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Stereophotometry of unsteady turbulent free flows

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STEREOPHOTOMETRY makes it possible to measure and to average a large ensemble of instantaneous velocity field of hundreds or thousands of tracing particles. This allows the effective use of stereometry of tracing particles for experimental investigations of statistically stationary as well as statistically nonstationary developed turbulent flows. The labour involved in counting large amounts of stereometric data is well known. Using large and precise stereometry of tracing IMK 10/13×18, NDME-2A type and stereometric correlators „Steco" made by Carl Zeiss Jena, it was possible to reduce the counting and perforation time of stereometric data, on the motion of 1000–1500 tracing particles, to 15–20 hours. The use of stereometric data is also effective for the investigation of visual three-dimensional structures of developed turbulent flows.

Stereofotometria daje możliwość przeprowadzenia pomiarów i uśredniania wielkich ensambli pól prędkości chwilowych zawierających setki lub tysiące cząsteczek. Pozwala to na efektywne zastosowanie stereofotometrii do eksperymentalnych badań statystycznie ustalonych, jak również statystycznie nieustalonych rozwiniętych przepływów burzliwych. Powszechnie znany jest wielki nakład pracy potrzebny do opracowania wielkich liczb danych stereometrycznych. Zastosowanie dużych i precyzyjnych kamer IMK 10/13×18 oraz korelatorów „Steco" firmy Carl Zeiss Jena umożliwiło zredukowanie czasu zliczenia i perforacji do 15–20 godzin. Wykorzystanie danych stereometrycznych okazuje się również efektywne przy wizualizacji trójwymiarowych struktur rozwiniętych przepływów turbulentnych.

Стереофотометрия дает возможность проведения измерений и усреднения больших ансамблей полей мгновенных скоростей, содержавших сотни или тысячи частиц. Это позволяет эффективно применять стереофотометрию к экспериментальным исследованиям статистически установившихся, как тоже статистически неустановившихся развернутых турбулентных течений. Повсеместно известны большие затраты труда необходимые для разработки больших чисел стереометрических данных. Применение больших и прецизионных камер ИМК 10/13×18, а также корреляторов „Стеко" фирмы Карл Цейсс Йена дает возможность свести время счета и перфорации к 15–20 часам. Использование стреометрических данных оказывается тоже эффективным при визуализации трехмерных структур развернутых турбулентных течений.

1. Stereometry of tracing particles

STEREOPHOTOMETRY allows to determine in a practical way the instantaneous field of velocities of a few hundred or even a few thousand suspended tracing particles in a large volume of developed turbulent flow. For sufficiently large distances between small suspended tracing particles, their motion practically does not affect the investigated flow, and their mutual interference is negligible. This allows to identify the instantaneous velocity field of particles with the velocity field of the developed turbulent flow. Using methods of regressive analysis [15], it is possible to determine the instantaneous three-dimensional field of the mean velocity, the mean square variation of velocity, Reynolds tension etc.

The use of stereometry of tracing particles for investigating statically steady developed turbulent flows as well as statically unsteady flows is found to be effective. For averaging instantaneous fields of velocity it is important to choose an appropriate model with required characteristics. It was assumed, in all investigated flows, that the fields of averaged characteristics within intervals of the investigated test volume, in a cylindrical system of coordinates, depends only on the radius and does not depend on the coordinate along the axis and the angle φ.

In the general case the fifth order polynomial was used as the test function. It has been shown that the profile of the mean and the fluctuating velocity is approximated by the function

$$u(r) = u_0 e^{-0,603(r/r_1)^n}, \quad \text{where} \quad n = 2, 4 \text{ or } 6. \tag{1}$$

Profiles of the mean velocity of the wake flow behind an axisymmetric ellipsoid are approximated by the function (1) with $n = h$ and behind a "cup" (see Fig. 1c) by the

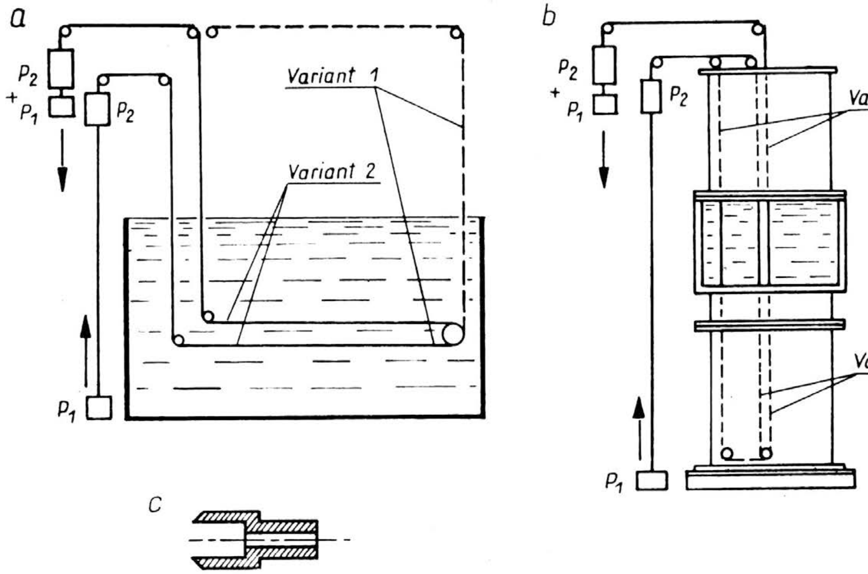

FIG. 1. The scheme of arrangement of thread; a) in a container, b) in a tube, c) the form of body "cup".

function (1) with $n = 4$. Profiles of fluctuating characteristics behind an axisymmetric ellipsoid are approximated by the function (1) with $n = 2$, behind a "cup" it has a maximum at $r = 0.4r_1$ (r_1 — the halfwidth of the field of the corresponding fluctuating characteristic). Together with it, the outer part of a profile ($r > 0.4r_1$) can be approximated by the function (1) with $n = 6$. This information allowed to use the function (1) as the model curve with not earlier defined parameters u_0, r_1 and n, in the case of a serial and of the same type of measurements. The testing calculations of u for a polynomial of the fifth order have been performed and close results have been obtained:

The stereophotometry of tracing particles allows to investigate the averaged instantaneous velocity fields of any single test flow and to perform averaging of the characteristics for large number of test flows corresponding to the same running time. In the general case the instantaneous velocity fields and averaged velocity fields for a large number of test runs may strongly differ.

For flows in the wake behind an ellipsoid and behind the "cup", and for flows generated by the axial motion of a long thread, the instantaneous velocity fields averaged over the test volume including the whole width of the turbulent flow for 3–5 diameters along its axis are almost identical. Hence they should be close to the averaged ensemble of test runs.

The wake flows in the body fixed coordinate system are also statistically stationary and for small Reynolds numbers $Re_x < 8 \cdot 10^6$ are sufficiently well investigated in aerodynamical tunnels [1–13]. The Reynolds numbers are referred to the running coordinate. This allows to compare the results of stereophotometric measurements of the individual flow test for comparatively large Reynolds numbers $Re_x \leqslant 8 \cdot 10^8$ with the results of a measurements in aerodynamical tunnels. A good agreement of these results is obtained and it is shown that the flows save the "memory" of the shape of the body also at high Reynolds numbers.

The scheme of experimental setups and the form of one of the tested bodies is shown in Fig. 1. In a horizontal container $1.0 \times 1.0 \times 1.9$ m^3 (see Fig. 1a) the visual investigation of flow was performed and in the vertical tube of the height b m and diameter 0.525 m (see Fig. 1b) the stereometry of tracing particles was investigated. The axisymmetric ellipsoid with the length l to diameter d ratio 14 and the blunt body "cup" (see Fig. 1c) were allowed to fall freely along the vertical string placed on the axis of the tube. At the distance of 2 m from the bottom of the tube the working chamber $0.7 \times 0.7 \times 1.0$ m^3 with a window of 0.5×0.7 m^2 for observation and three auxiliary windows were placed. A white polystyrene of large porosity spheres of the diameter 0.2–0.4 mm was used as tracing particles. The tracing particles were inserted into the test chamber, through a free surface and through a special pipe in the vicinity of the string, at the distance of 1 m above the test chamber. The mean effective immersion velocity of the tracing particles was 0.6 mm/s.

A set of five stereophotographic flashes was taken, starting at the present time t_n after crossing the test section. The interval between consecutive flashes in a given test was equal to 3:5:7:9. This allows to determine reliably the direction of motion of the particles. The interval of time between the first and fifth flash was determined to guarantee the maximum extension of the particle trajectory between 30 mm and 50 mm. The total number of particles was chosen to ensure a number 1000–1500 particles within the turbulent domain. The first flash was set for t_n: 2, 4, 8 and 12 s or 1, 5, 9, 13 and 19 s.

Flows behind an ellipsoid and a "cup" (see Fig. 1c), and flows generated by the motion along one thread or two parallel threads were investigated. The threads were fixed in a container and in a tube as shown in Fig. 1a and b. The section of the thread placed along the wall of the tube is inserted inside a thin tube to avoid its influence on the flow. The threads were set in motion by a falling load $P_1 + P_2$ connected to one end of the thread and a light counterbalance on the other end.

The motion of a thread was only in one direction, or in two opposite directions but according to the same law. For that purpose, at the completion of the first phase of the motion, when the load $P_1 + P_2$ touched the lower buttress the load P_2 was automatically disconnected and at the ether end of the thread the same load was automatically attached, and the thread moved in opposite direction. The time t is counted from the moment the thread was fully arrested. To compare the test results with earlier investigations, the extension of the flow x/d is calculated according to the formula

$$\frac{x}{d} = \frac{U_\infty t}{d},$$

where $U_\infty = 8.2$ m/s, $d = 40$ mm corresponds to the ellipsoid and $U_\infty = 5.4$ m/s, $d = 25$ mm corresponds to the "cup".

The large stereocameras IMK 10/13×18, NPME-2A and stereometric correlator "Steco" made by N. P. Carl Zeiss Jena GDR was used. After equipping stereometric correlators with an automatic devices, the time of counting the stereometric data for 100–1500 trajectories was reduced to 15–20 hours.

The Reynolds number for the diameter of the tested bodies was $3.5 \cdot 10^5$ and related to the flow extension x $\mathrm{Re}_x \leqslant 8 \cdot 10^8$ and 10^8. This exceeds considerably the earlier results obtained in aerodynamical tunnels where $\mathrm{Re}_x < 8 \cdot 10^6$. In all cases the value of Reynolds numbers for the maximum of local velocity and the local width of a flow exceeded 1000. The results of the measurements show that the influence of the shape of the body on the characteristics of the self-similar flow are saved at least for Reynolds numbers $\mathrm{Re}_x \leqslant 8 \cdot 10^8$; at the same time the results of measurements behind such slender bodies as an ellipsoid with an aspect ratio $c/d = 14$ and behind such blunt bodies as a "cup" correlate well with the previously obtained results.

At the same time, the shape of the body influences the value of the self-similarity parameters of the mean velocity field S_0 and the velocity fluctuation field S_1, the values of which were found from the expressions

$$S_i = \frac{r_i(x) \cdot U_\infty}{U_{mi}(x)(x - x_{0i})} = \frac{r_i(t)}{U_{mi}(t)(t - t_{0i})}, \tag{2}$$

where the index $i = 0$ denotes the mean velocity field, and $i = 1$ the velocity fluctuation field, U_{mi} — maximal mean value of the velocity ($i = 0$) and fluctuation of the the velocity ($i = 1$), r_i — halfwidth of the field of mean velocity ($i = 0$) and of the fluctuating velocity ($i = 1$), x_{0i}, t_{0i} — virtual coordinates origin of the field of mean velocity and the fluctuating velocity.

In the general case the value of the virtual origin of coordinates of the mean velocity field, x_{00} and t_{00} and of the field of the fluctuating velocity x_{01} and t_{01} differ one from another considerably and it is necessary to take that difference into consideration in the analysis of the experimental results in a limited range of extension of the flow $x/d < 100$.

The general solution of this suddenly generated circular self-similar free turbulent flow can be given in the form

$$\frac{U_{mi}(x) S_i}{U_\infty} = a_i \left(\frac{x - x_{0i}}{\sqrt{S_i}\, \delta^{**}} \right)^{-\frac{2}{3}}, \qquad \frac{r_i(x)}{\sqrt{S_i}\, \delta^{**}} = a_i \left(\frac{x - x_{0i}}{\sqrt{S_i}\, \delta^{**}} \right)^{\frac{1}{3}}, \tag{3}$$

$$U_{mi}(t) = a_i \left[\frac{S_i(t - t_{0i})}{\sqrt{2J}} \right]^{-\frac{2}{3}}, \qquad r_i(t) = a_i [2JS_i(t - t_{0i})]^{\frac{1}{3}}, \tag{4}$$

where δ^{**} — thickness of loss of momentum, J — output of the fluid across the transverse section of the flow.

The analysis of the experimental results [1–9] and the results [11, 12] for water and for polymer solutions show that in all cases $a_i \approx 1/2$, i.e. that a_i is a universal constant. These results are shown in Fig. 2 where, in accordance with the solution (3), $U_i^* = U_\infty/S_i$ is

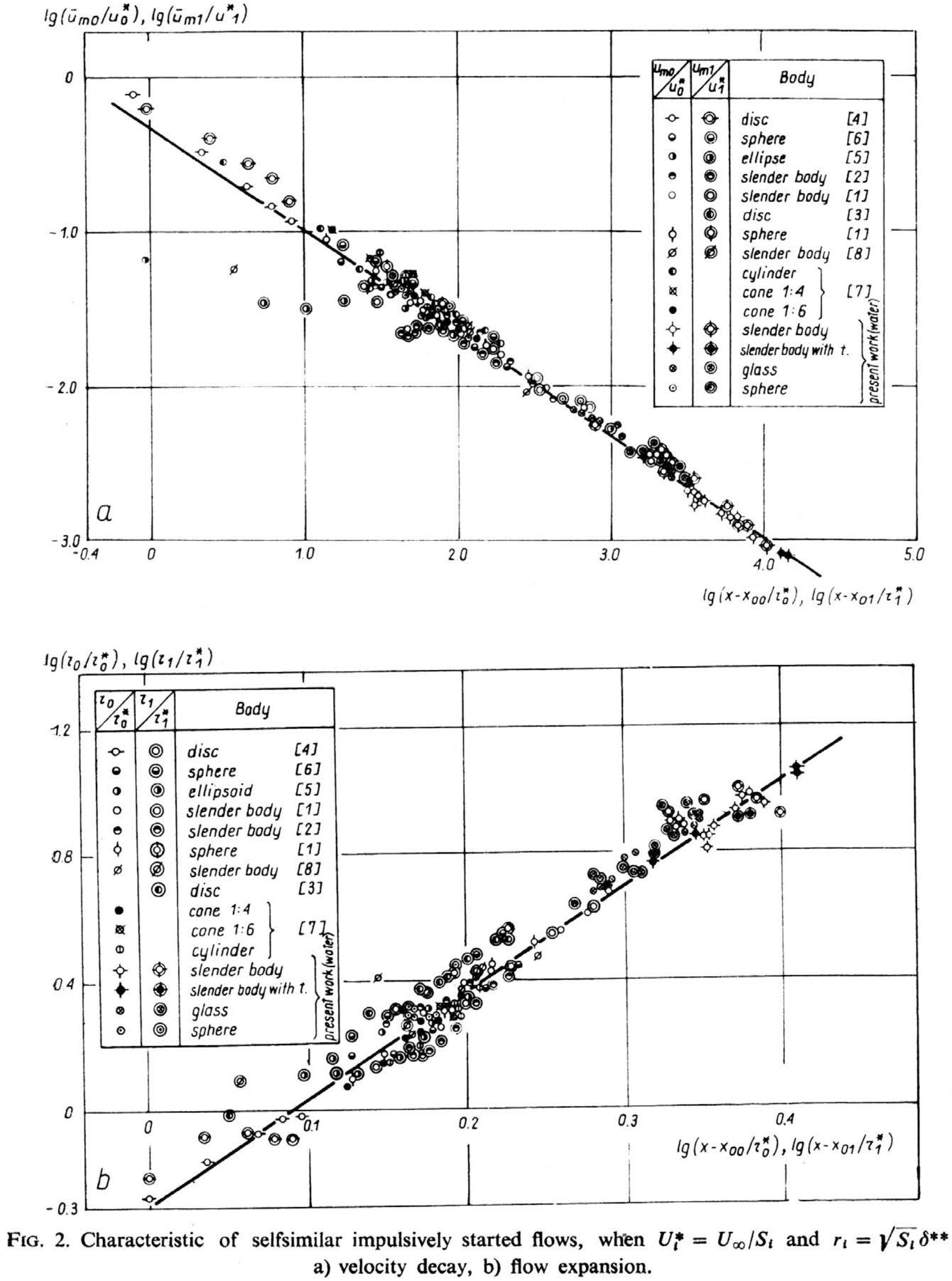

FIG. 2. Characteristic of selfsimilar impulsively started flows, when $U_i^* = U_\infty/S_i$ and $r_i = \sqrt{S_i}\,\delta^{**}$; a) velocity decay, b) flow expansion.

taken as the scale of velocity, and $r_i^* = \sqrt{S_i}\,\delta^{**}$ is the scale of length to satisfy the relation $U_i^* r_i^{*2} = U_\infty(\delta^{**})^2$.

Further analysis showed that other types of free turbulent flow also have this important property, in particular nonimpulsively started circular flows considered in [8, 9], (see Fig. 3) and plane flows considered in [14].

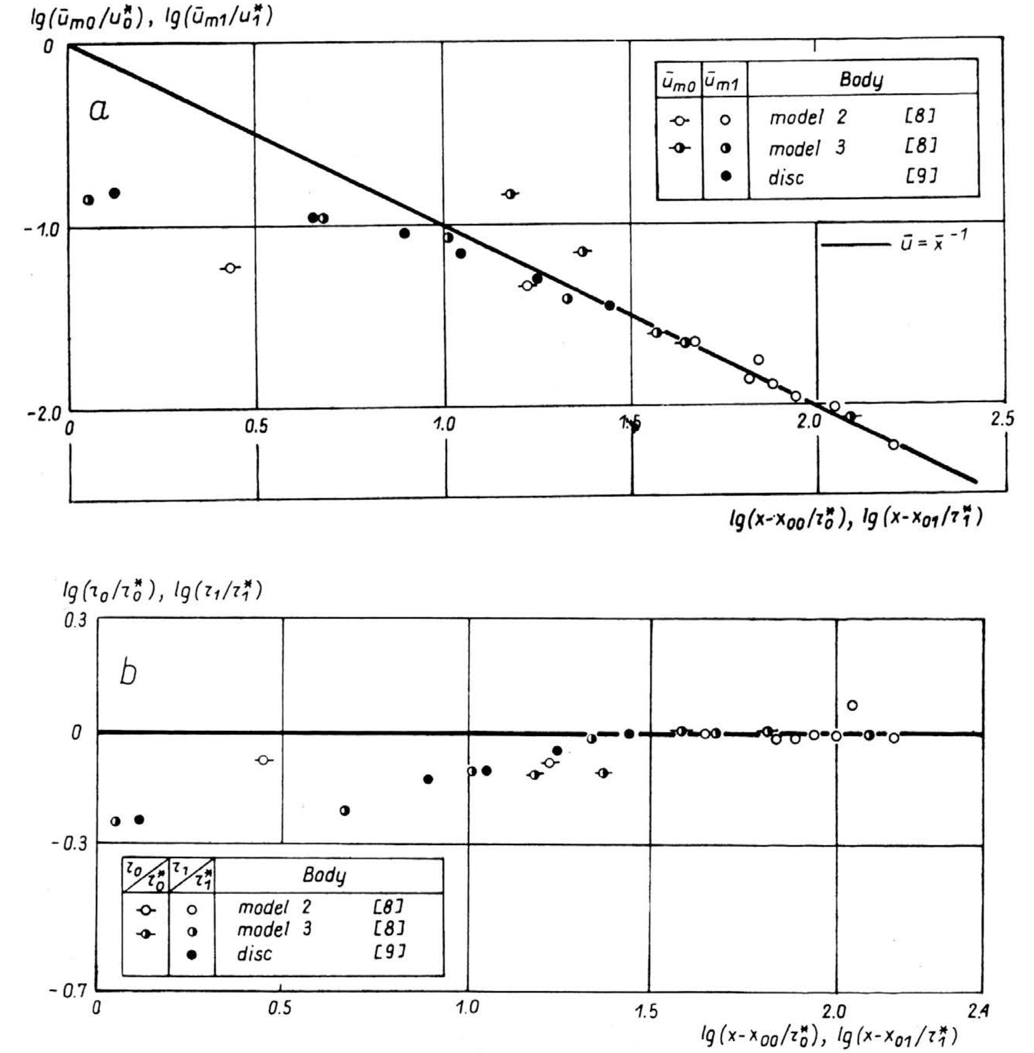

FIG. 3. Characteristics of nonimpulsively started flows [8, 9], if $U_i^* = U_\infty/S_i$ and $r_i = \max r_i$; a) velocity decay, b) flow expansion.

Experimental stereophotometrical investigations of flows generated by an axial motion of a long thread in one direction show that these flows are self-similar as described by Eqs. (4) with $a_i = 1/2$. These flows are statistically unsteady in any coordinate system and, according to the author's knowledge, have not been experimentally investigated so far.

The motion of a rope forward and backward along one line generates a flow, according to the same law, with a typically unimpulsive form of mean velocity profile (see [8, 9]). As in the first phase the thread moves in an unperturbed medium, and in the second phase the thread moves in a disturbed medium, the output of the fluid across a transverse section of the flow differs from zero. Hence for large t the mean velocity profile should take a form as in [8].

The stereometry of tracing particles has shown that the maximum value of the velocity

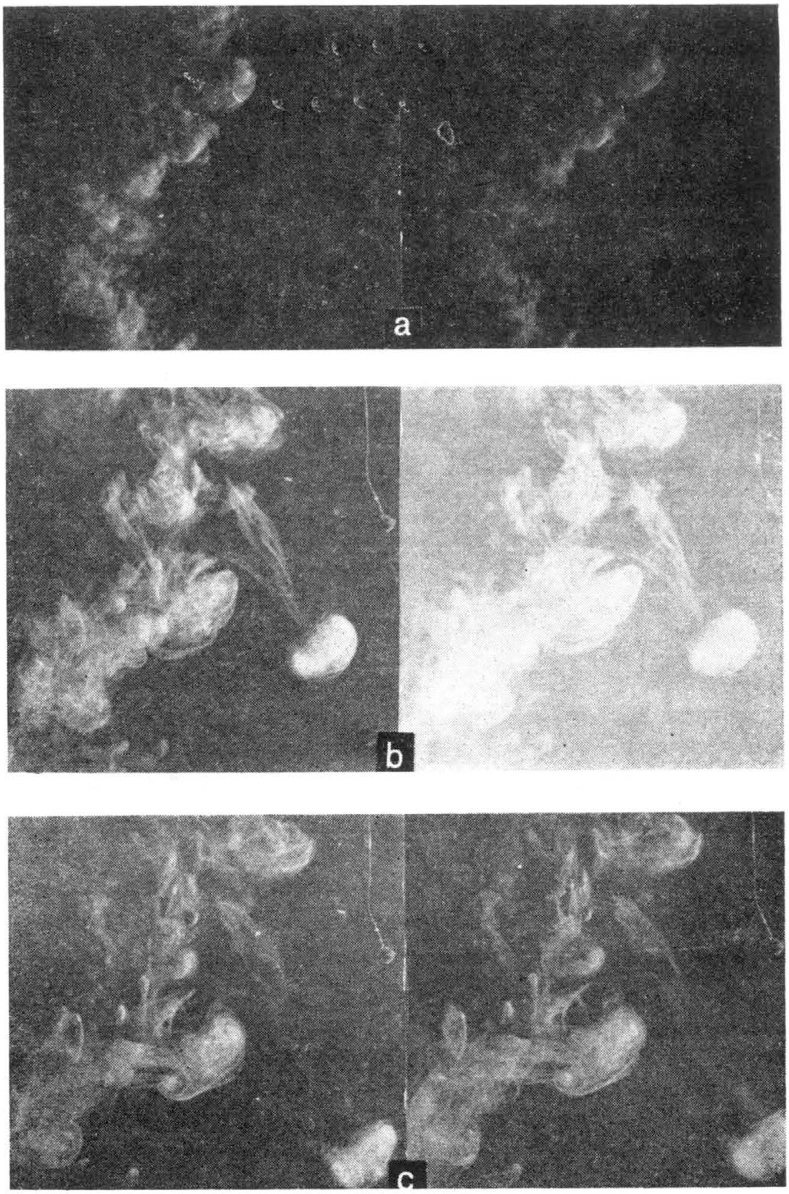

FIG. 4. The flow behind a fallong sphere $d = 10$ mm.

on the axis of a flow U_0 decays as $U_0 \sim t^{-4/5}$ while the maximum value of the velocity in the periphery of the flow U_{00} decays as $U_{00} \sim t^{-2/3}$. All fluctuating characteristics decay as $t^{-2/3}$. In the case of a flow generated by the motion of two parallel threads, all fluctuating velocities decay as $t^{-4/5}$.

2. Stereometry of visualized flows

When a frame of reference at rest relative to the observer and transparent dyes are used, stereometry of free turbulent flows developing in the fluid is an effective instrument

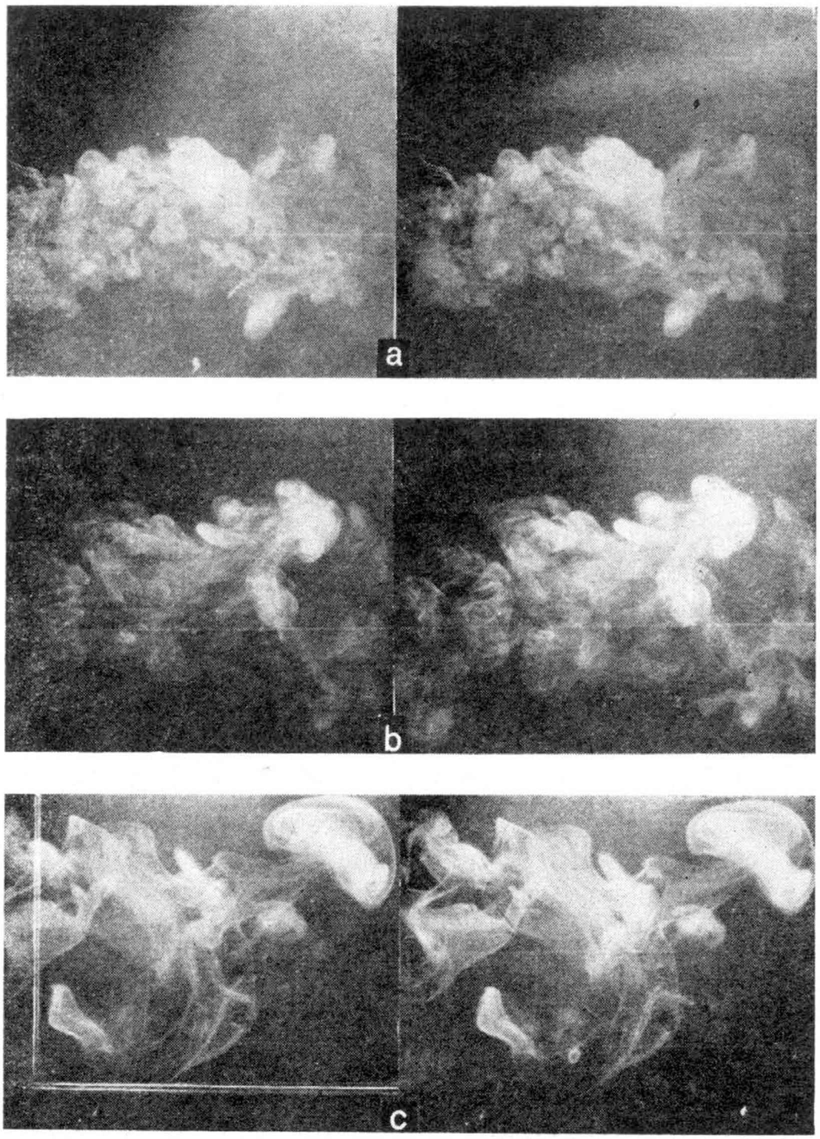

FIG. 5. The flow generated by the motion of fishing-line $d = 1$ mm in one direction.

for the investigation of three-dimensional regular intermittents in developed turbulent flows. In [16, 17] it was reported that behind a freely falling sphere (see Fig. 4) and in a flow generated by an axial motion of a thin thread in one direction (see Figs. 5 and 6) the process of generating laminar circular vortexes in free turbulent flow takes place. A part

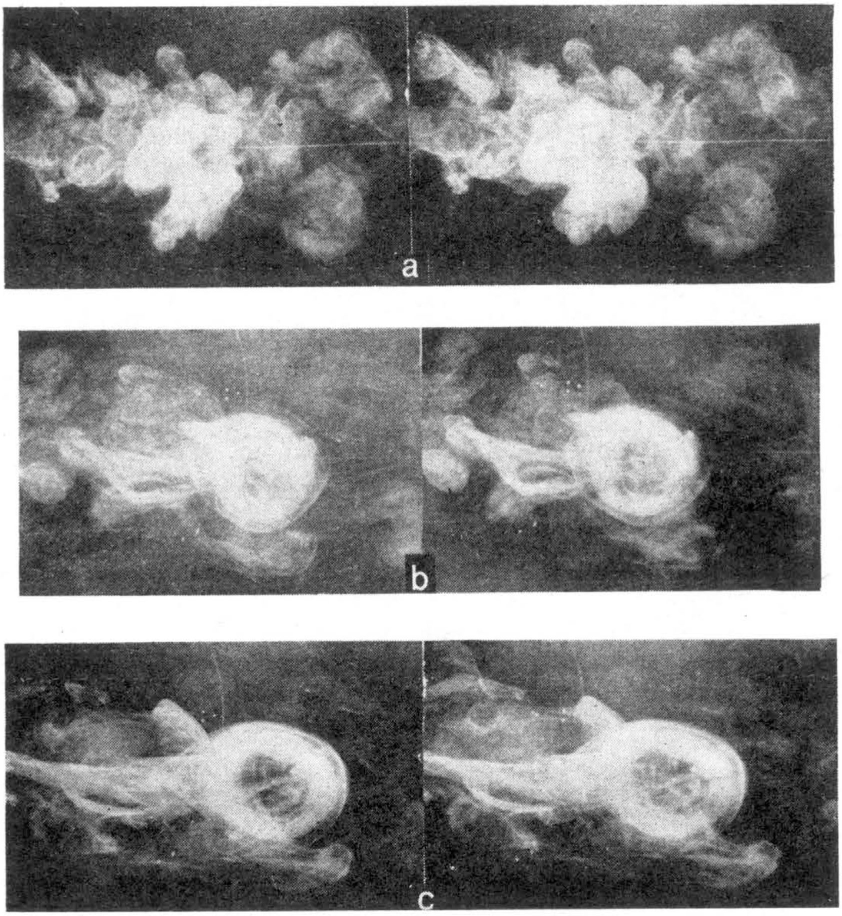

FIG. 6. The flow generated by forward and backward motion of a fishing-line $d = 1$ mm.

of circular vortexes did not follow the basic flow and continued their motion, in the unperturbed medium, leaving behind then a trail of coloured fluid.

Further investigations showed that the process of generating circular vortexes is probably typical for free turbulent flows. A sharp increase of the local Reynolds numbers causes a part of the circular vortexes to become turbulent. In Fig. 7 the flow generated by the motion of a thread in one direction is shown and in Fig. 8 the flow due to a forward and backward motion of a thread. On the third frame (see Fig. 8) the disintegration of a circular turbulent vortex due to interaction with a free surface is registered. Already in the first stage of development ($t = 5$ s) at the periphery of a flow, many relatively small circular vortexes are generated, moving away radially from the axis (see Figs. 9 and 8). Thereafter the small vortexes disintegrate and large whirls are formed. These formations have sometimes a very complicated initial structures, as can be seen on the second frame

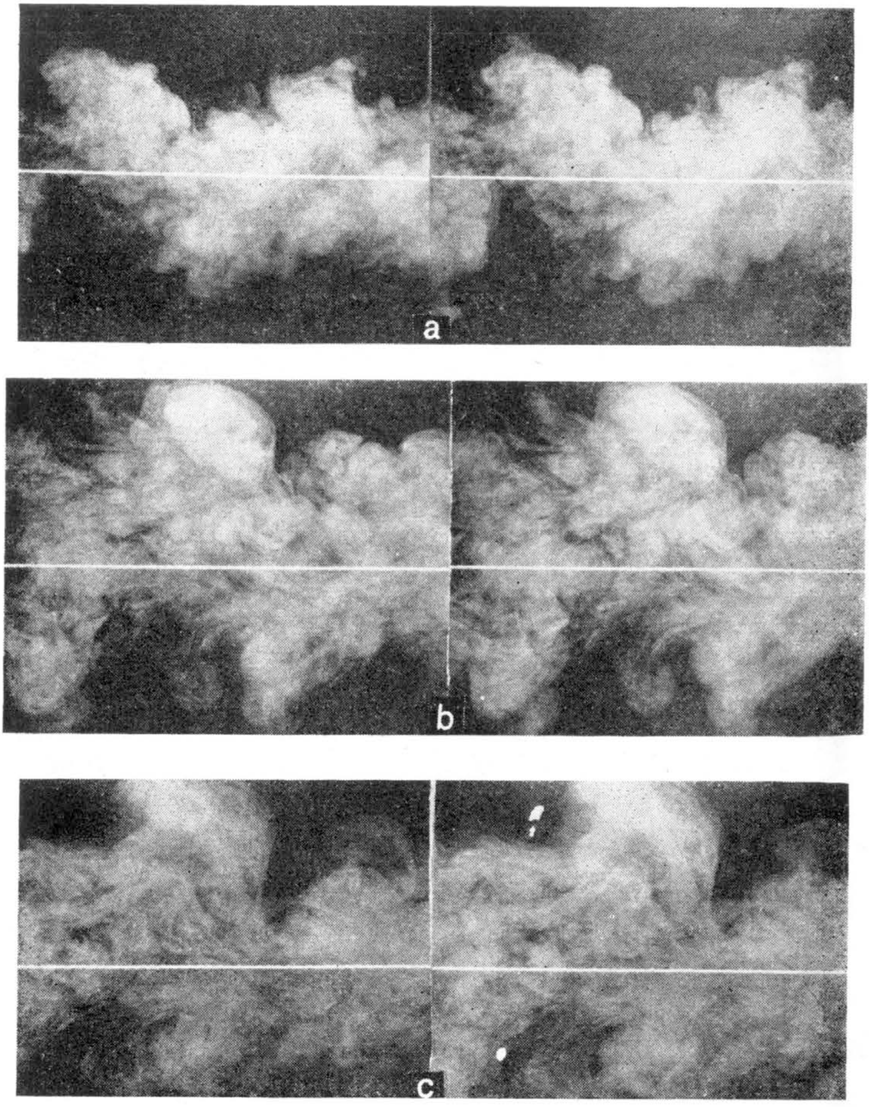

FIG. 7. The flow generated by the motion of a rope $d = 4$ mm in one direction.

of Fig. 10. Such complicated whirl formations disintegrate or collapse into a single developed circular vortex (see Fig. 10, frame 3). Short three-dimensional jets are also generated in the flow. Circular vortexes are formed at forward parts of these jets, as shown in Fig. 11.

Often, the generation of a large circular vortex is preceded by the formation of a blob of concentration dye, distinctly visible in the background of the dyed fluid (see Figs. 5, 9 and 10). From this blob either one circular vortex (see Figs. 5 and 9) is generated, or a complicated system of vortexes (see the second frame of Fig. 10) is generated. Such

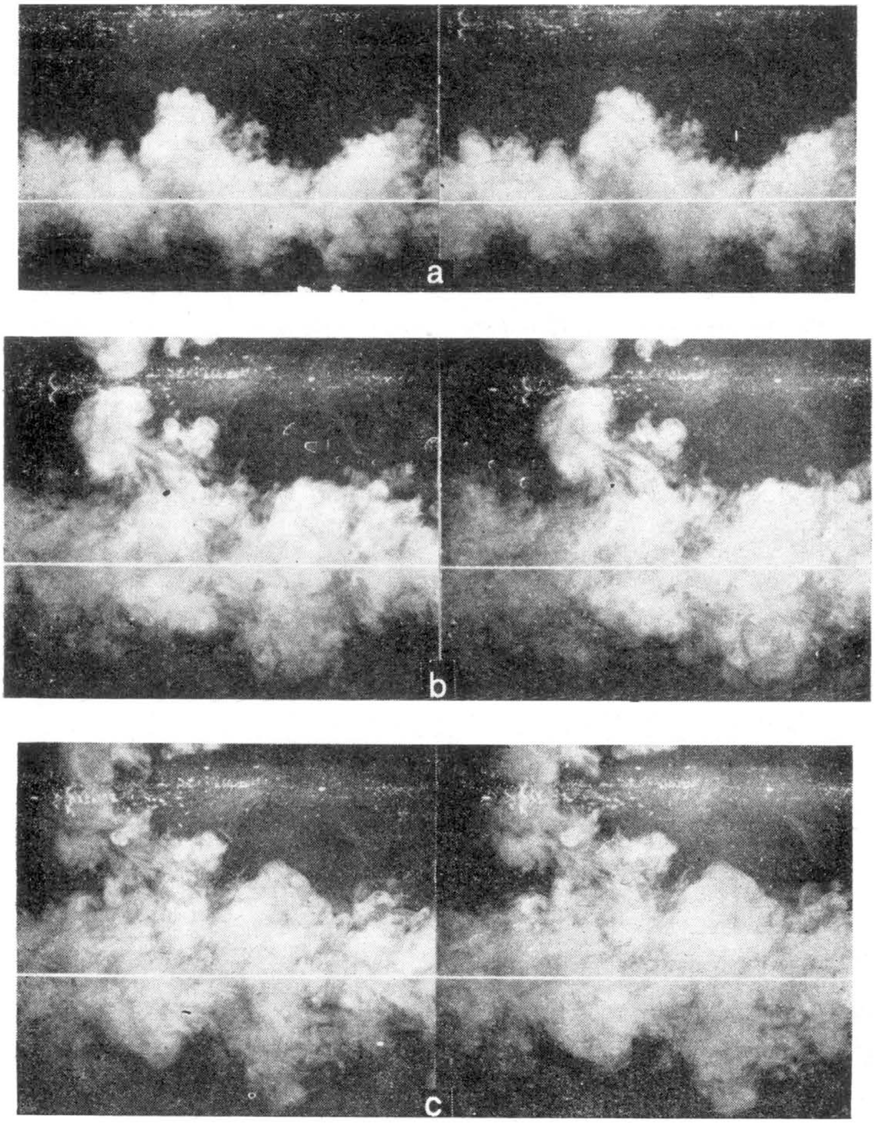

FIG. 8. The flow generated by forward and backward motion of a fishing-line $d = 1$ mm.

a large turbulence system is either rapidly disintegrated or is transformed into a single circular vortex.

The above described variety of forms of generation of circular vortexes in free turbulen flows proves that this phenomenon is very common. These observations, concerning circular vortexes in developed turbulent flows, should have important implications in further investigations leading to the theoretical description of turbulence.

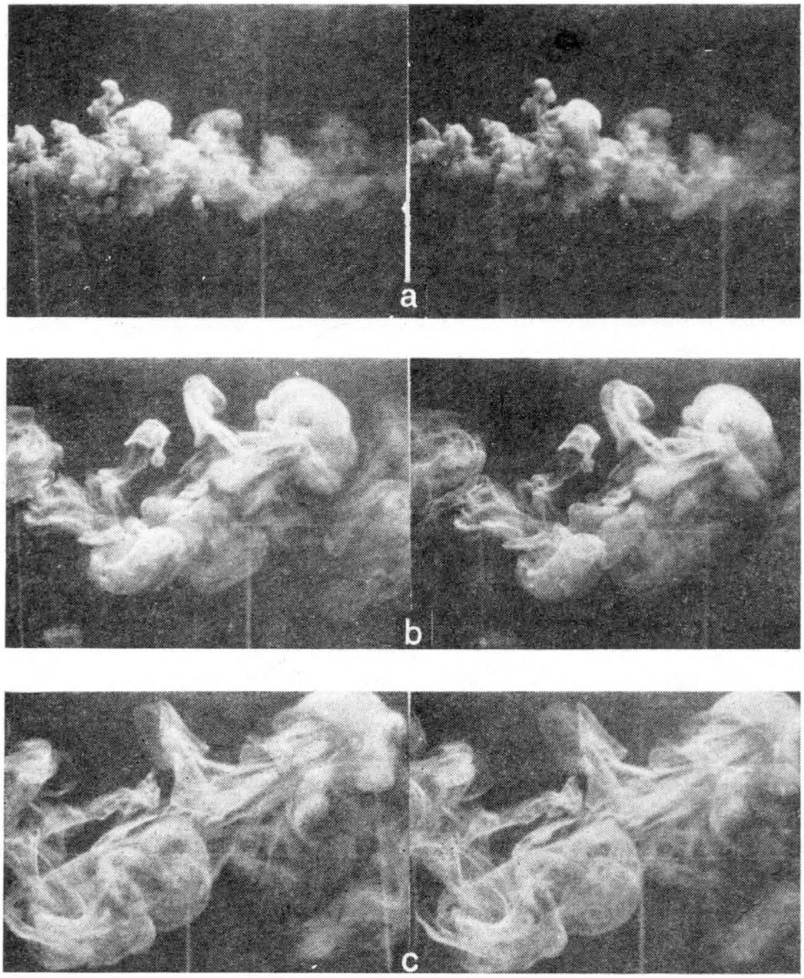

FIG. 9. The flow generated by the motion of a fishing-line $d = 1$ mm in one direction.

3. Conclusion

The described results of quantitative investigations and visualization of three-dimensional structures of developed free turbulent flows confirm the high effectiveness of stereophotometry in experimental investigations of flows at sufficiently high Reynolds numbers and especially of statistically unsteady flows.

The stereometry of tracing particles behind the falling ellipsoid and "cup" allowed to extend the range of experiments to Reynolds numbers two orders larger in comparison with previous results. It was also shown that the form of the body significally influences the characteristics of self-similar flows at high Reynolds numbers, using the velocity of the body and the loss of momentum thickness as reference values. If the ratio of velocity

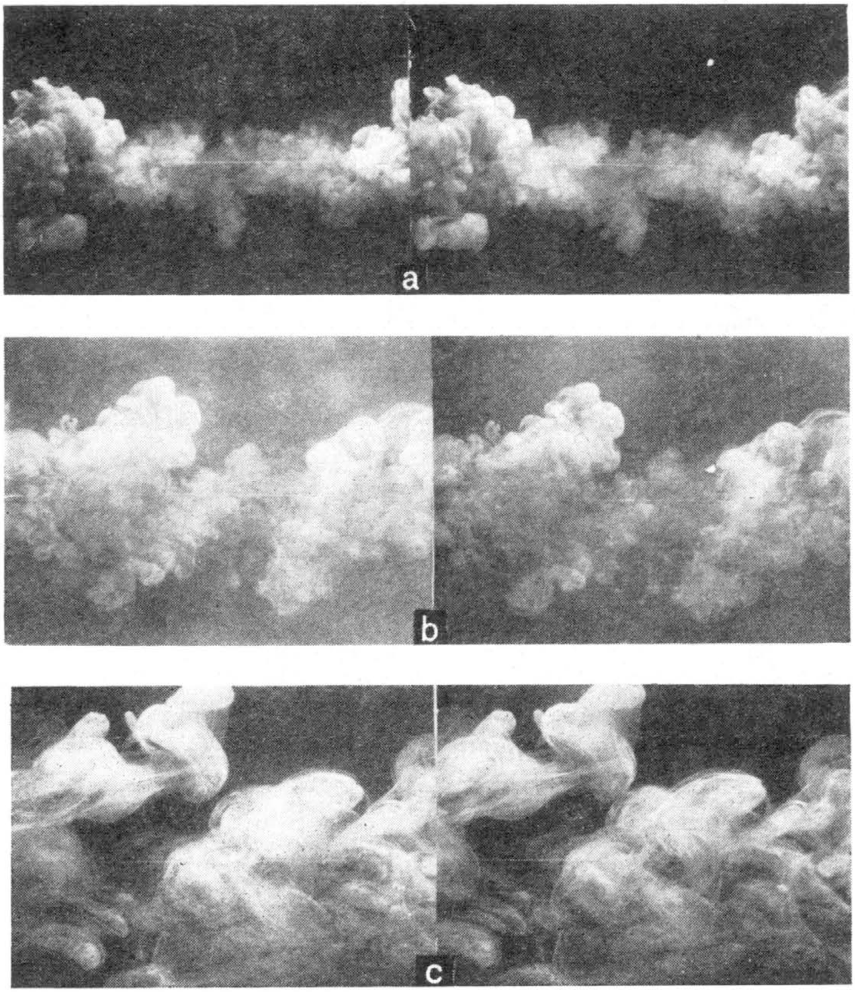

FIG. 10. The flow generated by forward and backward motion of a fishing-line $d = 1$ mm.

of the body to the corresponding parameter of self-similarity for mean and fluctual velocity fields is taken as a reference velocity and the product of thickness of a loss of momentum and square root of the parameter of self-similarity as the length scale, then the dimensionless characteristics of self-similar flow are independent of the initial and boundary conditions. It is shown that the flow generated by the axial impulsive motion of a long thread exhibits also the property of universal self-similarity. The stereophotometry of free turbulent flows made possible the investigation of the process of natural generation, development, motion and disintegration of laminar and turbulent circular vortexes.

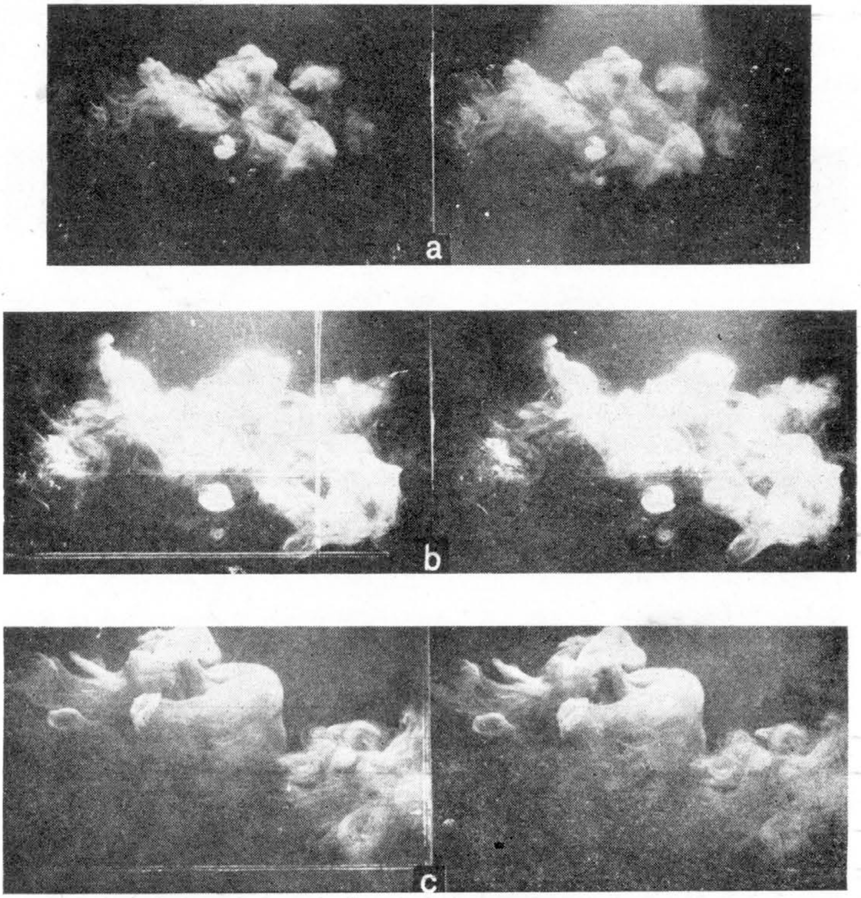

FIG. 11. The generation of the jet and circular vortices.

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