Some observations of the vortex breakdown phenomenon

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This paper describes an experiment in which a cylindrical vortex, formed in a long tube, was used to study the 'vortex breakdown' that has been previously reported in investigations of the flow over slender delta wings. By varying the amount of swirl that was imparted to the fluid before it entered the tube, it was found that the breakdown was the intermediate stage between the two basic types of rotating flows, that is, those that do and those that do not exhibit axial velocity reversal. In addition, it was shown that an unusual flow pattern was established after the breakdown and that certain features of this pointed to it being a 'critical' phenomenon. The tests were concluded by measuring the swirl angle distribution a short distance ahead of the breakdown and comparing these results with the prediction of Squire's theory (1960).

1. Introduction

In this paper, it is proposed to present briefly the results of a simple experiment that was made to investigate the fundamental nature of the vortex breakdown which frequently has been observed to occur in the flow fields of slender delta wings. It was the opinion of the author that this phenomenon had far wider implications than had been attributed to it because of its isolated appearance, and that in it might be found a key to understanding the reasons for the broad division of swirling flows in the two groups of those that do and those that do not exhibit axial flow reversals. To some readers, this might sound a far-fetched idea, but the results of the present investigation confirmed it and added some interesting and unexpected details of the flow geometry that resulted after the breakdown. However, before embarking upon a description of this experiment, a short review of the observations that have been made with delta wings will be helpful.

It is well known that when a slender wing is set at an angle of attack, the boundary layers from the upper and lower surfaces flow outwards and separate from the leading edges to yield two shear layers which in turn roll up into a pair of vortices situated above the wing. As the flow develops progressively further away from the apex of the wing, this continual feeding of vorticity by the shear layer causes the vortices to strengthen, but at the same time spoils any natural axial symmetry that they would have. Further downsteam, the shedding of vorticity from the trailing edge complicates the flow even more. As may be expected, an increase in the angle of attack strengthens the vortices until, as was first discovered by Peckham & Atkinson (1957), eventually an impressively sudden change in the nature of their cores occurs. This 'breakdown', as it has been subsequently called, is best described as giving the impression that an imaginary body of revolution has been placed on the axis of the vortex, around which the fluid is obliged to flow. In practice, the imaginary object takes the form of a hemispherical bubble of almost stationary fluid headed by a free stagnation point. It appears that the pressure field which normally balances the centrifugal forces in the vortex has failed to maintain an equilibrium; this concept has been discussed previously with reference to the flow over curved surfaces, and more recently in a paper by Strscheletzky (1957), who extended to vortex flows the idea of centrifugal forces alone causing separation. The presence of the free stagnation point with its inherent instability accounts for the continual shifting of position of the breakdown along the vortex axis.

The downsteam end of the bubble does not close, but instead the flow degenerates into an unsteady swirling motion which has led (erroneously, it is now thought) to the conclusion that the phenomenon is an instability closely analogous to turbulence. The work of Elle (1958, 1960), Werlé (1960) and Gray (1958) deserve to be mentioned here, for they were chiefly responsible for constructing a detailed picture of the flow field near the breakdown; but, despite their and others' efforts, progress towards a complete understanding of the flow has, for several reasons, been severely hindered. First, a difficulty arises because of the unsteadiness already mentioned, for the continual slight random movement of the breakdown's position renders any set of measurements made with a probe meaningless. In practice, the situation is even worse because the breakdown exhibits a hypersensitivity to any form of disturbance. This is so serious that even a probe introduced a little upstream of the breakdown can produce enough interference to cause it to be precipitated ahead of the probe. As a consequence, measurements made with probes have to be ruled out and a complete reliance placed on methods of flow visualization.

The second factor which has handicapped progress has been the very complicated nature of the leading-edge vortex on a delta wing. The lack of axial symmetry of this flow may account for the rapid deterioration into a disorganized unsteady swirling motion a very short distance downstream of the breakdown. In addition, the gradients of vorticity and pressure which are produced in the direction of the axis of swirl, while likely to have been responsible for initially setting the right conditions for the breakdown to occur somewhere in the flow field, add unnecessary complications which hinder more objective experimentation.

Clearly, a study of the breakdown in a different environment is indicated, especially if a relatively simple flow such as the 'classical' cylindrical vortex is to be used. The fact that this has been the subject of a great many previous experiments without the breakdown being noted gives little encouragement, for it indicates that the phenomenon can only be expected for a very limited range of initial conditions, if, in fact, it will occur at all. Here, a paper by Squire (1960) was of special help in planning an experiment, for although oversimplifying the problem, he made use of the powerful idea of deriving the conditions necessary for a sinusoidal perturbation of unspecified wavelength first to be sustained. This method is specially useful because it is equally applicable to stability problems and to those that are characterized by subcritical and supercritical régimes. Squire concluded that, for a constant axial velocity and a given distribution of swirl velocity, the ratio of the maximum tangential velocity to that in the axial direction† is the only characteristic parameter determining whether the breakdown will occur, and that for three considerably different swirl distributions the critical value would be in the range 1·0 to about 1·2. This result, for want of anything more refined, was used as a welcome basis for the experiments, since the reduction of the number of variables to one greatly simplified the search for the apparently elusive breakdown condition.

2. The apparatus

It is proposed here to give but a brief description of the apparatus, since it was used earlier by Titchener & Taylor-Russell (1956) for their work on turbulent vortices and the details of its design were given in their paper. Basically, it is comprised of a Perspex tube, of $3\frac{1}{2}$ in. diameter and a little over 4 ft. long, through which air is drawn by a small fan mounted at the downstream end. An initial swirl was imparted to the air by a set of adjustable vanes (see figure 1) which is mounted in the inlet section. Some modifications had to be made to improve the flow in this section and so insure a steady laminar flow for these tests, which were conducted at speeds about 5 ft./sec. As later measurements will show, the vortex produced in the tube approximated closely the classical 'exponential' form, i.e. having a swirl angle distribution given by the expression

$$\phi = \tan^{-1}[Ar^{-1}(1-e^{-Br^2})], \tag{1}$$

where ϕ is the swirl angle measured from the free-stream direction, r is the radial distance, and A and B are arbitrary constants. The viscous core was derived from the boundary layer shed from the pointed centre-body. By applying suction to an annular slot near the apex of the centre-body, this boundary layer could be significantly thinned, which in turn reduced the diameter of the core in the vortex. Thus the ratio of the core diameter to the tube diameter could be varied, enabling an indirect check to be made on whether the walls were causing any measurable interference.

In order to observe the flow visually, titanium tetrachloride smoke was fed into the centre of the vortex through a hole in the tip of the centre-body. The slightly sub-atmospheric pressure at this point provided a natural mechanism by which the dense smoke could be injected slowly enough to avoid disturbing the flow. This ability to inject the agent for the flow visualization with certainty on the centre-line of the vortex was felt to offer definite advantages over most of the experiments that had been made using delta wings.

In figure 1, a gauze screen is shown mounted on the downstream end of the

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† I.e. the tangent of the maximum swirl angle, henceforth referred to as $\tan(\phi_{\max})$.

vortex tube. This was inserted for some of the tests to check whether the downstream configuration has any effect on the measurements.

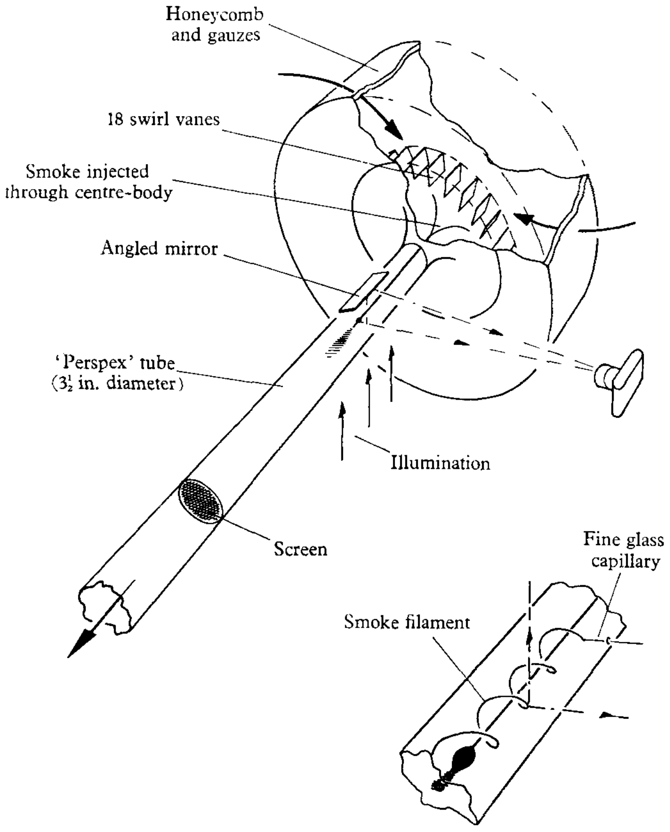

Figure 1. A general view of the vortex tube.

3. The observations

As has already been said, the search for the breakdown was to be based upon the prediction by Squire that its occurrence was dependent only on the maximum swirl angle, and thus the velocity at which to perform the tests could be chosen to obtain laminar steady flow and the best results from the flow visualization. After experimenting a mean axial velocity about 5 ft./sec was found to be most suitable.

From this point the procedure was simple, for all that remained was first to establish the classical vortex in the tube, and then, by very small increments, to increase the angle of the swirl vanes while watching the smoke. Fortunately, after a short time a breakdown very similar in form to that photographed by Gray (1958) appeared downstream in the tube, and with a small increase in the swirl this moved up to within about 15 in. of the tip of the centre-body. The abandonment of the delta-wing vortex in favour of the tube apparatus had paid a dividend, for now the bubble region was free to develop undisturbed and, instead of a hemispherical region downstream of which was a ragged unsteady flow, the bubble closed (see figures 2 and 3, plate 1) into a slightly elongated sphere within which the smoke collected. The flow downstream of the bubble showed no signs of a reversed core, but appeared rather to have returned to a form similar to that upstream of the breakdown. Figure 2, which was taken with an electronic flash, shows that, after this reversion to the normal vortex, there was an onset of turbulence; however, figure 3 (plate 1), for which an exposure of a tenth of a second was used, gives a better impression of what the eye sees, namely that within this turbulent flow there is a definite appearance of a second breakdown.

The first series of tests was concluded by further increasing the angle of the swirl vanes and thereby increasing the ratio of the tangential to axial velocity. The result was to move the bubble upsteam until eventually the whole length of the tube was filled with a central core region in which the axial velocity was reversed.

At this point, two striking conclusions can be drawn from the results. It is apparent that, for low swirl settings, the classical vortex was obtained, but as the vanes were changed to give more swirl the breakdown was precipitated and then finally this disappeared to leave the second type of vortex flow, i.e. one with a core region in which the general flow direction was reversed. From this, the important conclusion is drawn that the breakdown is the phenomenon bridging the gap between the two fundamental types of rotating flows.

The second conclusion is drawn from the observation that the flow, after suffering the breakdown, did not immediately degenerate into an unsteady random motion, as on the delta wing, but instead it retained a well organized character to the extent that the bubble closed and the normal vortex flow was restored. Now, if the breakdown had been essentially due to the onset of some sort of instability, this observation would have been difficult to explain for two reasons. First, an instability implies a state in which a perturbation will grow unchecked. In fluid mechanics, this usually means that the flow degenerates into an unsteady motion. The smoothness with which the bubble was formed in this experiment, while being of course no proof, is felt to point away from its being an instability embodying a diverging process. Secondly, the reversion to the normal flow downstream of the bubble showed that the change from one régime to another is reversible, which is a characteristic of 'critical' phenomena and not instabilities.

At this stage in the experimentation, the first of these conclusions could be affirmed with certainty, but not so the second. The smoke, due to the onset of turbulence, did not give a clear visualization of the flow, and moreover it could be argued quite justifiably that the second breakdown followed so closely upon the first that, although the reversed flow core had disappeared, there had never been a true return to the same sort of flow as had existed upstream of the bubble. Thus, the conclusion that the process was reversible is uncertain. To clarify this point, another simple experiment was devised making use of the fact that accelerating the flow in the tube delayed the formation of the bubble.

A second Perspex tube was made to fit exactly inside the $3\frac{1}{2}$ in. tube. The centre 4 in. of this had an internal diameter of 3 in., and the remaining 4 in.

left at each end were internally tapered to give sharp edges. This was inserted into the main tube and can be seen in figure 4 (plate 2). The main tube is difficult to see in the photograph because the lighting had been carefully arranged to eliminate reflexions from it, so avoiding confusion of the smoke photographs. The inner tube's position was adjusted until the flow pattern shown in the photograph was achieved. Here the breakdown has been artificially precipitated by a probe, because in starting the flow the bubble always appeared downstream and then moved upstream to its final position when the flow became steady. However, with the second tube in place, the breakdown was unable to move from the 3 in. section to the $3\frac{1}{2}$ in. section because of the pressure gradient formed by the change in area and so the flow had to be set up artificially.

The result of the experiment is clear, and any misgivings about the evidence from the second conclusion are now removed. The complete reversion from the broken-down flow to the vortex without a core is positively demonstrated and all difficulties arising from the nearness of the second breakdown can be said to have been eliminated.

On occasions during the course of these tests, boundary-layer suction was applied to the centre-body to determine the extent to which changing the core size would affect the results. Applying gentle suction caused no observable change in the flow except to reduce slightly the bubble diameter. By applying a strong suction, it was possible to reduce the bubble to half its former diameter; but no other details of the flow were altered. From this it was concluded that the tube wall was having no serious effect on the results.

The final section of the experiment was devoted to making a set of measurements specifically to help substantiate the results of Squire's analysis (1960). Fortunately, this required a knowledge of the swirl-angle distribution, one of the very few parameters that can be measured reliably with smoke. As the present method of injection places smoke only on or near the axis, a method was devised to produce a fine filament anywhere in the flow field. To do this, a series of very thin glass capillaries (order of 0·005 in. diameter) were made which were small enough to be inserted into the tube without affecting the flow. By forcing titanium tetrachloride through these and photographing the resulting smoke trace, the swirl distribution several core diameters ahead of the bubble was obtained. (An inclined mirror was used in the photographic recording of these data so that simultaneous information of radial position and swirl angle could be made—see figure 1.) The result of the survey is presented in figure 5 together with an indication of the size of the sphere. A repeat was made of this test using gentle boundary-layer control on the centre-body. In figure 5, the continuous line is the 'exponential' swirl distribution given in equation (1), A and B having been chosen to give the best root-mean-square fit to the experimental points. It appears that for the purpose of analysis the exponential vortex would be a suitable analytic expression to adopt for the swirl distribution.

An interesting result was that close agreement between the measured value of $\phi_{\max}$ of about 50·5° and Squire's predictions lying between 45° and 50·2°. The value of $\phi_{\max}$ for the survey made with boundary-layer suction was 51°, and the ratio of the bubble diameter to the radius at which the maximum swirl occurred remained the same within the accuracy of the measurements.

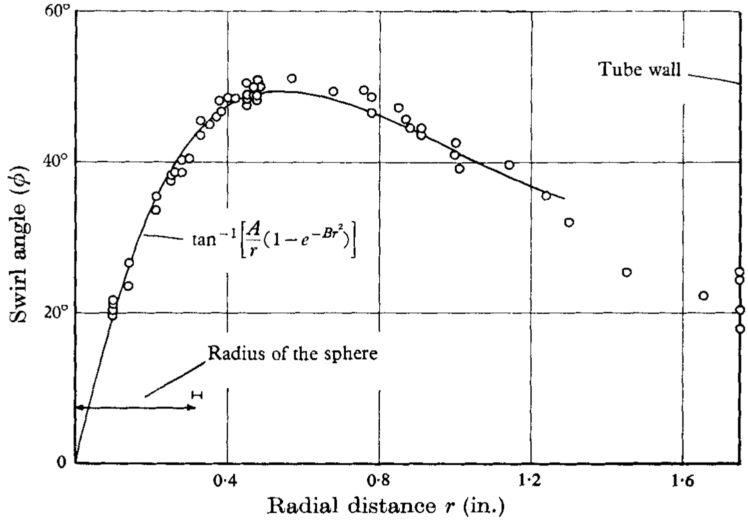

FIGURE 5. The distribution of swirl angle measured ahead of the breakdown.

4. A résumé of the findings

(i) The breakdown appears to be the 'bridging' flow between the two basic rotating flows.

(ii) When free to develop, the breakdown flow is characterized by a spherical bubble of stagnant fluid downstream of which conditions similar to those ahead of it are restored for a short distance until a second breakdown occurs.

(iii) The ability to change from the 'non-reversed' vortex to the 'reversed' and vice versa, plus the orderly nature of flow after the breakdown, point to it being a division between subcritical and supercritical régimes, rather than an onset of instability.

(iv) These observations were made on a vortex whose profile closely resembled the 'exponential' form.

(v) The maximum swirl angle agreed well with Squire's prediction for the value at which the breakdown occurs.

Because of the rather subtle distinction between problems of criticality and stability, and because the elusive nature of the breakdown makes more decisive testing very difficult, conclusions (ii) and (iii) must be proposed with some reservation, so far as the experiments are concerned. Conclusion (iii) is given considerable backing by Brooke Benjamin's theoretical analysis (Brooke Benjamin 1962). The chief merit of this experiment has been in identifying the breakdown with rotating flows in general, rather than the specific case of the delta wing, and in demonstrating that after the bubble had been formed there was not necessarily an immediate degeneration into an unsteady flow but that under suitable conditions, a normal vortex could be restored.

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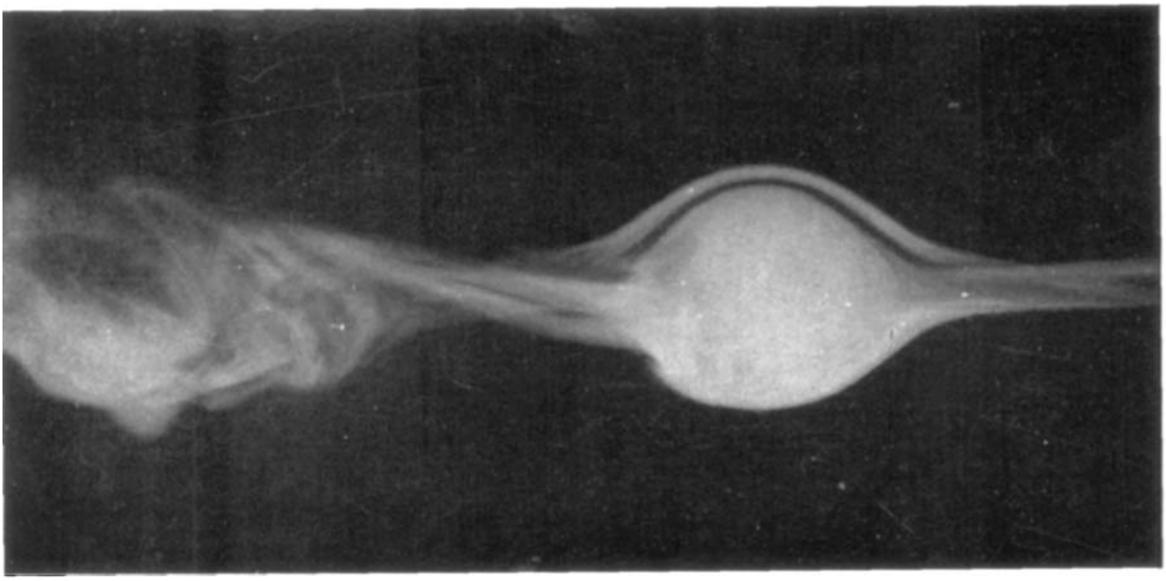

FIGURE 2 (plate 1). A photograph of the breakdown using an electronic flash.

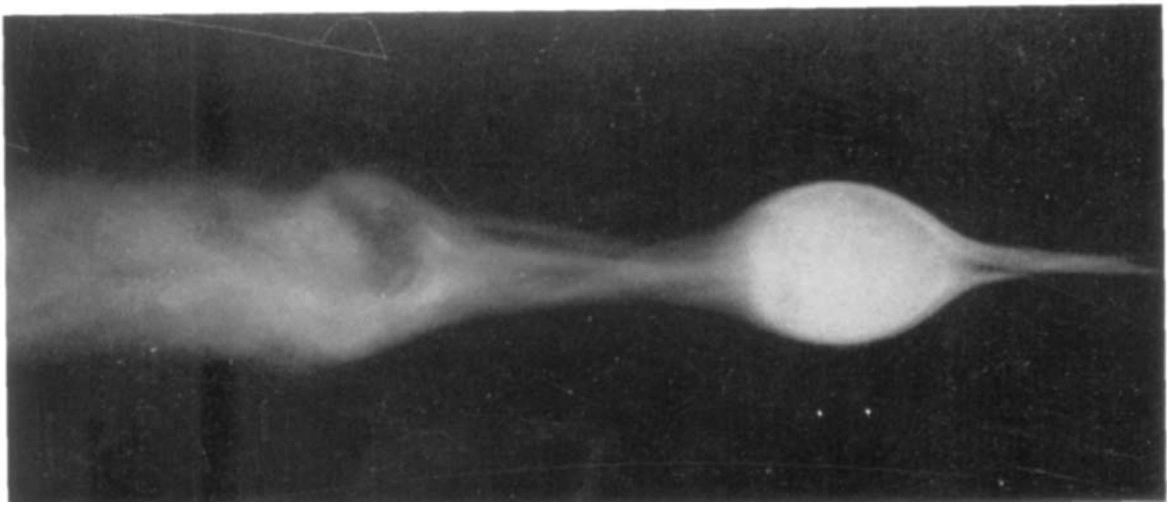

FIGURE 3 (plate 1). A photograph of the breakdown taken with an exposure of 0·1 sec.

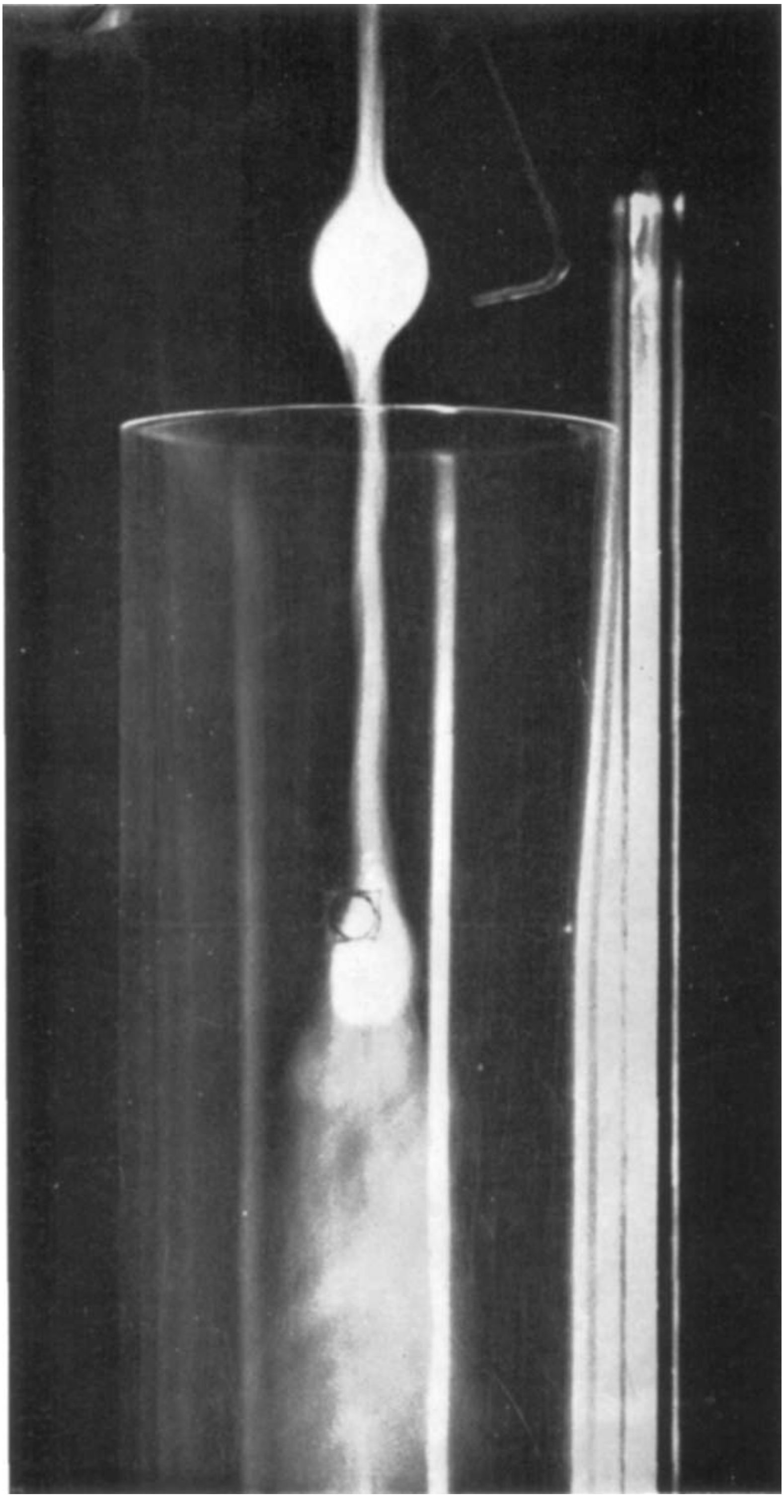

FIGURE 4 (plate 2). The configuration that was obtained as a result of accelerating the flow downstream of the bubble.