6th Australasian Hydraulics and
Fluid Mechanics Conference
Adelaide, Australia, 5-9 December 1977

The Turbulent Flow through a Sudden Enlargement at Subsonic Speeds

S. KANGOVI
Scientist, Aerodynamics Division, National Aeronautical Laboratory, Bangalore, India
and
R. H. PAGE
Professor, Department of Mechanical and Aerospace Engineering, Rutgers University, New Brunswick, U.S.A.

SUMMARY The flow through a sudden enlargement was experimentally investigated in the Mach number range of 0.1 to 0.95. Results include variation of base pressure and recovery pressure with reference Mach number. The upstream influence distance and the locations of reattachment and secondary separation points are also reported.

1 INTRODUCTION

The flow through a sudden enlargement is a common occurrence in many engineering applications; however the near-wake associated with it (figure 1) has not been extensively studied. The term "near-wake" denotes a separated flow region which includes the separation line, shear layer and the reattachment line.

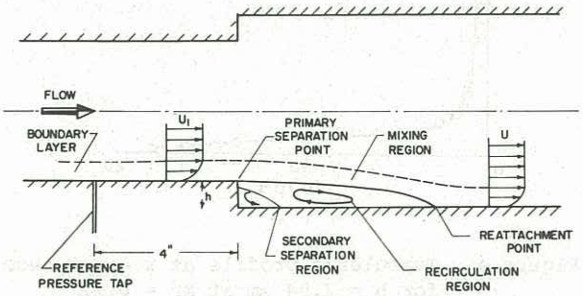

Figure 1 Near-wake of an annular step

Heskestad (1964) conducted experiments on abrupt enlargements in an incompressible flow with a turbulent boundary layer ahead of the step. His investigation of the effect of suction showed that it enhanced turning of flow towards the reattaching surface. The results are useful for qualitative comparisons only because the base pressure was used as the reference to calculate the pressure coefficients. Detailed investigation of the near-wake of an annular step was made by DeRossett (1973). The flow was incompressible and the boundary layer was turbulent. Measurements were made of the upstream boundary layer profiles, turbulence levels in the approaching boundary layer and the base pressure and static pressure along the downstream wall. The reattachment point was located by using a dual element film probe. The reference pressure was taken at a point four step heights upstream of the step. The results showed that the base pressure coefficients proved to be generally insensitive to small changes in flow velocity and boundary layer thickness. The region over which reattachment occurred was found to broaden with an increase in step height or initial boundary layer thickness. The reattachment point was found to be located at a distance approximately five step heights downstream of the step. This location was rather insensitive to the changes in step height and boundary layer thickness. The pressure after the reattachment region levelled off to the recovery pressure, which was in close agreement with the value calculated by one-dimensional theory. A study of the rms levels of wall static pressure was also made. DeRossett (1973) found that the rms pressure signals peaked in the vicinity of the reattachment point. Teyssandier and Wilson (1974) applied an integral analysis to the problem of a sudden enlargement in a pipe. Their analysis predicted the static pressure distribution downstream of the step, the maximum recirculating velocity variation along the axial direction and the shape of separation streamline. The predictions of Teyssandier and Wilson depend on the empirical constants which were assumed for turbulent parameters. Also, the assumption of a self-preserving velocity profile immediately downstream of separation and reattachment is not valid. In addition, it is well known that the subsonic separated flow problem is elliptical in nature and therefore excluding the upstream influence would introduce errors. Benedict et al. (1966, 1976) developed generalised solutions for flow across an abrupt enlargement. They assumed the base pressure to be equal to the reference static pressure in subsonic flow and thus neglected the effect of separation. They also assumed that the maximum static pressure occurred at the reattachment point. These omissions were pointed out by Przirembel and DeRossett but Benedict et al. (1976) dismissed the omissions as "microscopic" and "academic". The present investigation will show that the separation and reattachment considerably influence the recovery pressure. The present paper also demonstrates that it is necessary to allow sufficient length downstream of the enlargement in order to receive the benefit of the full pressure recovery.

2 NOTATION

x	Axial distance from base (positive: downstream, negative : upstream).
h	Step height.
y	Radial distance from model wall
θ	Angular position
M_1	Reference Mach number at x = -4.0 inches

P Pressure

P_1 Reference pressure at X= -4.0 inches.

P_b Base pressure.

P_4 Recovery pressure measured at x = 14.0 inches.

C_p Pressure coefficient = $\frac{P - P_1}{kM_1{}^2 P_1/2}$

U Velocity.

U_{max} Maximum velocity

u' Root mean square value of velocity fluctuations

u* Friction velocity.

δ Boundary layer thickness

δ_1 Boundary layer displacement thickness.

δ_2 Boundary layer momentum thickness

3 EXPERIMENTAL TECHNIQUE

The experiments were carried out in the second generation Rutgers Axisymmetric Near-Wake Tunnel (RANT II). The test section is shown in figure 2.

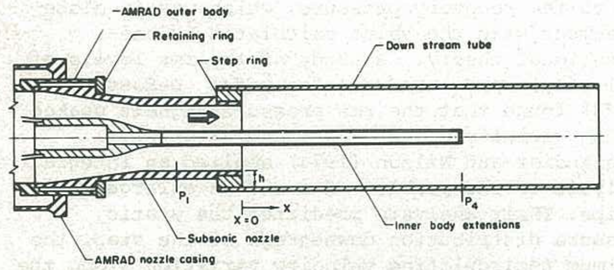

Figure 2 Test section schematic for h = 2.54 cm

Four step heights of 0.63 cm, 1.27 cm, 1.89 cm and 2.54 cm were obtained by changing the intermediate step ring and the downstream tube. The test section reference conditions were measured at 10.16 cm upstream of the step. Mach numbers at various locations upstream of the step were obtained by isentropic relations and also by Fanno-line analysis. There was practically no difference between the two analyses indicating that the approaching flow was nearly isentropic.

The approaching boundary layer was measured with pitot tube and hot-wire probes. In case of the pitot tube measurements, the velocity profiles were corrected for the velocity gradient and proximity of the wall effects as suggested by MacMillan (1956). Power law and polynomial law fits to the data were obtained by the method of least squares. The power law was found to be more representative of the data points. Knowing the power law exponent, various boundary layer parameters were calculated. Compressibility effects were included by expressing density in terms of the Crocco number (Merz 1975). The velocity distribution was also plotted in wall coordinates. Figure 3 shows the normalized velocity-defect data. The friction velocity was obtained using a method suggested by Bradshaw (1959). The figure shows that the velocity defect is less as compared to the standard logarithmic law of pipe based on the work of Laufer (1954). This indicates a steeper velocity profile as compared to fully developed turbulent velocity profile in a smooth pipe.

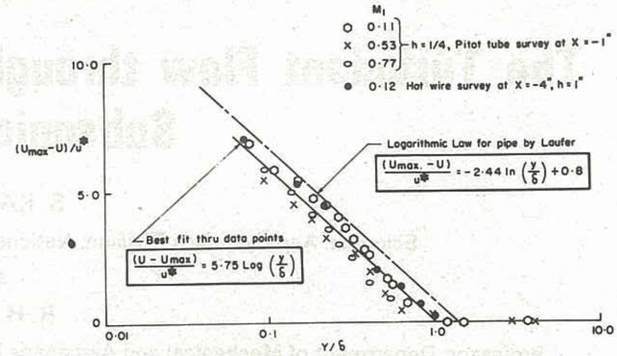

Figure 3 Logarithmic velocity distribution

The results of the hot-wire measurements are also shown in Figure 3. The variation of the turbulence intensity is shown in figure 4. On average δ was 0.61 cm, δ_1 was 0.074 cm and δ_2 was 0.056 cm. The Reynolds number varied from 2.95 x 10^6 m^{-1} to 20.34 x 10^6 m^{-1}.

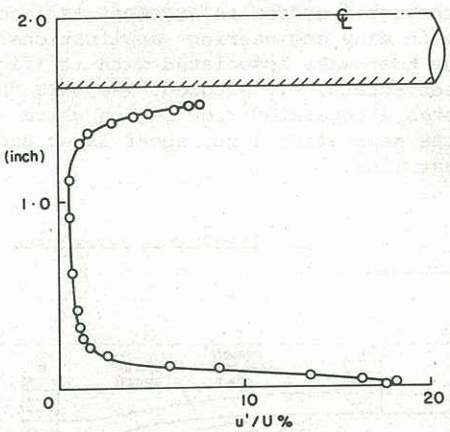

Figure 4 Turbulence profile at x = -2.54cm for h = 2.54 cm at M_1 = 0.12

An aerodynamic check of the flow symmetry was made by measuring the base pressure along the circumference at different angular locations for various Mach numbers. The results of the measurements are shown in Figure 5. It can be seen that the nozzle exit flow was axially symmetric.

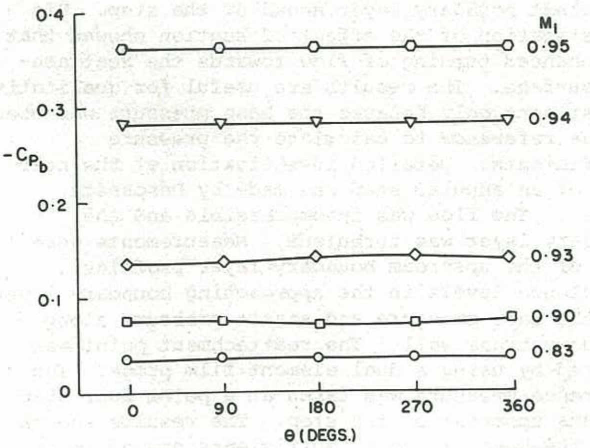

Figure 5 Circumferential distribution of C_{P_b}

4 RESULTS AND DISCUSSIONS

4.1 Base Pressure

The time averaged pressure was measured on all the four step models in the Mach number range of 0.1 to 0.95. Figure 6 shows the base pressure coefficient as a function of reference Mach number. C_{P_b} has a nearly constant value of about -0.02 for the Mach numbers between 0.1 and 0.8. This is in excellent arrangement with the available data of DeRossett (1973). For Mach numbers above 0.8, there is a sharp fall in the base pressure. Similar results were obtained for other annular step models.

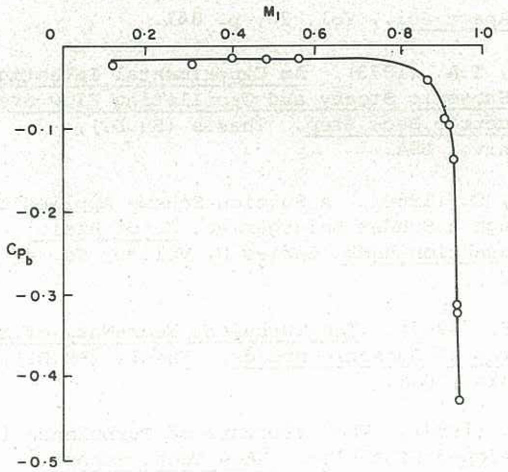

Figure 6 C_{P_b} versus Mach number for h = 1.27 cm

4.2 Static Pressure Survey

The static pressure distribution was obtained by measuring the wall pressures both upstream and downstream of the step. Figure 7 shows the static pressure distribution at various reference Mach numbers.

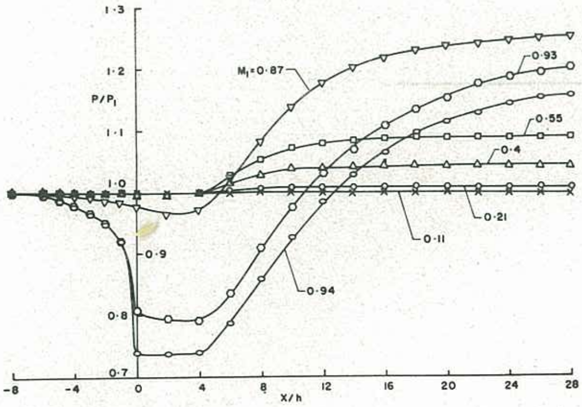

Figure 7 Static pressure survey for h = 1.27 cm

As the step is approached along the flow direction, the pressure drops below the reference pressure. At the step, the pressure becomes equal to the base pressure. Downstream of the step, the pressure is practically constant up to a distance of four step heights. This is followed by a pressure rise which is characteristic of the reattaching flows. The pressure starts levelling off at about x/h = 12.0 for Mach numbers upto 0.5 and at about x/h = 20.0 for Mach numbers greater than 0.5.

4.3 Recovery pressure

The recovery pressure P_4 measured at x = 31.6 cm is plotted in Figure 8. It is evident that the variation of P_4 is not monotonic with Mach number.

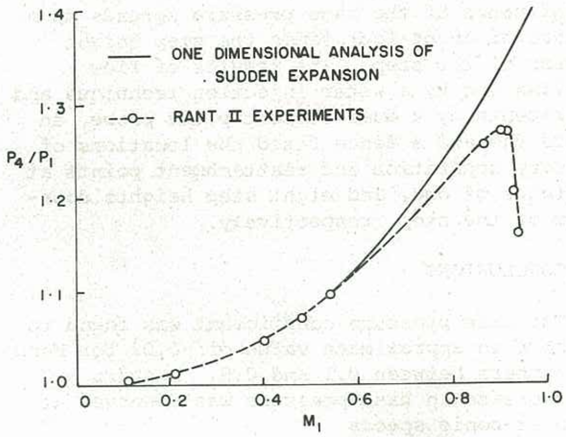

Figure 8 Recovery pressure variation with reference Mach number for h = 1.27 cm

The results obtained by the theoretical analysis of a sudden expansion (Benedict et al., 1966,1976) is also shown in the Figure 8. It is obvious that at Mach numbers upto 0.4 the recovery pressure agrees with the theoretical prediction but in the Mach number range of 0.4 to 0.8 it is lower than the theoretical prediction and at Mach numbers greater than 0.8, the experimental results show an entirely different trend as compared to the theory. This difference can be traced to the assumption in the theoretical analysis that the base pressure is equal to the reference static pressure. According to experiment, this is valid only at low subsonic Mach numbers, but at higher Mach numbers the departure is considerable (Figure 7). In order to check the validity of this argument, the datum was changed from reference pressure to base pressure and the results are shown in Figure 9.

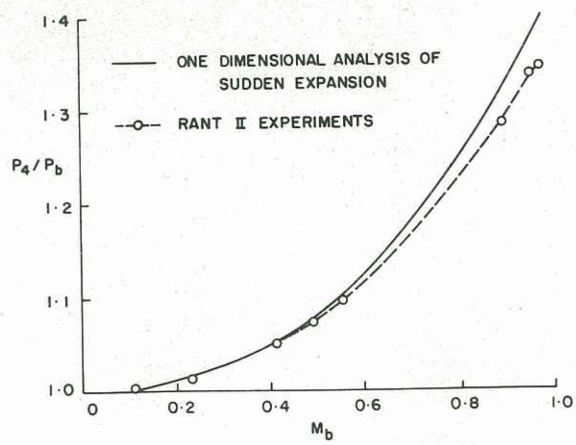

Figure 9 Recovery pressure variation with base Mach number for h = 1.27 cm

These results are limited to the subsonic case only. It can be seen that the trend of the recovery pressure is now similar to the theoretical prediction. The small difference between theory and experiment can be traced to the fact that the theory neglects the effect of shear stress in the recirculation region and also to the fact that the pressure recovery is not complete at x = 31.6 cm, the location where P_4 was measured. Nevertheless it is clear that neglecting the effect of base pressure in the theoretical analysis could lead to serious over estimation of recovery pressure in a sudden enlargement.

The investigation (Kangovi, 1977) also showed that the influence of the base pressure spreads to a distance of about four times the step height upstream of the step. The results of flow visualisation by a water injection technique and measurements by a dual element pitot probe, an orifice dam and a fence fixed the locations of secondary separation and reattachment points at a distance of one, and eight step heights downstream of the step, respectively.

5 CONCLUSIONS

(i) The base pressure coefficient was found to have an approximate value of -0.02 for Mach numbers between 0.1 and 0.8. A sharp decrease in base pressure was observed at near-sonic speeds.

(ii) At near-sonic Mach numbers, the experimental value of the recovery pressure showed a considerable departure from the theoretical predictions using one-dimensional analysis.

(iii) The locations of the secondary separation and reattachment points were found to be at a distance of one, and eight step heights downstream of the step, respectively.

6 ACKNOWLEDGEMENTS

The authors sincerely thank Dr. C.E.G.Przirembel of Rutgers University for his valuable suggestions and interest in the work. The cooperation of Dr. R.A.Merz of the Air Force Institute of Technology, USA, is gratefully acknowledged.

7 REFERENCES

BENEDICT, R.P., et al. (1966). Flow Losses in Abrupt Enlargements and Contractions. J. of Engineering for Power, Transaction ASME. Series A, Vol. 88, No. 1, pp.73-81.

BENEDICT, R.P., et al. (1976). Generalized Flow across an Abrupt Enlargement. J. of Engineering for Power, Transaction ASME. Series A, Vol. 98, No.3, pp. 327-334.

BRADSHAW, P. (1959). A simple Method of Determining Turbulent Skin Friction from Velocity Profiles. J. Aero. Apace Sci., Vol. 26, p. 841.

DeROSSETT, T.A. (1973). An Experimental Investigation of Subsonic Steady and Oscillating Flow over an Axisymmetric Back Step. Thesis (Ph.D.), Rutgers Univ., USA.

HESKESTAD, G. (1964). A Suction Scheme Applied to Flow through a Sudden Enlargement. J. of Basic Engg. Transaction ASME. Series D, Vol.90, No. 4, pp.541-552.

KANGOVI, S. (1977). The Turbulent Near-Wake of an Annular Step at Subsonic Speeds. Thesis (Ph.D.), Rutgers Univ., USA.

LAUFER, J. (1954). The Structure of Turbulence in Fully Developed Pipe Flow. NACA Tech. Report. No. 1174.

MacMILLAN, F.A. (1956). Experiments on Pitot-Tubes in Shear Flow. ARC Rep. & Mem., No. 3028.

MERZ, R.A. (1975). The Turbulent Near-Wake of an Axisymmetric Blunt Based Body at Subsonic Speeds. Thesis (Ph.D.), Rutgers Univ., USA.

TEYSSANDIER, R.G., and WILSON, M.P. (1974). An Analysis of Flow through Sudden Enlargements in Pipes. J. of Fluid Mechanics. Vol. 64, Part 1, pp. 85-95.