Visualization of relaminarizing flows

P. R. VISWANATH*, R. NARASIMHA AND A. PRABHU
Department of Aeronautical Engineering, Indian Institute of Science, Bangalore 560 012

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Abstract

Simple flow visualization experiments are described to demonstrate the phenomenon of relaminarization of an originally turbulent flow by a variety of different mechanisms.

Key words: Relaminarization, Reverse transition, Reversion, Boundary layer transition, Flow visualization.

1. Introduction

It has often been said that turbulence is the natural state of fluid motion—so much so that reports claiming to have observed a reversion from turbulence to a laminar state have been (and sometimes still continue to be) greeted with varying degrees of disbelief. Occasionally, it is even contended that such reversion—or relaminarization, as it is also called,—represents a transition from disorder to order and so must be thermodynamically impossible.

The thermodynamic objection is of course not valid, as the systems claimed to be reverting are by no means closed ; if crystallisation is possible, so is reversion. Furthermore, a great variety of such reverting flows have been studied in some detail in recent years (see *e.g.* a recent survey by Narasimha[1]). Nevertheless, there appears to be a lingering suspicion that whatever effects are observed cannot be considered to have resulted in complete relaminarization of the flow. Such suspicions are naturally strengthened by many dubious claims of having observed reversion ; there has been an unfortunate tendency to attribute any observed departure from some presumed turbulent law to relaminarization. But there are few universally valid turbulent laws ; those that pass as such (*e.g.*, the log law in wall flows) are often only asymptotically valid, and in particular may fail in flows that, while being unusual or abnormal, are nonetheless turbulent.

It is the purpose of the present paper to describe some simple flow visualization experiments that, it is hoped, will convince any doubters that may still remain that relaminarization is indeed possible. In particular, an example is provided to demonstrate each

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* Presently at NASA, Ames, California, U.S.A.

of the three classes of reversion that have been distinguished by Narasimha.[1] In the first of these, turbulence energy is dissipated by the action of a molecular transport parameter, like viscosity or conductivity. For example, flow through a pipe that is enlarged from one diameter to another in a short divergence may revert to the laminar state downstream if the Reynolds number there drops to a sufficiently low value. In the second class, an external agency (like gravity) may work against turbulence energy and so destroy it ; an example is the suppression of turbulence in a stably stratified flow, such as an inversion in the atmosphere. This class may be called the Richardson type, after the author of the first studies of inversions.[2]

There is a third category of reversions in which the absolute value of the turbulent stresses is not necessarily reduced everywhere, but the mean momentum balance is determined largely by the presence of an additional force which overwhelms the Reynolds stress. This is what happens in a turbulent boundary layer subjected to severe acceleration. The reversion observed here is only in part due to the two mechanisms mentioned above ; the major factor is the domination of pressure forces over the slowly-responding Reynolds stresses in an originally turbulent flow, accompanied by the generation of a new laminar sub-boundary layer stabilized by the favourable pressure gradient.

The experiments to be described below employ flow visualization by dye in water, and colour schlieren photography in air. The *dynamics* of the observed phenomena will not be discussed at length here, as this has been done elsewhere.[1]

2. Dissipative reversion

This can be demonstrated most easily in a bifurcating pipe—say across a T-tube, arranged as shown in Fig. 1 *a*. The division of the flow between the downstream branches of the T can be controlled by valves. The flow is kept turbulent in the upstream branch by increasing the Reynolds number well above the critical ; in the present experiments this Reynolds number was about 3,000 (based on average velocity and pipe diameter). By operating the valves, the downstream Reynolds number in the straight section of the T is reduced to about 500.

Fig. 1 *b* is a photograph of the flow visualized using dye. The purple dye injected upstream diffuses rapidly, showing turbulence in the flow; the green dye injected about 30 diameters downstream of the bifurcation remains a clean, thin filament, showing that the flow has reverted to the laminar state. (To avoid mixing of colours, the photograph was taken just before the time that the purple dye-injected upstream reached the downstream injection station.)

It is interesting that, in the human lungs, a reversion from turbulent flow in the wind pipe to laminar flow in the bronchioles occurs by an essentially similar mechanism, multiplied many times over in the branchings that occur in the respiratory airways.

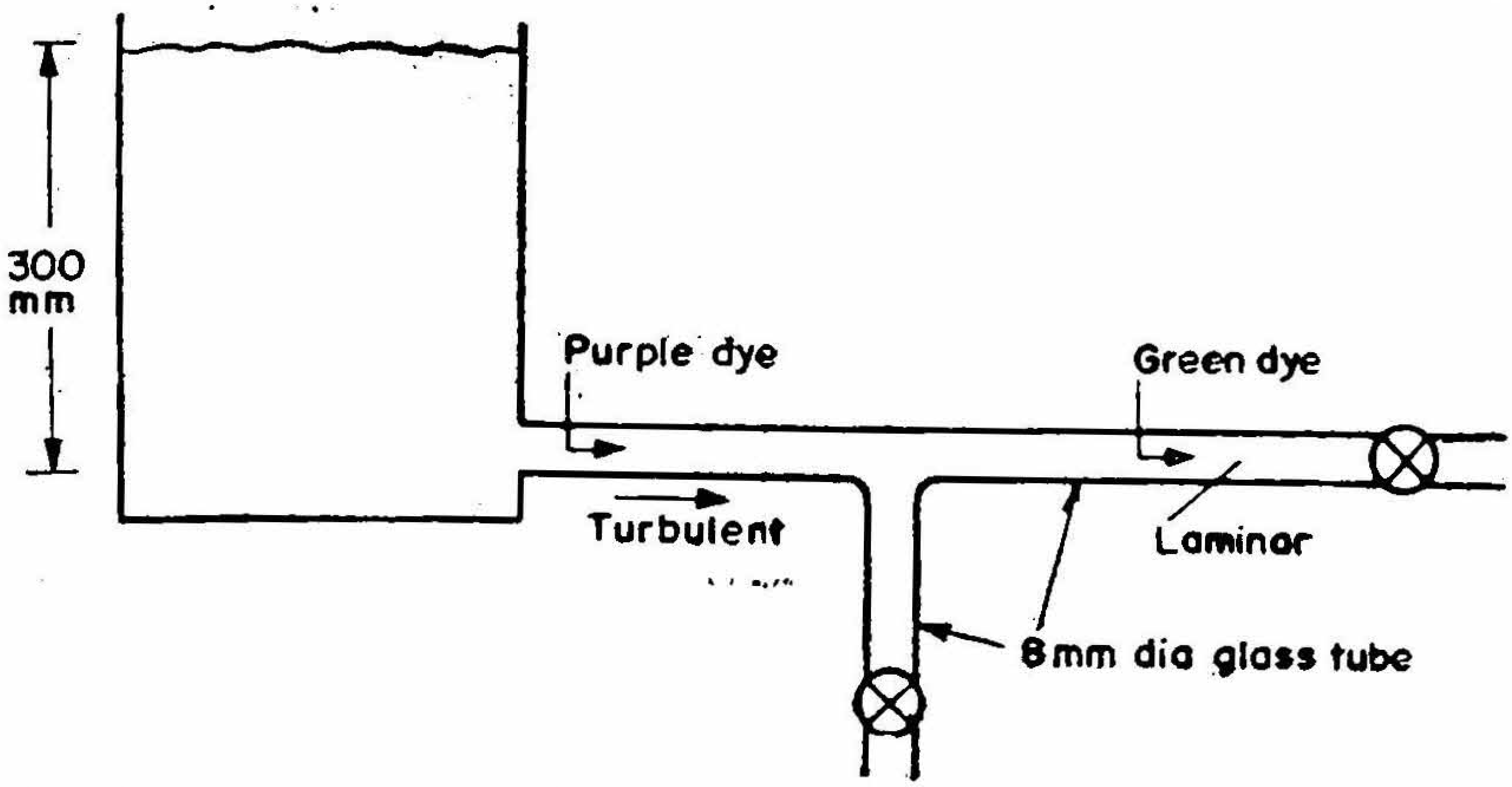


FIG. 1 *a*. Apparatus to demonstrate dissipative reversion in bifurcating pipe flow.

3. Richardson type reversion

Fig. 2 *a* shows an experimental arrangement consisting of a square tank with two parallel walls of 0·25 in (6·25 mm) thick glass. A jet of dye issues from a vertical tube (1 mm i.d.) at the centre of the floor of the tank. The tank is filled with cold water to about three quarters of its height ; the upper layers of the water may be heated radiatively using a conventional circular heating coil. With a coil rated at 2 kW the heating time was typically 4–5 min to obtain a temperature rise near the free surface of about 8–10° C.

In the absence of heating, one finds that the jet of dye first undergoes a transition from laminar to turbulent flow, and then mixes rapidly with the water in the tank (Fig. 2 *b*), all of which gets coloured in less than a minute. If the heating is switched on, and, after the period of 4–5 min noted above, the jet is also turned on (the velocity being controlled again by a pinch cock so that turbulence in the jet is seen clearly), it is found that eventually the purple dye jet collects in a 'cloud' layer near the top (Fig. 2 *c*). There is very little activity in the cloud as the turbulence is suppressed ; the thickness of the cloud at the top of course keeps increasing if the jet is continuously on. Note incidentally that direct transition in the jet followed by reversion in the cloud may be easily observed in Fig. 2 *c*.

The phenomenon observed in this experiment has similarities with atmospheric inversions. An inversion is a narrow layer in which the temperature locally increases with altitude, so that the associated buoyancy forces have a stabilizing influence. (A destabilizing density stratification, on the other hand, leads to free convection resulting in increased turbulent activity.) The turbulence in a rising cloud which encounters such an inversion is suppressed, and the cloud flattens out horizontally into a rather smooth shape which contrasts strongly with its ragged outline before meeting the inversion.* The cloud is replaced by a turbulent jet in the laboratory experiment.

* Smog accumulation in the atmosphere is often again due to such inversion layers.

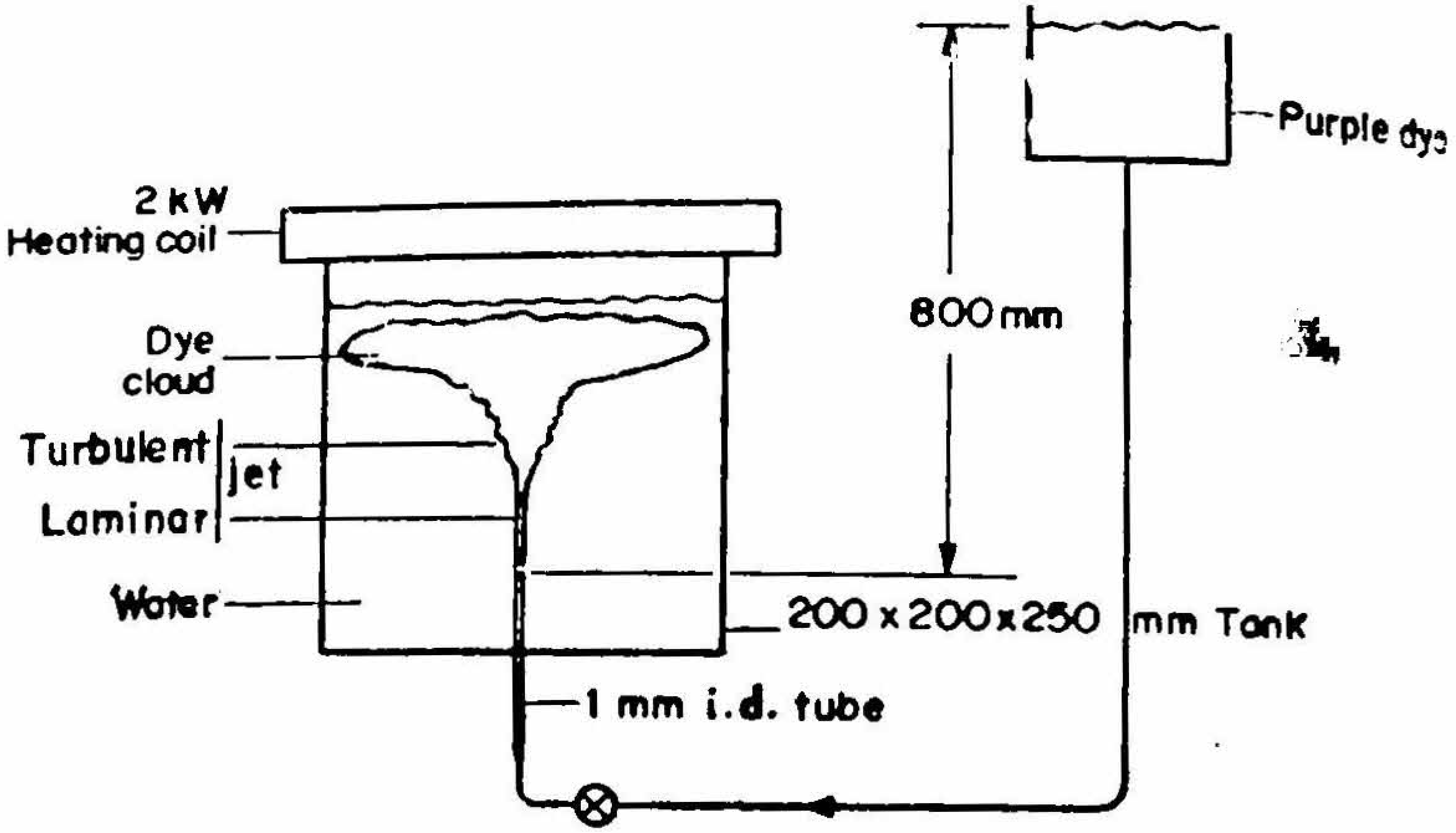


FIG. 2 *a*. Experimental set up to demonstrate reversion in a stably stratified fluid.

4. Reversion by domination

Here we demonstrate reversion in a supersonic turbulent boundary layer subjected to sudden acceleration at an expansion corner. A sharply boat-tailed backward facing step (*see* Fig. 3 *a*) was chosen so that, in addition to reversion in the boundary layer, other interesting flow features may be seen.

This experiment was performed in a 7 in. × 5 in. (17·5 cm × 12·5 cm) supersonic wind tunnel. The experimental conditions are summarised below :

Mach number	1·5
Stagnation pressure	200 kPa (abs)
Boundary layer upstream of corner	turbulent
thickness	8 mm
Boat-tail (or expansion) angle	15 deg.

The expansion angle of 15 deg. was chosen to satisfy the criterion for reversion found by Narasimha and Viswanath.[3] A conventional two-mirror schlieren technique (described, *e.g.*, in ref. 4) was used for flow visualization, with colour filters in place of the knife edge. The filters were Kodak gelatin type, and were horizontal strips of red, green and blue, respectively 4 mm, 1 mm and 4 mm wide.

If ρ is the density and y is the coordinate upwards from the base (Fig. 3 *a*), the schlieren picture gives measures of $\partial\rho/\partial y$; the filters were arranged to give the following correspondence :

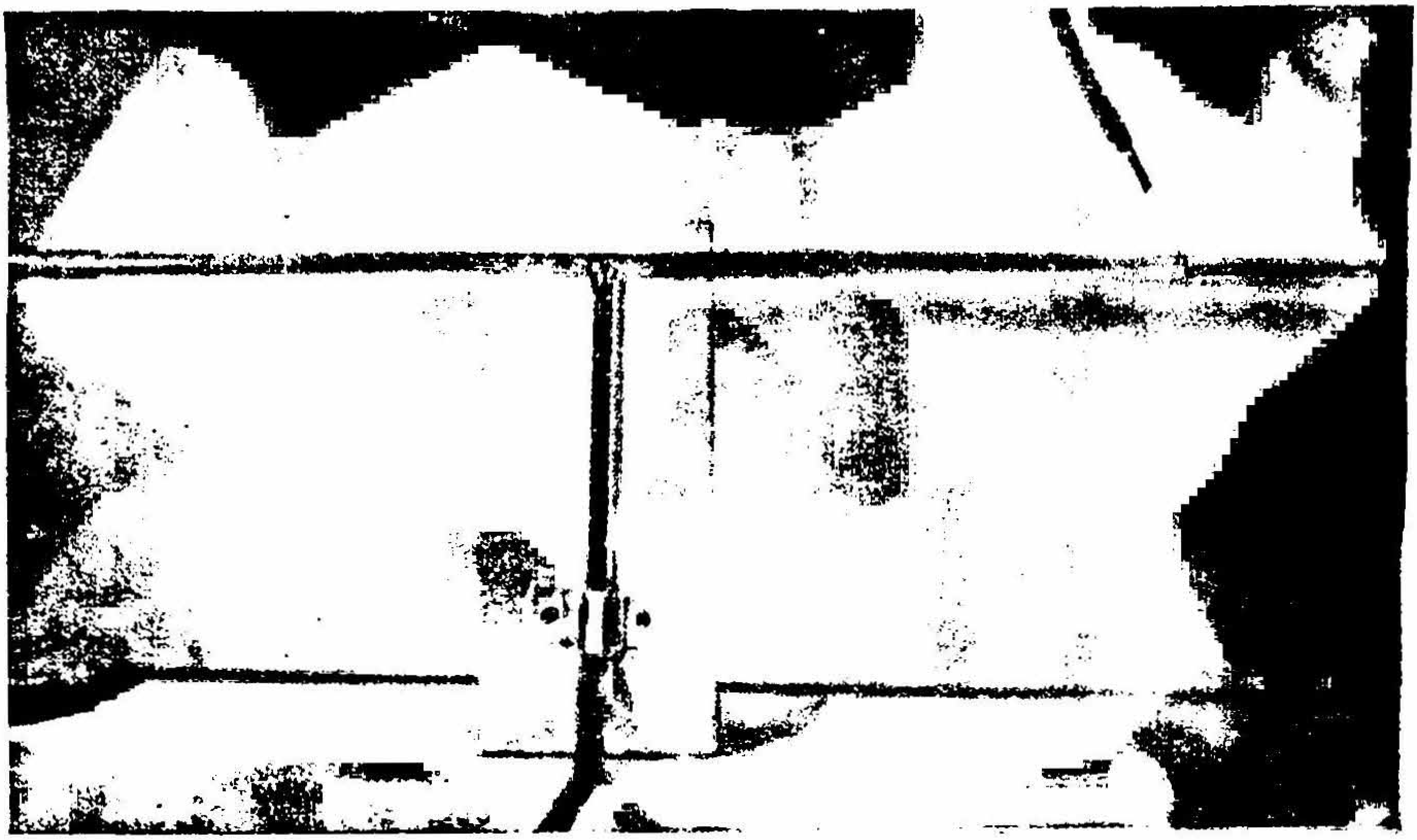


FIG. 1b. Relaminarization in bifurcating pipe flow.

FIG. 2b. Flow without heating.

FIG. 2c. Reversion, with heating coil switched on.

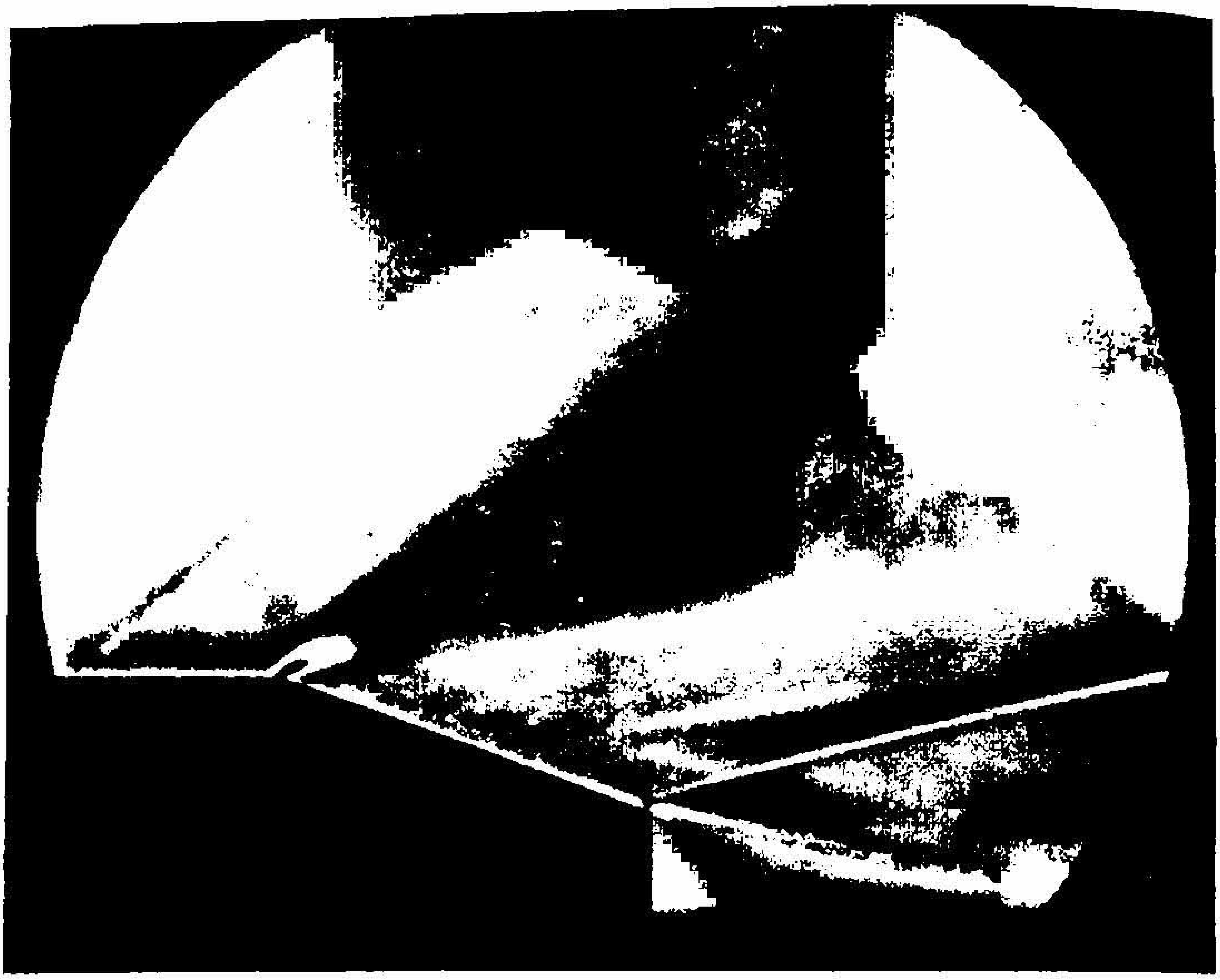
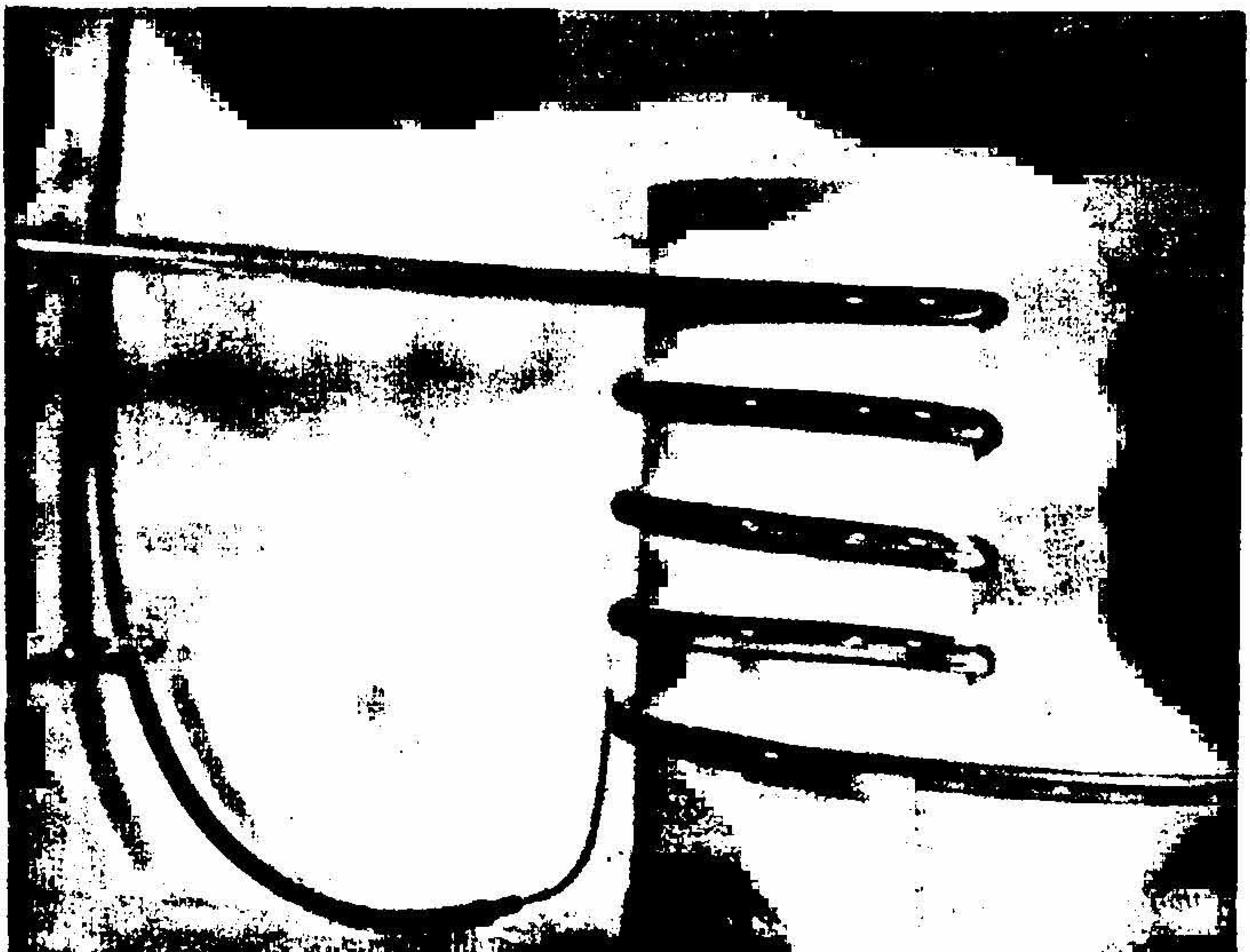


FIG. 3b. Relaminarization at an expansion corner in supersonic flow.

FIG. 4b. Reversion in a coiled tube.



$\partial\rho/\partial y$ < 0 : blue
$= 0$: green
> 0, moderate : red
> 0, strong : white.

'Strong' density gradients $\partial\rho/\partial y$ cause correspondingly large deflections of the light beam, which goes beyond the filters on to the transparent glass, resulting in white.

Fig. 3 *b* shows a schlieren photograph taken on Agfa colour sheet film of size 6·5 cm × 8 cm, 40 ASA, with a mercury vapour lamp of 250 watts (although a white source would have been preferable). One may discern here (*see* also key in Fig. 3 *a*) :

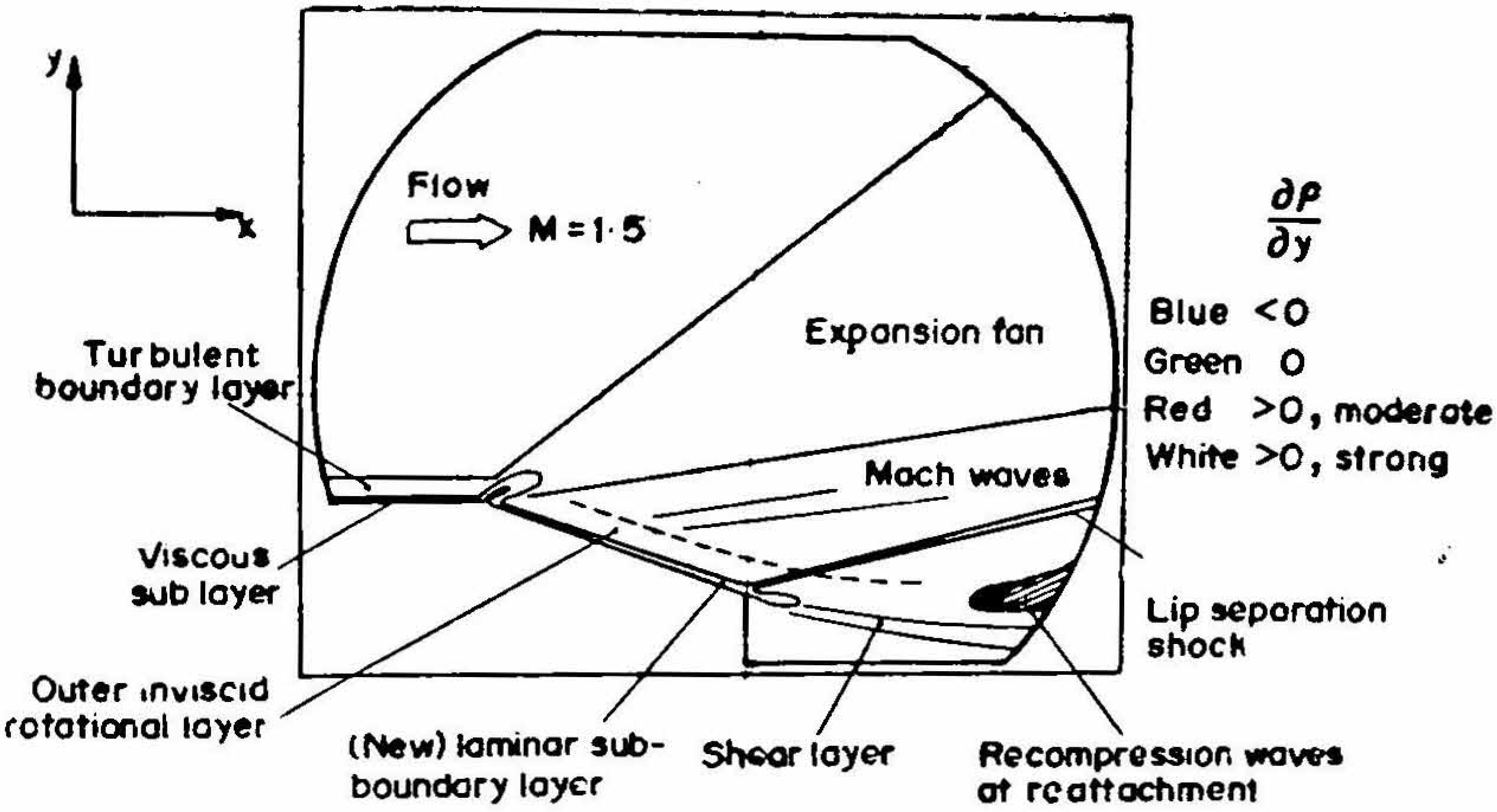


FIG. 3 *a*. Supersonic flow past a boat-tailed step, also serving as key to Fig. 3 *b*.

a region of strong density gradients corresponding to the viscous sublayer (white streak) in the approaching flat plate turbulent boundary layer (red strip), upstream of corner ; the *growing* laminar (sub-) boundary layer (another white streak) downstream, following reversion ; above this, a thicker, weakly sheared layer (pale red) that is a remnant of the outer region of the approaching turbulent boundary layer. A few Mach waves, both upstream and downstream of the corner, help to display the local Mach angles. The downstream Mach waves run into the lip separation shock (usually present on boat-tailed bases at large angle^5) formed near the separation point. The Prandtl-Meyer expansion fan, the free shear layer following separation, as well as the recompression waves at reattachment, can also be clearly seen.

5. Reversion in coiled tubes

This is a most interesting and spectacular phenomenon. It is easily demonstrated in a tube of some flexible, transparent material like tygon. The present experiment uses an 8 mm i.d. tygon tube, which has an initial straight section about 20 cm in length, is then curled around a cylinder of 11 cm diameter and has a final straight section of 15 cm length (*see* Fig. 4 *a*). The fluid velocity is so adjusted that the Reynolds number in the initial section is about 3,000 and flow is turbulent. As Fig. 4 *b* shows, the purple dye injected in this part of the tube mixes rapidly, indicating turbulence. However, the green dye injected at the fourth coil does not diffuse at all, showing that the flow is laminar there. (To avoid mixing of colours, the photograph was again taken just before the time that the purple dye injected upstream reached the fourth coil.) Further downstream along the straight section, the green dye diffuses and the flow becomes turbulent again, but this occurs outside the field covered by the photograph.

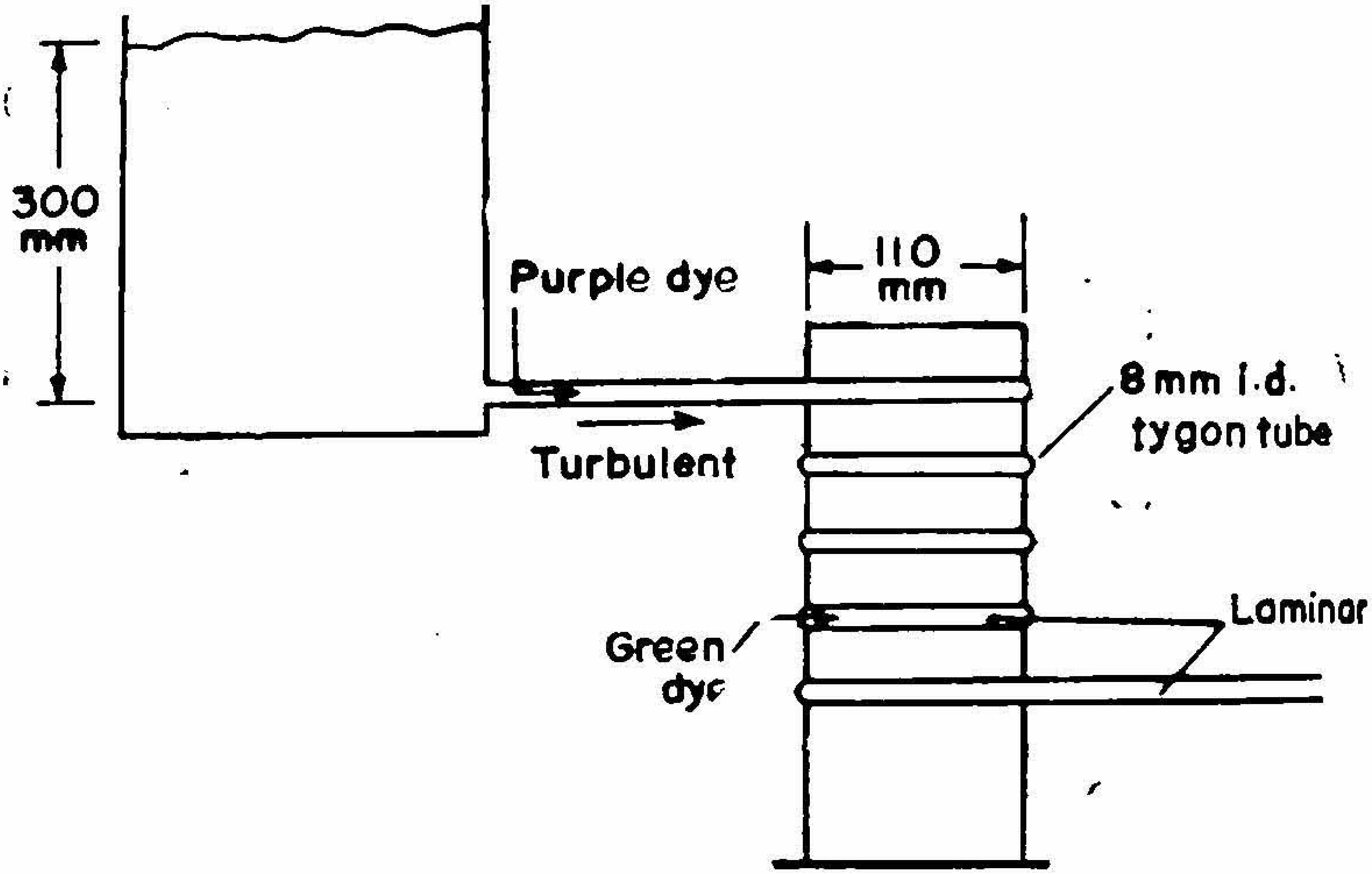


FIG. 4 *a*. Apparatus to show reversion in a coiled tube.

Although this kind of effect was observed by Taylor[6] in 1929, no detailed investigations of reversion in coiled tubes appear to have been made yet. It is therefore not possible yet to identify the mechanism unambiguously ; indeed it is likely that several mechanisms are operating simultaneously in this case. First of all turbulence on a convex wall is suppressed by a Richardson-type effect[7] ; then the curvature induces a secondary flow in the pipe, shifting the velocity maximum outwards and creating a thin layer there of much lower Reynolds number. Further work is necessary to elucidate the role of these (and possibly other) factors in this flow.

6. Conclusion

It is hoped that the simple flow visualization experiments described here demonstrate beyond all reasonable doubt the possibility of reversion from turbulent to laminar flow in a variety of situations.

7. Acknowledgement

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