = (2\xi g h)^{1/2} \sim 40$ m/sec, and the time of cloud separation from the surface is $\tau_s \sim 5$ sec.

With this velocity, an air flux that acts continuously for 5 sec can fell trees and their tops will of course be directed toward the center.

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