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A glimpse of fluid mechanics research in Bangalore 25 years age

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Abstract. This paper gives a brief historical account of how fluid mechanics research began in the Aeronautical Engineering Department of the Indian Institute of Science. The motivation for the various investigations carried out in the 1950s and 1960s is recalled and some of the major results are summarized.

Keywords. Fluid mechanics; transition; base flows; separation bubbles; wall jets; turbulent spots.

1. Introduction

Fluid mechanics research at the Indian Institute of Science (IISc) has evolved over the years in a spectrum of directions in six different departments, namely, Aeronautical, Chemical, Civil and Mechanical Engineering, Applied Mathematics, and Centre for Theoretical Studies. I would like to recall here how fluid mechanics research began in the Aeronautical Engineering Department, which has the oldest traditions in the subject, and with which I was personally associated.

The Department came into being in 1942 towards the end of World War II, mainly in view of the requirements of the Indian aircraft industry, Hindustan Aeronautics (then called Aircraft) Limited (HAL). Early activities in the Department were chiefly confined to teaching postgraduate courses in aeronautical engineering to engineering graduates; the annual admission was around ten, and there were a few research students as well. The main facility in those days was the 5 ft × 7 ft wind tunnel having a speed of about 250 ft/s. Dr. V. M. Ghatage who had designed the tunnel had moved on to HAL as chief designer. When I joined the Department in 1951, Prof. O. G. Tietjens was the head of the Department; faculty members included Prof. T. N. Krishnaswamy, Prof. C. V. Joga Rao, Prof. K. Karamcheti, Prof. G. V. Ramana Rao and a few others. Around that time, the Government granted Rs. 16 lakhs (US $ 200,000 approx.) for developing new experimental facilities. In a period of about five years thereafter, four high speed wind tunnels (1 in. × 3 in., $M = 2$; 1 in. × 4 in. and 1 in. × 2 in. transonic tunnels with ventilated walls; 5 in. × 7 in. supersonic, $M = 4$), and three low speed wind tunnels (20 in. × 20 in. boundary layer tunnel, 9 ft × 12 ft open circuit tunnel and 15 ft diameter spinning tunnel) were established. Figure 1 (plate 1) showing a 1/4 in. blowdown supersonic tunnel is a good indication of how experimental research started in high speed aerodynamics. The compressed air storage for this tunnel consisted of two oxygen tanks from an aircraft. Some pictures of supersonic jet flow were taken in this tunnel using a simple Schlieren set-up (figure 2, plate 2).

Fluid mechanics research started around 1952–53 when the 1 in. × 3 in. supersonic tunnel and the 20 in. × 20 in. boundary layer tunnel went into operation (Badrinaryanan 1958, on base flows; Narasimha 1957, on transition). The base flow studies were made in the light of the Crocco-Lees mixing theory, and included investigation of the effect of small bleed on base pressure. The transition studies arose from tests in progress at that time in the 5 ft × 7 ft tunnel for HAL on the Marut supersonic fighter (HF 24), the Kiran jet trainer (HJT 16), and an advanced double delta configuration. Typical Reynolds numbers in the tunnel were low (about $1 \cdot 5 \times 10^6$/ft), and turbulence level was high (about 1–3%). Difficulties were experienced in extrapolating experimental data on these aircraft models, and led to a series of transition studies in the 20 in. × 20 in. tunnel.

2. Studies in transition

These transition studies were greatly influenced by Emmons's modelling of the transition process. He stipulated that the process is characterised by a source density or spot production function which determines the probability of any point on a surface in the flow experiencing turbulence. This probability, called the intermittency γ, is then given in terms of the spot production function $g(x, z, t)$, x and z being longitudinal and spanwise coordinates, and t time, by

$$\gamma = 1 - \exp \int - g(x, z, t)\, dxdzdt. \tag{1}$$

Observations at IISc (Narasimha 1957) showed that the breakdown was pointlike and random in time but the events were confined spatially to a very narrow band across the flow; the location of this band also defines the transition 'point' x_t. Various passive disturbance agents were studied, including screens, trip wires, roughness elements, wakes of rods and plates, etc. It was found that the spot production function g could be approximated by a narrow Gaussian distribution centred at x_t. Approximation of this function by a Dirac delta function gives

$$\gamma = 1 - \exp(-A\xi^2), \quad A = 0 \cdot 412, \ \xi = (x - x_t)/\lambda, \tag{2}$$

where λ is a measure of the extent of the transition zone, being the distance between the points where $\gamma = 0 \cdot 25$ and $\gamma = 0 \cdot 75$. As shown in figure 3, this gives a very good approximation to the intermittency, regardless of the details of the transition agent.

It is possible to make a reasonably complete calculation of the mean flow during transition by using superposition of mean flow velocities in turbulent and laminar flow. In particular, the following two relations, for the velocity profile and skin friction, were found to be fairly satisfactory:

$$(u/U)_{\text{transition}} = \gamma (u/U)_{\text{turbulent}} + (1 - \gamma)\,(u/U)_{\text{laminar}}, \tag{3}$$

$$c_{f_{\text{transition}}} = \gamma c_{f_{\text{turbulent}}} + (1 - \gamma) c_{f_{\text{laminar}}}. \tag{4}$$

Detailed studies at the National Bureau of Standards (Schubauer & Klebanoff 1955) had just then shown that spot growth is virtually linear and that its shape is preserved as the spot moves downstream.

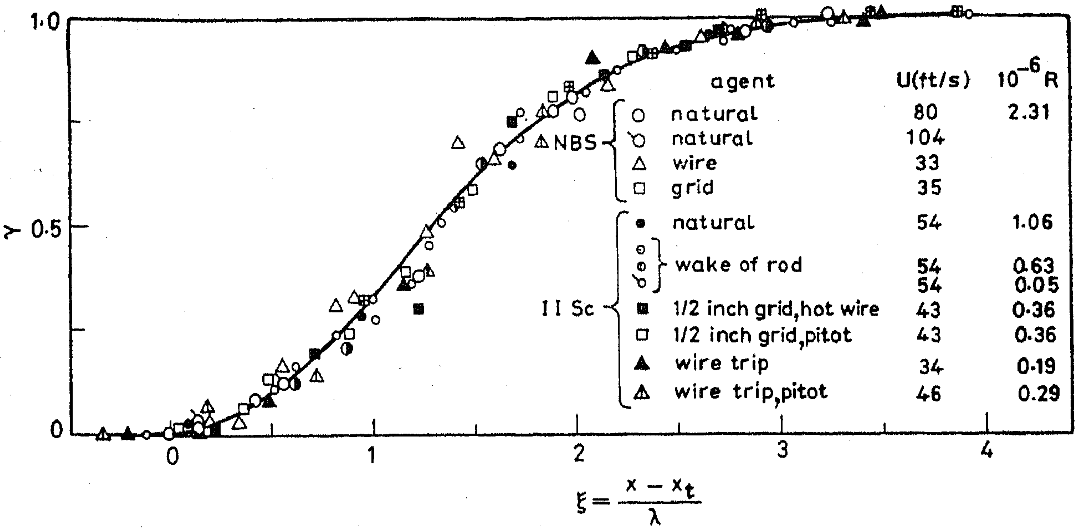

Figure 3. Universal intermittency distribution during transition on a flat plate, with a variety of agents causing transition.

These investigations were extended to the case of a pipe and an axial cylinder. Reynolds had observed that the classical pipe flow had turbulent " flashes ". At Reynolds numbers just above the critical value of about 2000, the flow becomes intermittent, spots grow rapidly into ' plugs ' of turbulence, and a one-dimensional extension of the arguments underlying (2) explains observed intermittency distributions, which follow the relation (Pantulu 1962)

$$\gamma = 1 - \exp(- B\xi), \quad B = 1{\cdot}1. \tag{5}$$

Figure 4 shows that the above description is a good approximation at relatively low Reynolds number for various ratios of pipe length to diameter. However, at Reynolds numbers greater than about 5,000, and length/diameter ratios greater than about 75, the turbulence plug production and growth strongly interact with the mean flow, causing reduction in the Reynolds number (for a given pressure drop along the pipe), and suspension of turbulence production, until the plugs are washed out.

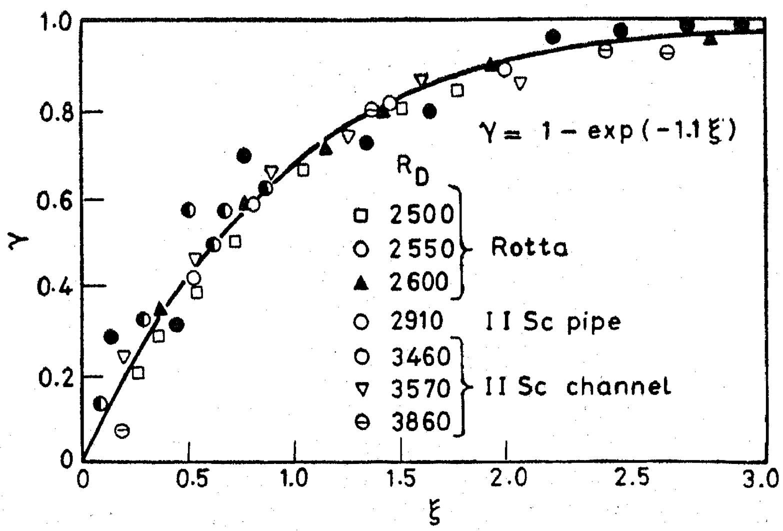

Figure 4. Universal intermittency distribution in duct flow.

The process becomes regular and periodic, and intermittency loses its significance. Figure 5 (plate 3) shows the events as Reynolds number and length-to-diameter ratio are increased. In the range of higher Reynolds number and higher length-to-diameter ratio, the rather regular and periodic turbulence production is characterised by a Strouhal number

$$S^* = nD/U^*,$$

where n = frequency, $U^* = (2\Delta p/\rho)^{1/2}$; S^* depends on the Reynolds number R^* (based on U^*) and the length-to-diameter ratio (figure 6). The propagation speeds of laminar-turbulence interfaces in ducts and boundary layers are shown in figure 7.

Transition on axial cylinders (Rao 1966) has some special features when the radius of the cylinder is comparable to or less than the boundary layer thickness. Stability is enhanced by the fuller profile characteristic of this axisymmetric flow. Except for short distances near the location of the transition agent, the turbulent spots wrap around the cylinder into sleeves and the intermittency distribution can be obtained from one-dimensional theory; so the distribution (5) is valid for thisflow also. Furthermore, in fully turbulent flow, the form of the law of the wall has to be modified on account of transverse curvature.

3. Reverse transition

Transition from turbulence to laminar flow was also investigated in supersonic flow around a corner (Vivekanandan 1963), and in a channel with a sudden expansion (Badrinarayanan 1966). Figure 8 (plate 4) shows a Schlieren photograph of supersonic

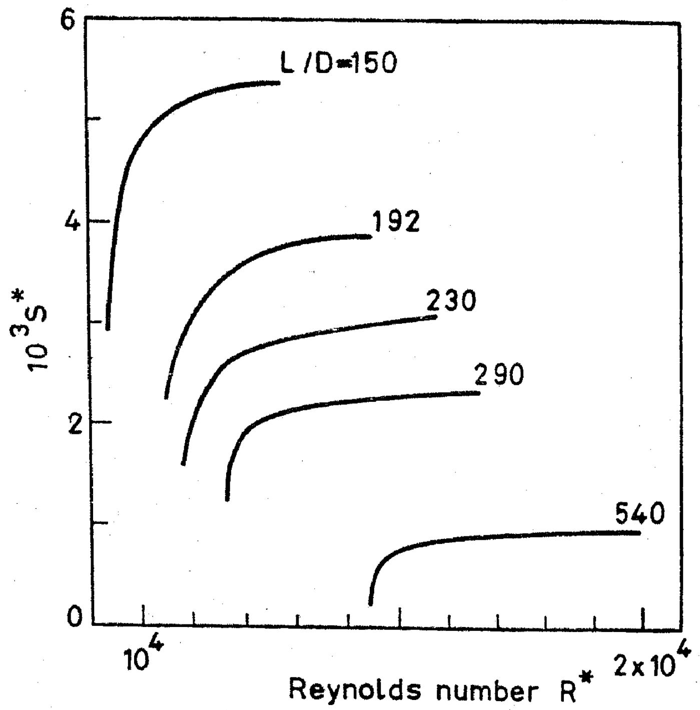

Figure 6. The frequency in the periodic turbulence production regime in pipe flow, as a function of pipe length and a pressure drop Reynolds number.

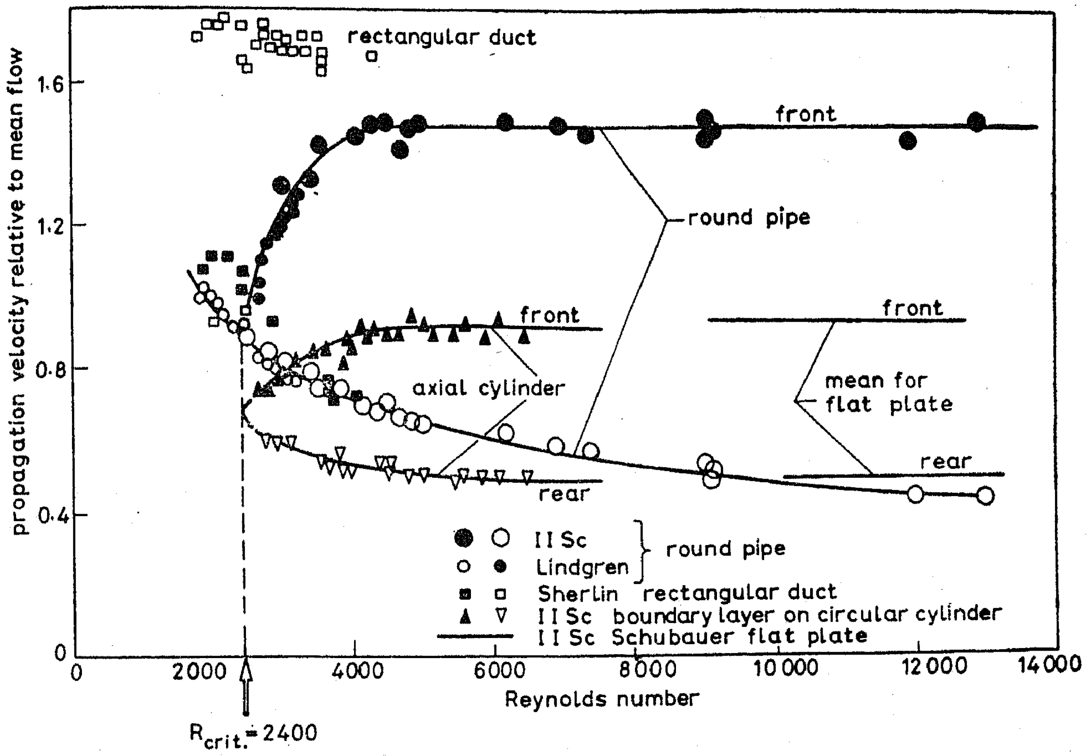

Figure 7. Propagation velocity of turbulent spots and plugs. Reynolds number based on section-average velocity and diameter or height for ducts, and on free-stream velocity and boundary layer thickness for flat plate.

expansion around a corner (Viswanath *et al* 1978). This flow was studied by Vivekanandan using the method of rotational characteristics, and an approximate calculation of the mean velocity profiles was found to be possible. Figure 9 shows the channel used for studying the reverse transition and figure 10 shows the behaviour of several related indicators of turbulence as Reynolds number is decreased.

Relaminarization has been subsequently studied extensively by Narasimha and his co-workers (Narasimha & Sreenivasan 1979).

4. Leading edge separation and laminar bubbles

The phenomenon of bursting of laminar bubbles has been observed on aerofoils with peaky pressure distribution. The adverse pressure gradient near the curved leading edge causes laminar separation and the laminar layer subsequently undergoes transition and reattaches forming a separation bubble. When the angle of attack is in-

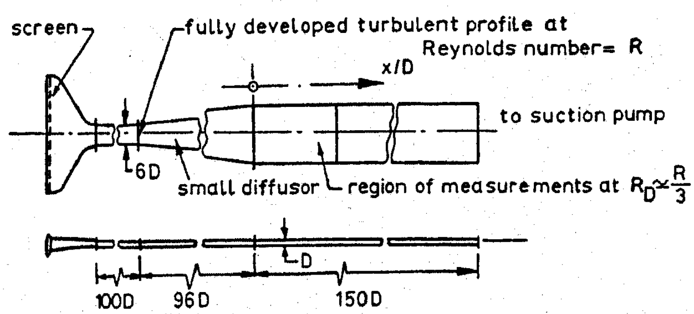

Figure 9. Channel in which the reverse transition from turbulent to laminar flow was studied.

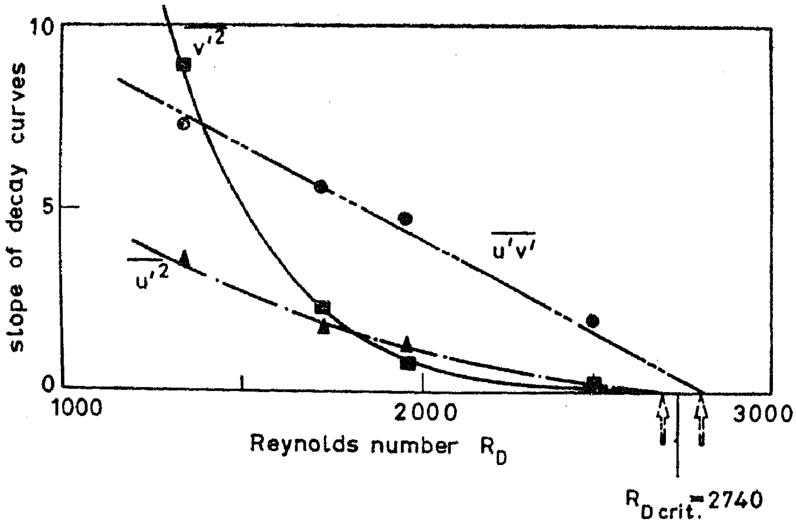

Figure 10. Decay of Reynolds stresses in two-dimensional channel, leading to the determination of the critical Reynolds number.

creased, the bubble length increases; finally the bubble bursts suddenly, which has adverse consequences on C_L *vs* α characteristics. The studies at IISc attempted to separate the effect of pressure gradient from that of curvature by producing laminar bubbles on a flat plate (figure 11, Ojha 1965). The curvature effects were studied by higher order boundary layer theory where not only the velocity but also velocity gradient at the edge of the boundary layer has to be matched. It was found that convex curvature tends to reduce the skin friction coefficient. An approximate method similar to Pohlhausen's was also developed.

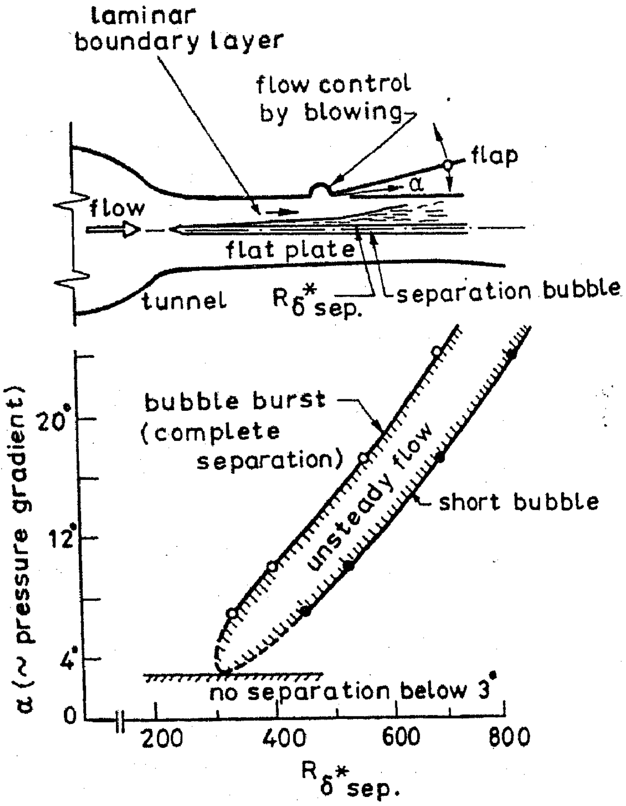

Figure 11. Different regimes of laminar separation bubbles. Also shown (above) is the schematic of the experimental arrangement used for producing separation bubbles on a flat plate.

5. Boundary layer flow control and wall jets

At this time there was significant interest in the intake tests for the Marut supersonic fighter (figure 12, plate 5). Slot blowing needed for velocity profile control in the duct led to interest in wall jets (Parthasarathy 1964). A skin friction balance was built (figure 13) and the effect of external flow on the wall jet was investigated on the basis of direct measurement of skin friction (figure 14).

6. Controlled production of turbulent spots

Although I moved away from active research from 1965, there was a short holiday from administration in 1972, when I was able to return to experimental studies in transition and large-scale turbulent structures. The ideas behind these studies originated from the Bangalore activities. Figure 15 shows the experimental set-up used by me at California Institute of Technology to generate controlled turbulent

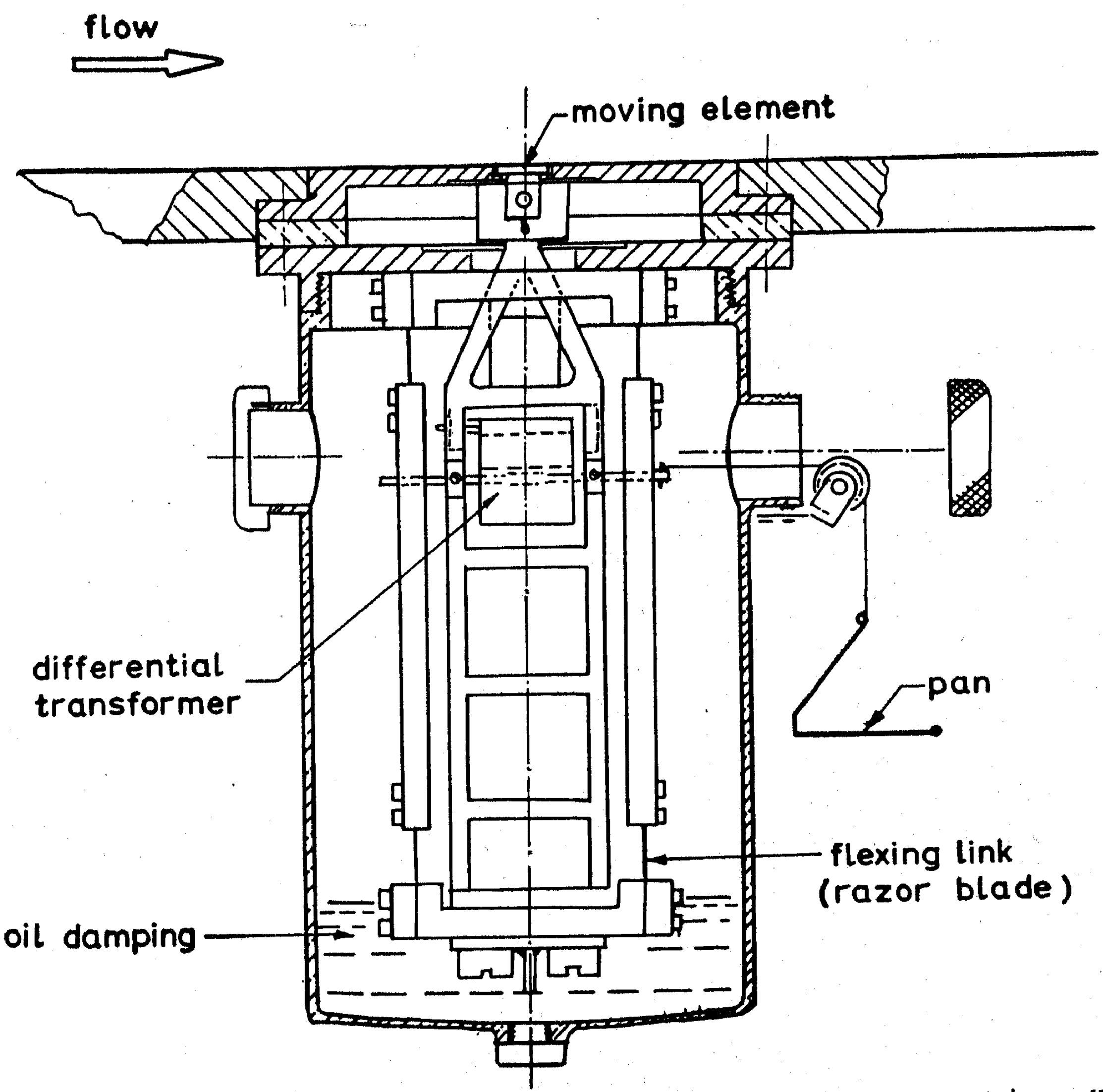

Figure 13. Skin friction balance, used for making wall stress measurements in a wall jet.

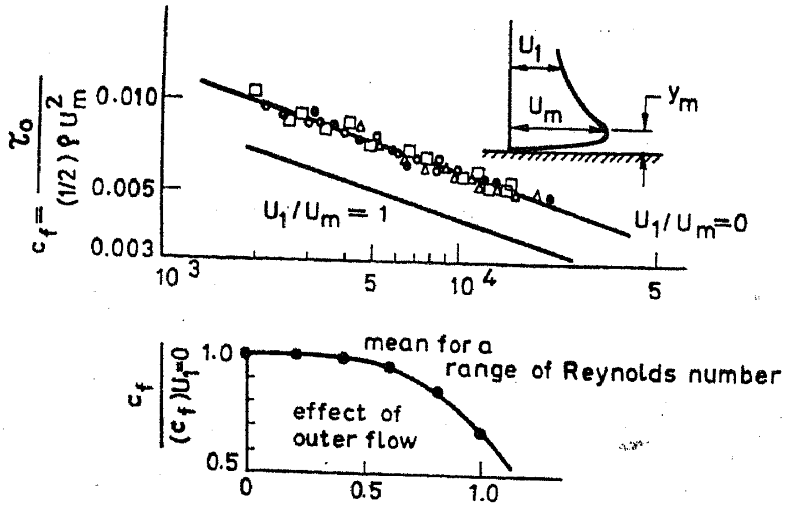

Figure 14. Skin friction in wall jets.

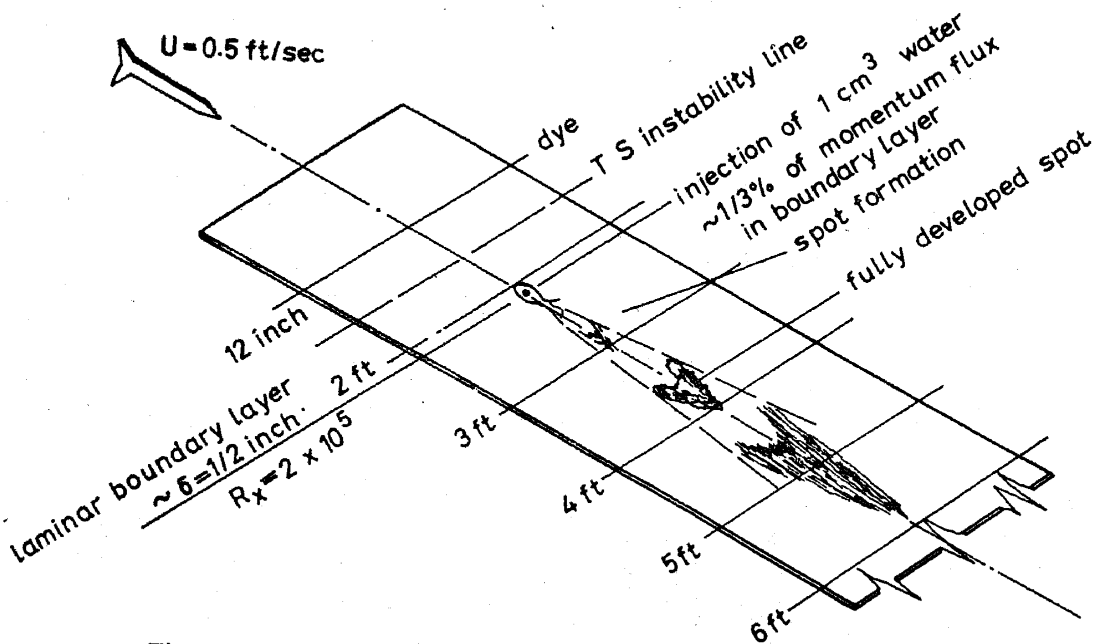

Figure 15. Experimental arrangement for production of turbulent spots by periodic injection of water.

spots by injecting dye in the boundary layer on a flat plate. Flow velocity was about 0·5 ft/s and injection frequency was once in 5 seconds and 2·5 seconds. The Reynolds number at injection was 2×10^5 and boundary layer thickness was 0·5 in. I made a short movie to show how the spots are formed and how they develop their typical arrow-head shape.

7. Concluding remarks and acknowledgements

Experimental work described here was carried out by many of my colleagues, some of whom were earlier students in the Aeronautical Engineering Department. It called for considerable ingenuity and dedication to work under adverse conditions, and the results reported in many papers in journals, not mentioned here, bear testimony to the spirit of scientific investigation. I should also mention again that I have limited my remarks to investigations that I personally know about, and there were many, which are not mentioned here, which have also contributed significantly to the development of fluid mechanics research in India.

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