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A steady–unsteady visualization technique for wake-flow studies

By J. O. ILEGBUSI AND D. B. SPALDING
Imperial College, London, U.K.

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A description is given of the principle and a preliminary embodiment of a flow-visualization technique in which the test body is pulled through water.

Initially, dyed and undyed parts of the water are separated by a plane horizontal interface; as the body emerges from below this interface, it carries dyed fluid upwards in its wake. A succession of photographs reveals the nature of the flow.

In principle, the flow is steady in a frame fixed relative to the body, and unsteady in one relative to the tank and the initial interface. Interpretation of the experimental results must therefore proceed by way of an analysis in which the steady-state equations are solved for velocity and turbulence quantities but an unsteady-state equation is solved for the dye concentration.

Preliminary results are reported for the flows behind a wedge and behind a bar. They reveal that these particular flows are unsteady even in the body-fixed coordinate frame, being strongly oscillatory.

1. Introduction

Insight into a physical process has been known to be improved if a pattern produced by or related to this process can be observed by visual inspection. However, most fluids are transparent media and means must be provided to make the flow visible. Such methods are called flow-visualization techniques. These techniques often provide information about the complete flow field under study without physically interfering with the fluid flow.

Extensive reviews of the literature on flow-visualization techniques for various applications have been made by Merzkirch (1974) and Hunter & Foughner (1982); none will therefore be provided here. However, a new technique is described which has been devised for investigating turbulent flows containing small regions of recirculation. A preliminary embodiment of the principle is reported and a few results from a study of the flows in the wakes of a slender wedge and of a thin bar are presented. Further developments are also described.

2. Description of the new technique

2.1. *The principle*

Wind tunnels and water channels are expensive to build and to run. It is much cheaper, and can be very instructive, to pull the flow-creating body through fluid at rest, as is routinely performed in 'towing-tanks' for ship research.

The technique to be described below is of the pulling-through-fluid-at-rest kind; but it has the novel feature of using *two* fluids one above the other, and making their flow-induced intermingling visible by the use of a dye.

The two fluids are at first kept separate by a small difference of density, sufficient to maintain a perfectly horizontal and well-defined interface, but not so great as to influence the flow generated by the movement of the test body. This latter condition simply requires the Froude number U^2/gl greatly to exceed the ratio $\Delta\rho/\rho$, where $U \equiv$ body velocity, $l \equiv$ body length, $g \equiv$ gravitational acceleration, $\Delta\rho \equiv$ density difference between the two fluids, and $\rho \equiv$ the density of one of them.

The body is at first immersed at rest within the lower fluid, which is coloured with a dye. A steady upward force is then suddenly applied to it, so that it rises, steadied by suitable guides, attaining a uniform velocity before it breaks through the interface.

As the body emerges from the lower fluid, it is seen to carry with it, in its boundary layer and wake, significant quantities of the lower fluid. Entrainment of clear (upper) fluid into the boundary layer and wake progressively dilutes the dye, with obvious visible consequences.

A succession of photographs enables the various states of mixing to be recorded, and subsequently measured.

2.2. *Quantitative interpretation of the results*

Experiments are especially valuable if they yield quantitative results which may be compared with the predictions of a general theory. It is therefore necessary to ask whether such comparison is possible in the present case. The answer is affirmative, provided that sufficiently powerful computational procedures are available.

In a frame of reference which is fixed relative to the test body, the flow may be expected to be steady. A suitable method of prediction for the velocity and turbulence fields is therefore a steady-state one; the new experimental technique shares this requirement with conventional wind-tunnel techniques.

However, the equation for the dye concentration, if solved in the same reference frame (moving with the body) as is used for the velocity and turbulence fields, contains *transient* terms; this is a consequence of the movement towards and through the initially flat interface between dyed and undyed fluids. Therefore to solve this equation more computational work must be done.

Fortunately, there is nowadays little difficulty about performing this extra work; for computer software and hardware are available. It is therefore the intention of the authors to adopt this method of analysis.

2.3. *A practical embodiment*

Figure 1 illustrates the apparatus which has been built so as to test the practicability of this method for flow visualization. The apparatus consists of two water tanks, a metal framework, and a system of smooth pulleys, rubber tube, steel wires, motor-wound camera, water, dye and weights. One of the tanks is made of 10 mm thick perspex with internal dimensions of $0.2 \times 0.2 \times 1.5$ m; and the other is a 15 litre glass jar.

The metal framework is an assembly of steel bars with provision for attaching two pairs of specially smooth pulleys each of 25 mm radius. The dye consists of nigrosine. The salt solution employed as the denser fluid has a concentration of 10 g/litre.

The operational procedure is as follows. The perspex tank is mounted on the metal framework about 0.65 m above the floor to avoid floor vibration. A graduated scale is attached to the tank so that the movement of the body at known time intervals could be recorded.

The two thin steel wires (each of which is attached to one side of the body) are used to suspend the body inside the tank. These wires are passed over the system of pulleys to known weights used to lift the test body.

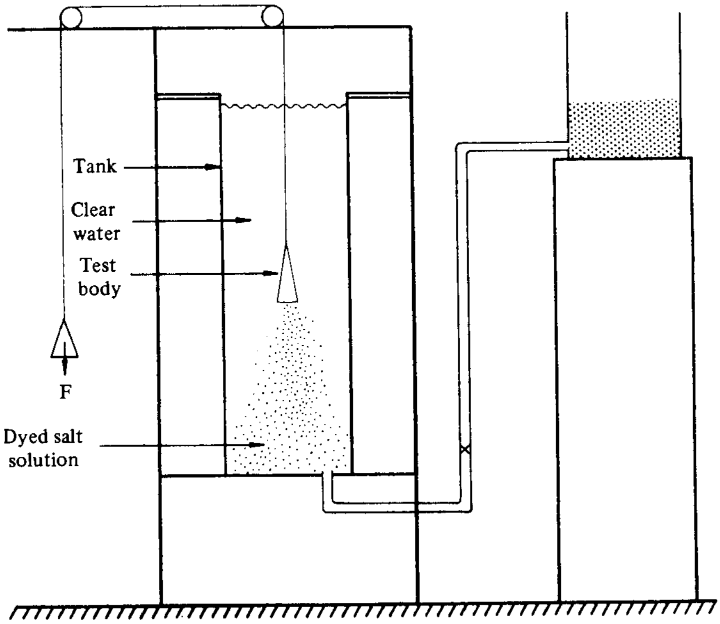

FIGURE 1. The experimental set-up.

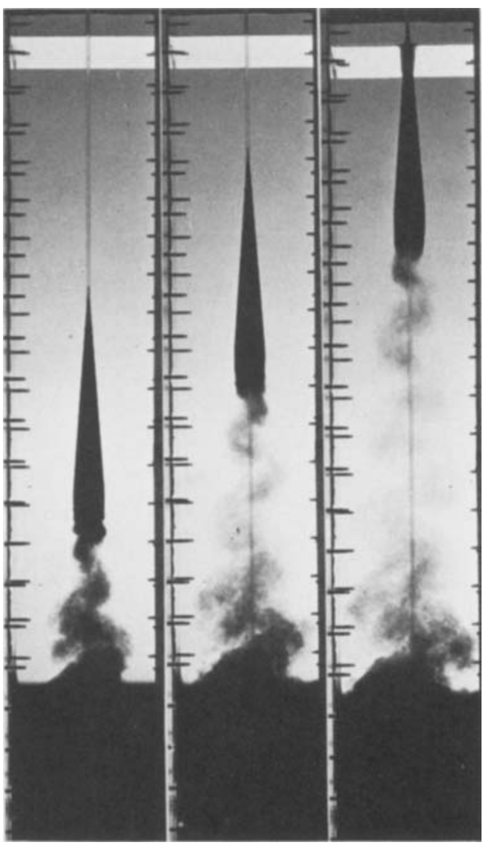

FIGURE 2. Laminar separation behind a wedge.

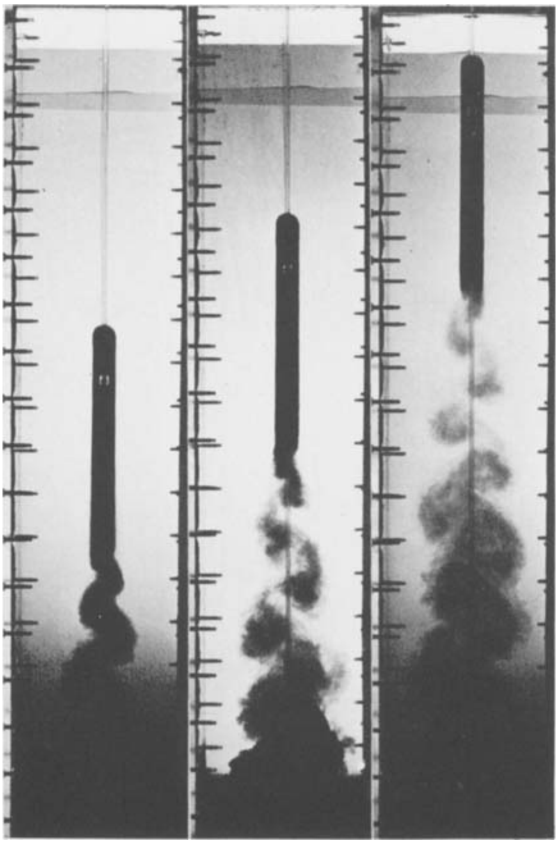

FIGURE 3. Laminar separation behind a bar.

The above technique of suspending the body partly reduces any lateral movement caused by careless handling. Rectilinear movement is further ensured by two slots cut into the tank wall (one at each side) along which the body moves on smooth guides.

The dyed fluid is contained in the glass jar placed adjacent to the first tank. The fluid is introduced via a rubber tube connected to the bottom of the perspex tank. The flow rate is controlled by a valve on the connecting tube.

A translucent polythene paper is attached to the side of the perspex tank away from the camera so as to diffuse the light used to aid photography.

The perspex tank is first filled to about two-thirds height with clear water. The test body is then lowered into it and the dyed fluid (of known concentration) is progressively introduced. The latter operation is performed slowly at first and later increased at a rate that will not disturb the interface.

The body is pulled upwards with known weights attached to the end of the suspension. Photographs of the boundary layer and wake formed behind the body are then progressively taken with the motor-wound camera.

The time taken to perform the whole operation is typically 30 minutes, of which the movement of the test body occupies five seconds.

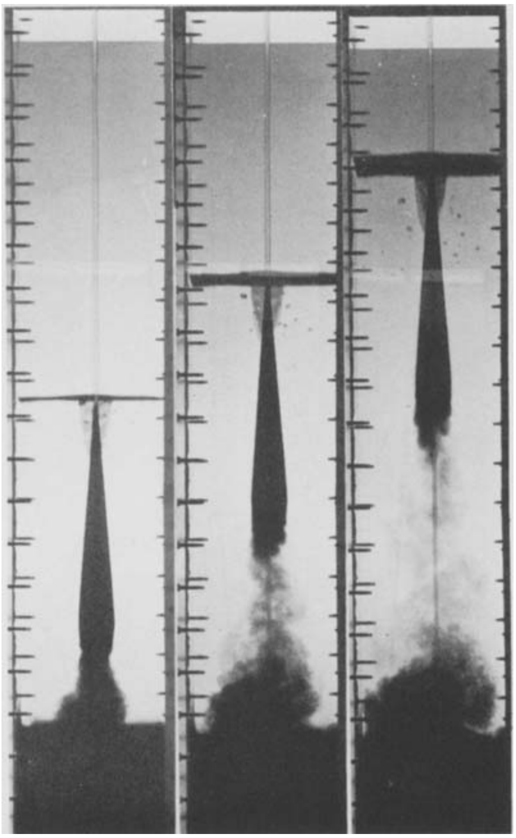

FIGURE 4. Turbulent separation behind a wedge.

3. Preliminary results

3.1. *Laminar separation*

The new flow-visualization technique has been employed in the authors' researches on the flow near blunt trailing edges.

The first test body consists of a wedge of which the cross-section is an isosceles triangle with an apex angle of 8.5° and a base of 30 mm. This wedge is pulled through the fluid layers at a speed of approximately 0.32 m/s. It is made of aluminium.

The second test body consists of a bar of which the cross-section is a rectangle of dimension 18 × 2.54 cm. The body length measured from the base of the semicircle is 23 cm. The bar is pulled upward at a speed of approximately 0.35 m/s.

Figures 2 and 3 show respectively successions of photographs taken during the rise of the wedge and of the bar. The boundary layers and wakes are clearly visible; and it is evident that the latter have strongly oscillatory character.

3.2. *Turbulent separation*

In the experiments just described, the Reynolds numbers, based upon body heights, are approximately 63400 and 80000 for the wedge and bar respectively. These are far too low to create turbulent boundary layers; and, even if they were not, the boundary layers would still be appreciably thinner than those which the authors wished to investigate.

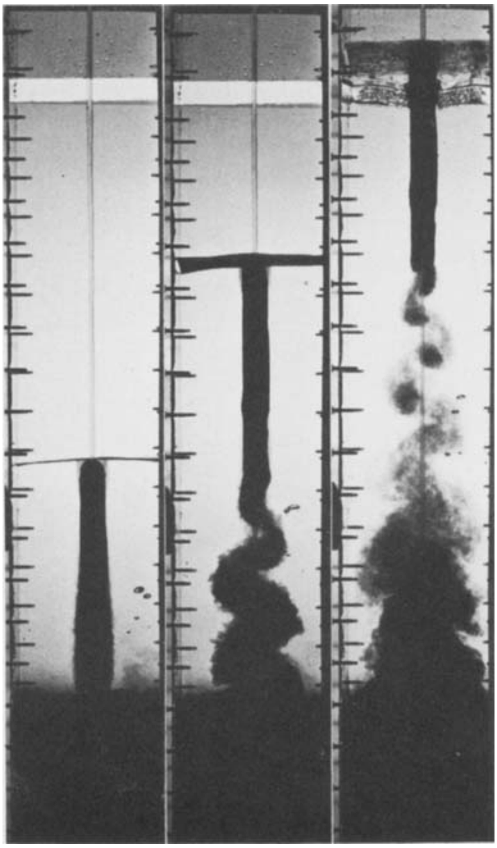

FIGURE 5. Turbulent separation behind a bar.

Therefore in a second set of experiments two measures have been adopted, which together ensure that the boundary layers on the surfaces of the bodies are both thick and turbulent: a wire gauze has been fixed to the leading edge of each body, with its plane at right-angles to the motion; and the body surfaces have been roughened.

Geometrical details of these measures are as follows:

Grid size of wire gauge: 2×2 mm;
Mesh size of wire gauge 25 grids/cm^2;
Average roughness height: 0.6 mm;

(the roughness element is a sandpaper coded 127-2-36 ECL MD BC).

Figures 4 and 5 present respectively a series of photographs taken with the rough wedge, and the rough bar each fitted with the wire gauze. They show very clearly the boundary layers and wakes behind the bodies and the strong oscillatory nature of the wakes. Indeed the generation and shedding of eddies very close to the body trailing-edges could be observed. This gives evidence of the vorticity fluctuations within the wakes and of the intermittent nature of turbulence.

4. Discussion: assessment of the suitability of the technique

The results achieved so far appear to have justified the quite modest effort which has been expended. Certainly the qualitative nature of the flow has been excellently revealed; and the presence of strong oscillation for both laminar and turbulent conditions might not have been so swiftly recognized had the technique not been used.

That only low Reynolds numbers are attainable is, of course, a disadvantage; but an increase of size can go some way towards alleviating this. For the purpose of the authors' investigation, the use of the gauze and the roughened surface will probably prove adequate.

5. Concluding remarks

The new flow-visualization technique has provided insight into the flow around and behind the bodies which are under investigation, and in doing so it has provided a challenge to workers in computational fluid dynamics who wish to predict the flows which it has revealed.

Developments are possible and desirable on both the experimental and the computational sides. The authors will be proceeding with these in future.

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