The authors are indebted to V. N. Shtern for his assistance in the study and valuable remarks.

LITERATURE CITED

1. J. R. Melcher, "Electrohydrodynamics," Magn. Gidrodin., No. 2 (1974).
2. G. A. Ostroumov, Interaction of Electric and Hydrodynamic Fields [in Russian], Nauka, Moscow (1979).
3. F. P. Grosu and M. K. Bologa, "One-dimensional thermohydrodynamic flows of a weakly conducting fluid," Magn. Gidrodin., No. 1 (1974).
4. I. B. Rubashov and Yu. S. Bortnikov, Electrogasdynamics [in Russian], Atomizdat, Moscow (1971).
5. V. V. Gogosov and V. A. Polyanskii, "Electrohydrodynamics: problems and applications, fundamental equations, discontinuous solutions," in: Liquid and Gas Mechanics [in Russian], 10th ed. (1976).
6. I. L. Povkh, Technical Hydrodynamics [in Russian], Mashinostroenie, Leningrad (1976).
7. M. A. Gol'dshtik and V. N. Shtern, Hydrodynamic Stability and Turbulence [in Russian], Nauka, Novosibirsk (1977).

EXPERIMENTAL INVESTIGATION OF THE INTERACTION BETWEEN THERMALS

T. N. Anokhina, B. I. Zaslavskii, and I. M. Sotnikov

UDC 532.517.4

Several results of investigations into the interaction between two thermals which are formed during the ascent of initially spherical volumes of a gas which is lighter than the external medium are presented in this paper. It is known that, during their ascent, such thermals are transformed into circular vortices and, moreover, the light gas passes into their toroidal cores [1-4]. The processes involved in the interaction at various different stages during this transformation have been investigated in the work which is being reported.

1. Let us consider the interaction between two thermals. It is assumed that they are formed as the result of the sudden synchronous or nonsynchronous emergence of two equal free spherical volumes with an effective radius R_0, filled with a gas with a density ρ_1 when the density of the external atmosphere is ρ_0. Let L be the distance between the centers of the volumes, τ be the time interval separating the moments when the first and second thermals emerge, H be the height, h be the height at which the thermals merge or at which they actively interact, g be the acceleration of free fall, and $\xi = (\rho_0 - \rho_1)/\rho_0$ be the relative drop in the density. If the effect of viscosity is neglected and it is assumed that the weight deficit $F = Q\xi g\rho_0$ [2], the distance L, and the time interval τ are the main parameters determining the motion being considered, we obtain from dimensional analysis that

$$h^0 = h^0(L^0, \tau^0),\ T^0 = T^0(L^0, \tau^0),\ \alpha = dR/dH; \tag{1.1}$$

$$h^0 = h/R_0,\ T^0 = T\sqrt{\xi g/R_0},\ L^0 = L/R_0, \tag{1.2}$$
$$H^0 = H/R_0,\ \tau^0 = \tau\sqrt{\xi g/R_0},$$

where T is any characteristic time, between the start of the motion and the moment of merging, for example, α is the aperture angle, and R is the radius of the axial periphery of the core of the vortex.

With such an approach, the dimensionless parameters determining the flow are L^0 and τ^0 or just L^0, when $\tau^0 = 0$. In the latter case $h^0 = h^0(L^0)$, $T^0 = T^0(L^0)$. The explicit dependence of the equations of motion and the boundary conditions for the problem on ξ is eliminated here by substitutions of the variables

$$t^0 = t\sqrt{\xi g/R_0},\ x_i^0 = x_i/R_0,$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 23-27, March-April, 1983. Original article submitted December 24, 1981.

 0021-8944/83/2402-0154$07.50

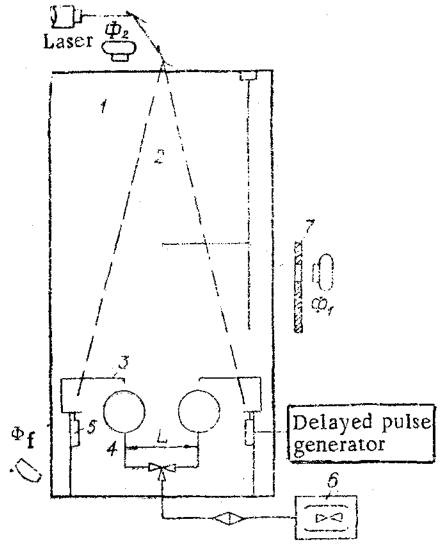

Fig. 1

$$v_i^0 = v_i / \sqrt{\xi R_0 g} \ldots$$

(x_i are the coordinates and v_i are the projections of the velocity vector or other characteristic velocities).

The model under consideration, in spite of the fact that the extent to which it is applicable to real flows has not been established, allows one to relate the results of experiments to the specified system and facilitates their interpretation. On account of this, the experimental data was treated in accordance with Eq. (1.2) and experimental dependences of the type of Eq. (1.1) were constructed using the results of the experiments.

2. The apparatus depicted in Fig. 1 was used for the investigation. The basic components of this apparatus were the chamber 1 with dimensions of 1.2 × 1.2 × 5 m, the optical cutter 2 formed by the laser beam which is spread out like a fan in the vertical plane and passes through the centers of the thermals, the camera Φ_1 and the strobing device 7 which allows one to obtain a kinogram of the motion of sections of the cores of the thermals in the plane of the optical cutter in a single picture, the camera Φ_2 and the photoflash Φf which are controlled by electrical pulses and were intended for the acquisition of a kinogram of the process involved in the interaction between the thermals in horizontal planes, a device for the preparation of the gas mixture 6, and a device 4 for the generation of the two thermals at prescribed moments in time and at a set distance from one another. A more detailed description of the apparatus has been given in [4].

3. The experimental technique consisted of the following operations. A gas mixture of the required density (helium, nitrogen, 2-3% oxygen) was created in the mixer 6 (Fig. 1). This mixture was fed into soap bubbles through a system of flexible tubes and valves. During the feed process the mixture was easily colored with smoke (due to the small amount of oxygen in it). The ascent of the thermal began at the moment when the soap film was ruptured. This rupture was brought about by a needle clamped to the end of the spoke 3 by moving it downwards. The motion began at the moment in time when the initiating pulse was fed to the electromagnet 5 coupled to the spoke carrying the needle. The time interval between this moment and the rupture of the film did not exceed 0.01-0.02 sec. The time interval τ between the initiating pulses was set with the help of a delayed pulse generator.

The horizontal dimensions of a thermal increases as it ascends and this allows one to bring the thermals into active contact at various different heights (various different stages of development) by varying the distance between the centers of the initial volumes (see Fig. 1). Hence, by triggering both thermals simultaneously, we succeeded in investigating their interaction at various different heights during their parallel motion and by introducing a delay τ and changing the initial distance L in investigating the interaction during the formation of the second thermal in the velocity field induced by the first thermal. During the experiments, the facts concerning the coalescence of the thermals or the destruction of the thermals were recorded at various different values of L and τ. The height at which

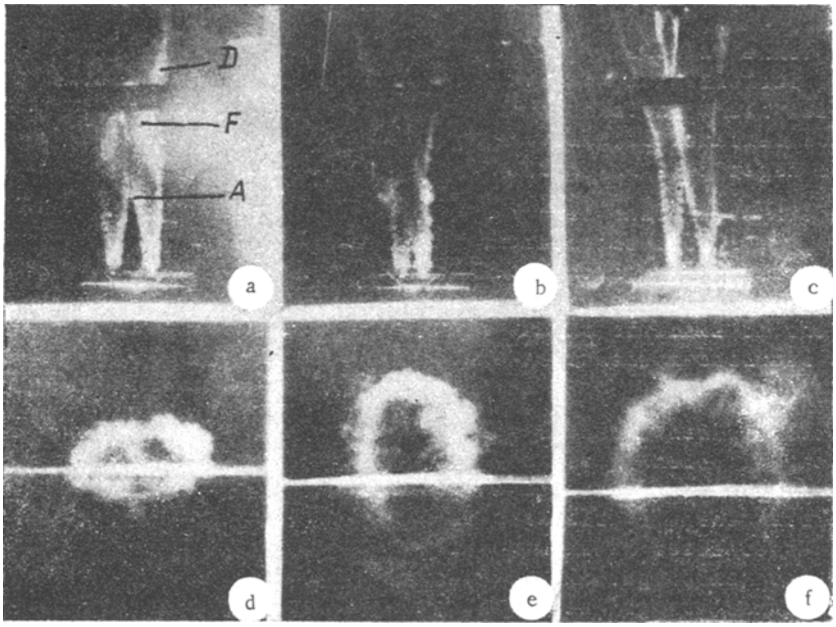

Fig. 2

coalescence occurred h, the time intervals T, and the parameters of the resulting vortex were measured.

4. Photographs taken with the help of the camera Φ_1 (a-c) and the kinetic camera Φ_2 (d-f) are shown in Fig. 2. The first three photographs are kinograms of the processes involved in the interaction between two thermals which were simultaneously generated at different distances L:

$$\text{a} - L \sim 4.4R_0 \text{ (220 mm)}, \ \xi = 0.4;$$
$$\text{b} - L \sim 2.4R_0 \text{ (120 mm)}, \ \xi = 0.195;$$
$$\text{c} - L \sim 3.8R_0 \text{ (190 mm)}, \ \xi = 0.83,$$

Moreover, in the first two cases (a, b), the thermals coalesced with the formation of a single circular vortex while, in the third case (c), they repelled one another and became spent. The configurations of the cores of the thermals (viewed from above) at the moment of coalescence after 0.2 and 0.4 sec are shown in the remaining three photographs (d-f). These pictures were taken from the motion pictures of the interaction process obtained by means of the camera Φ_2 (see Fig. 1) at the same time as the motion picture shown in Fig. 2a. It can be seen from this that, after coalescence in the plane of the optical cutter, there was an undulatory decrease in the visible size of the core (a reduction in R) which had been formed as the result of the coalescence of the thermal. This "compression" upon the coalescence of the thermals took place in all cases. Its nature is revealed with the help of the motion pictures for the movement of the thermals in the horizontal planes. It can be seen from Fig. 2d (the central light band is the track of the optical cutter) that, at the moment of coalescence, the core assumes an ellipsoidal shape with the major axis directed along a line passing through the cores of the thermals. The shape of the core from above during the following stage of the motion, corresponding to the point F on the lateral motion picture (see Fig. 2a), is shown in Fig. 2e. The shape of the core of the thermal at the final stage of its formation (point D in Fig. 2a) is shown on the following picture (see Fig. 2f). On the whole, both of the motion pictures show that, after the coalescence of the cores and simultaneously with the general expansion of the resulting thermal, rapid decay of the vibrational motion of its core took place. In practice, the first half period is well scanned. Moreover, it seems that the initial amplitude of this vibration is close to the limiting amplitude since, in many cases, the vortex rings were destroyed in the process of the vibrational motion.

The picture of the coalescence which has been considered was observed when $L^0 \geqslant 3$–5.5. When $L < 3$, the interaction was of quite a different nature. In this case, the thermals still interacted until each of them had finally been transformed into a circular vortex.

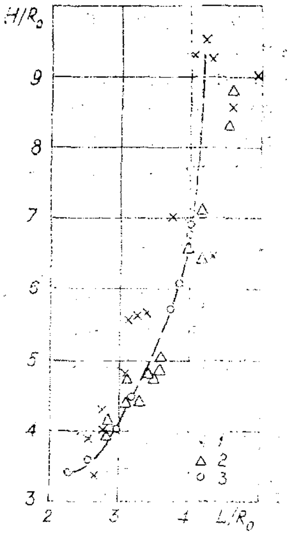

Fig. 3

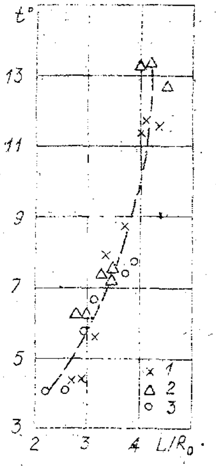

Fig. 4

During the ascent they approached one another and a single circular vortex was rapidly formed at the moment of contact (see Fig. 2b). The large amplitude vibrations of the core which were noted above were not observed in this case.

Modes of interaction similar to those shown in Fig. 2c, where the two thermals repel one another and become spent, are usually observed in the case when the axes of the thermals are not parallel but are at a certain angle to one another at the moment of interaction.

In the treatment of the motion pictures, the height h at which the thermals coalesced and the time intervals T between the moments when they were generated and the moment when they coalesced were measured. In a series of experiments the principal kinematic and geometric parameters of the resulting vortex were measured. The results of measurements of $h^0 = h^0(L^0)$ and $T^0 = T^0(L^0)$ for $\xi = 0.83$, 0.403, and 0.195 are shown in Figs. 3 and 4 (points 1-3, respectively). We were unable to measure the mean value of the ratio $dR/dH = \alpha$ for the resulting thermal sufficiently accurately on account of its vibrations and rapid break up. These values lie between 0.2-0.4 (usually 0.25 ± 0.03).

5. Experiments involving the generation of the thermals at different times were carried out both using the technique described above as well as with the use of the stroboscope of a "Konvas" type cine camera instead of the camera Φ_1. Three frames (the 7th, 10th, and the 14th) from a motion picture filmed with the aid of the "Konvas" motion-picture camera are shown in Fig. 5. The exposure rate was 25 frames/sec. As in the first case, cross sections of the toroidal cores of the thermals, visualized by means of the optical cutter, were also photographed. The moments of the approach and coalescence of the two thermals have been recorded in Figs. 5a and 5b. Figure 5c corresponds to the moment when the resulting thermal has been completely formed. Coalescence of the two thermals took place at values of $\tau < \tau_{max}(L^0, \xi)$, where τ_{max} is the delay time at which the second thermal stops catching up the first thermal. A curious phenomenon was observed close to the boundary $\tau < \tau_{max}(L^0, \xi)$. The thermals initially approached one another as in the case which has been considered but, at a

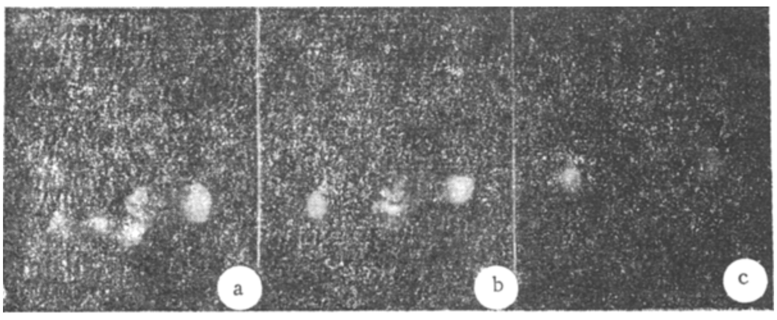

Fig. 5

distance approximately equal to the diameter of the upper thermal, they ceased to approach one another. The two thermals were subsequently aligned in such a manner that the projections of the central peripheries of their toroidal cores on a horizontal plane touched one another (external contact) during the whole of the time interval which was investigated. The distance between the planes in which these peripheries lie remained constant on the $5R_0$–$10R_0$ part of the trajectory for their combined motion and then began to increase slowly.

6. The experiments which had been carried out showed that there are three modes in which the objects being considered can interact: coalescence into a single ascending circular vortex, mutual repulsion, and mutual destruction during the interaction process. The first is usually observed when the two thermals are fairly similar with respect to the conditions of initiation and their dimensions. If the amount of smoke in the initial volumes is substantially different, their rapid and complete destruction occurred when the thermals interacted in all the experiments.

The processes involved in the coalescence of the formed (when $L \gtrsim 3R_0$) and forming ($L \lesssim 3R_0$) thermals are substantially different from one another. While, in the first case, the overall nature of the process under consideration is apparently analogous (in any case superficially) to that observed when migrating vortices interact [5], the nature of the process is completely different in the second case. At the moment of coalescence the ascending thermals are immediately transformed into a single vortex ring. The process involved in this interaction takes place appreciably more rapidly (see Fig. 2b) and the height at which they coalesce is not so dependent here on L^0 as in the first case and, moreover, the vibrations of the core which were noted above are also absent during this interaction.

The results of the measurements shown in Figs. 3 and 4 solely refer to the first of the modes of interaction which have been enumerated. When plotted in the coordinates of Eq. (1.2), they are completely and unequivocally concentrated around the corresponding curves $h^0(L^0)$ and $T^0(L^0)$ for all values of ξ which is a confirmation of the assumption that viscous forces have no substantial effect on the motions being considered and the model as a whole.

It should be noted that the latter claims are based on experiments with thermals with characteristic dimension which do not exceed 0.1–0.2 m with the numbers $5\cdot10^2 < Re < 4\cdot10^3$ and, moreover, the relative height at which coalescence occured h^0 did not exceed 10. On the basis of the experiments, the results of which are shown in [4], exchange processes at the boundary of the center of a thermal begin to have an effect on the development of the motion when $H^0 \approx 12$–14. In this case, it is obvious that Eq. (1.1) and, in fact, the whole model may be considered as a certain approximation.

The authors express their gratitude to S. A. Khristianovich, A. T. Onufriev, and M. D. Shcherbin for their interest in the work and useful discussions.

LITERATURE CITED

1. A. T. Onufriev, "The theory of the motion of a ring under the action of the gravitational force. The ascent of the cloud due to an atomic explosion," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1977).
2. J. S. Turner, Buoyancy Effects in Liquids, Cambridge Univ. Press (1973).
3. V. F. Tarasov, "On the motion of an ascending vortex ring," in: Dynamics of a Continuous Medium [in Russian], No. 23, Izd. Inst. Gidrodinamiki Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1975).
4. B. I. Zaslavskii and I. M. Sotnikov, "Experimental investigation of the motion of ascending vortex rings," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1983).
5. Y. Oshima, T. Kambe, and S. Asaka, "Interaction of two vortex rings moving along a common axis of symmetry," J. Phys. Soc. Jpn., 38, No. 4 (1975).