A GLIMPSE OF FLUID MECHANICS RESEARCH IN BANGALORE 25 YEARS AGO

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1.0 INTRODUCTION

Fluid mechanics research at the Indian Institute of Science 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. On the occasion of the First Asian Congress of Fluid Mechanics, it is appropriate for me to recall how fluid mechanics research began in the aeronautical engineering department, which has the oldest traditions in this field, and with which I was personally involved.

The Department was set up in 1942 towards the end of World War II, mainly in view of the requirements of the Indian aircraft industry, that is, Hindustan Aeronautics Limited (then called Hindustan Aircraft Limited). Early activities in the Department were chiefly confined to teaching post-graduate 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 1.5 x 2.1m (5 ft x 7 ft) wind tunnel having a speed of about 76 m/sec (250 ft/s). When I joined the Department in 1951, Prof. G.G. Tietjens was the head of the Department; faculty members included Prof. T.N. Krishnaswamy, Prof. C.V. Joga Rao, Prof. K. Karmachetl, Prof. G.V. Ramana Rao and a few others.
Around that time, a government grant of Rs.16 lakhs (US $ 200,000 approx.) was given for developing new experimental facilities. In a period of about five years, four high speed wind tunnels (2.5 × 7.5 cm (1" x 3"), H = 2; 2.5 × 10 cm (1" x 4") and 2.5 × 5 cm (1" x 2") transonic tunnels with ventilated walls; 12.7 × 17.8 cm (5" x 7") supersonic, H = 4), and three low speed wind tunnels (50.8 × 50.8 cm (20" x 20") boundary layer tunnel, 4.74 × 3.66 m (9' x 12') open circuit tunnel and 4.57 m (15") dia. spinning tunnel) were established. Figure 1 showing a 0.64 cm (1/4") 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 a Dakota. Some pictures of supersonic jet flow were taken in this tunnel using a simple Schlieren set up.

Fluid mechanics research started around 1952-53 when the 2.5 × 7.5 cm (1" x 3") supersonic tunnel and the 50.8 × 50.8 cm (20" x 20") boundary layer tunnel went into operation (Badrinarayanan 1958 /1/, on base flows, Narasinha 1957 /2/, on transition). At that time studies were in progress in the 1.5 × 2.1 m (5" x 7") tunnel for Harop on the Harop supersonic fighter (HF 24), Kiran jet trainer (HF 16), and an advanced double delta configuration. Typical Reynolds numbers were low, about 4.9 × 10^5/m or 1.5 × 10^6/foot 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 50.8 × 50.8 cm (20" x 20") tunnel.

2.0 STUDIES IN TRANSITION

These transition studies were greatly influenced by Emmen's modelling of the transition process. He stipulated that the process is characterised by a source density or the 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, y, t), x and y being longitudinal and spanwise coordinates, and t the time, by

\[ γ' = 1 - e^{-\int g(x, y, t) dx \int ds \int dt} \]  \hspace{1cm} (1)

Observations at IIAS (Narasinha, 1957 /2/) showed that the break down was point-like 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_e.

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_e. Approximation of the function g by a Dirac delta function gives

\[ γ' = 1 - e^{-N\pi^2}, \quad A = 0.412, \]

\[ \xi = (x-x_e)/\lambda \]  \hspace{1cm} (2)

Where \( \lambda \) is a measure of the extent of the transition zone, being the distance between the points where \( \gamma' = 0.25 \) and \( \gamma' = 0.75 \). As shown in Figure 2, this gives a very good approximation to the intermittency, regardless of the details of the transition agent.
It is possible to calculate the mean flow during transition by using superposition of mean flow velocities in turbulent and laminar flow. In particular, the following two relations were found to be fairly satisfactory.

\[
\begin{align*}
\frac{(u/U)}{\text{transition}} &= \frac{1}{\text{Re}_{\text{crit}}} \left(\frac{u}{U}\right)_{\text{turbulent}} \\
&+ \left(1 - \frac{1}{\text{Re}_{\text{crit}}}ight) \left(\frac{u}{U}\right)_{\text{laminar}}
\end{align*}
\]

\[
\begin{align*}
\frac{c_f}{\text{transition}} &= \frac{1}{\text{Re}_{\text{crit}}} \left(\frac{c_f}{U}\right)_{\text{turbulent}} \\
&+ \left(1 - \frac{1}{\text{Re}_{\text{crit}}}ight) \left(\frac{c_f}{U}\right)_{\text{laminar}}
\end{align*}
\]

Detailed studies at the National Bureau of Standards (Schubauer and Klebanoff 1955 /3/9) showed that spot growth is virtually linear and the shape is preserved as the spot moves downstream.

Reynolds had observed that the classical pipe flow had turbulent "flashes". At Reynolds numbers just above the critical Reynolds number of about 2,000, the flow becomes intermittent, and Emmons' theory can be extended to explain observed intermittency distributions, which are found to obey the following relation (Pantelis 1962 /4/).

\[
\gamma = 1 - e^{-B\xi}, \quad B = 1.1.
\]

Figure 3 shows that the above description is a good approximation at relatively low Reynolds number for various rations of pipe length to diameter. However, at Reynolds number greater than 5,000, the turbulence plug production and growth strongly interact with the mean flow, causing a reduction in the Reynolds number (for a given pressure drop across the pipe), and suspension of turbulence production until the plugs are washed out. The process becomes regular and periodic, and intermittency loses its significance. Figure 4 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 characterized by a Strouhal number.

\[
S^* = nU/U^*
\]

where \( n = \) frequency, \( U^* = \left(2 \Delta p/\rho \right)^{1/2} \);

\( S^* \) depends on the Reynolds number \( R \) and length-to-diameter ratio (Figure 5). The propagation speeds of laminar-turbulence interfaces in ducts and boundary layers are shown in Figure 6.

Transition on axial cylinders has some special features when the radius of the cylinder is comparable to or less than the boundary layer thickness. The stability is enhanced by the fuller profile characteristic of this axisymmetric flow. Except for short distances near the location of transition agent, the turbulence spots wrap around the cylinder into vortices and the flow can be treated as one-dimensional. Also, in fully turbulent flow, the form of the law of the wall has to be modified on account of transverse curvature (Rao 1968 /5/).

3.0 REVERSE TRANSITION

Transition from turbulence to laminar flow was also investigated in supersonic flow around a corner (Vivekanandan 1963 /6/), and in a channel with a sudden expansion (Badrinarayanan 1966 /7/). Figure 7 shows a schlieren photograph of supersonic expansion around a corner (Viswanath et al.
1978 (8). This flow was studied by the method of rotational characteristics. Figure 8 shows the channel used for studying the reverse transition and Figure 9 shows the behaviour of several related indicators of turbulence as Reynolds number is decreased.

Relaminarization was subsequently studied extensively by Narasimha and his co-workers (Narasimha and Sreenivasan 1979/89).

4.0 LEADING EDGE SEPARATION AND LAMINAR BUBBLES BURSTING

The phenomenon of bursting of laminar bubbles has been observed on airfoils with peaky pressure distribution. The adverse pressure 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 increased, the bubble length increases; finally the bubble bursts suddenly, which has adverse consequences, on $C_l$ vs. $C_D$ characteristics.

The studies at IITC attempted to separate the effect of pressure gradient from the effect of curvature. Laminar bubbles were produced on a flat plate (Figure 10, Ojha 1965/107). 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 effect. An approximate method similar to Pohlhausen method was also developed.

5.0 BOUNDARY LAYER/FLOW CONTROL WALL JETS

At this time there was significant interest in the intake tests for Harum supersonic fighter (Figure 11). Slot blowing needed for velocity control in the duct led to interest in wall jets (Parthasarathy 1964/117). A skin friction balance was built (Figure 12) and the effect of external flow on the wall jet was investigated on the basis of direct measurement of skin friction (Figure 13).

6.0 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 spend time on experimental studies in transition and large scale turbulent structures. Figure 14 shows the experimental set up used by me at California Institute of Technology to generate controlled turbulent spots by injecting dye in the boundary layer on a flat plate. Flow velocity was about 15 cm/s (0.5 ft/s) and injection frequency was once in 5 seconds and 24 seconds. The Reynolds number at injection was $2 \times 10^7$ and boundary layer thickness was 1.27 cm (5/16). A short movie shows how the spots are formed and how they develop their typical arrow-head shape.

7.0 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.

8.0 REFERENCES


Figure 1. 0.64 cm (1/4") blow down supersonic tunnel

Figure 2. Universal distributions of intermittency during transition

Figure 3. Intermittency distribution for flow through ducts
Figure 4. Hot-wire traces of turbulence in a pipe, $R_t \approx 5500$

Figure 5. Periodic turbulence production in a pipe
Figure 6. Propagation of turbulence

Figure 7. Schlieren photograph of supersonic expansion around a corner
Figure 8. Reverse transition in a 2-dimensional channel flow

Figure 9. Variation of turbulence quantities with Reynolds number

Figure 10. Factors controlling the bursting of a laminar separation bubble
Figure 11. Marut supersonic fighter

Figure 12. Skin friction balance

Figure 13. Skin friction in wall jets
FURTHER STUDY OF THE EFFECTIVENESS OF DISCRETE SPACERS FOR SUPPRESSING VORTEX-TURBULENT OSCILLATIONS OF CYLINDRICAL BODIES
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One of the popular remedial measures for suppressing vortex-induced oscillations of cylindrical bodies has been the three-start helical strake of Scurton /1/. The use of discrete spacers was also attempted /2,3/. In connection with suppression of large oscillation of oscillations of in-line chimneys due to mutual aerodynamic interference, discrete strakes, inter alia, have been evolved, recommended and implemented /4,5,6/.

The discrete strake system consists of discrete rectangular plates mounted along three-start helix over the top one-third or so of the chimney height. The projected area of each strake was required to be in the range of 1% to 3% of the cross sectional area of the chimney /7/. There will be some drag penalty when the strakes are used /7/. The increment on C_{L} for continuous strake is 4000 at 8% of a million and 1500 at 8% of six million whereas in the discrete strakes developed at IITK, the increase in measured stream-wise tip deflection was at most 5% only.

Further study to examine the influence of the radial height of discrete strakes on their effectiveness was attempted /8/. Strips of thin PVC sheet were used and the radial height of the strakes is then systematically reduced. The tests were made using four different models: a) tapered chimney model, b) straight chimney model, c) two-dimensional hollow cylinder and d) two-dimensional stranded conductor. The first two were tested in the 4.27 m x 2.74 m Open Circuit Wind Tunnel and the last two were tested in 0.3 m x 0.3 m low speed tunnel. A miniature accelerometer was used to measure the amplitude of