CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Flow field of abrupt axi-symmetric expansion is a complex phenomenon characterized by flow separation, flow recirculation and re-attachment. Such a flow field may be divided by a shear layer into two main regions, one being the flow recirculation region and the other the main flow region. The point at which the dividing streamline strikes the wall is called the re-attachment point.

There is a large amount of data about sudden expansion problem in Literature. However, they are for specific cases of flow and geometrical parameters. It will become voluminous if the entire literature is scanned in this chapter. Therefore, the information which is directly associated with the present investigation only is reviewed here.

Borda (1929) seems to be the first to investigate the problem of sudden enlargement in flow of water through sudden increase in duct cross-section. Nusselt (1929) appears to be one of the first to conduct experiment with high velocity gas flow through ducts with sudden increase in flow cross-section. From his intensive experimental study in subsonic and supersonic flows, he concluded that the base pressure will be equal to the entrance pressure if the entrance velocity is subsonic, but if the entrance flow is supersonic, the base pressure could be equal to or less than or greater than the entrance pressure. But no attempt was made by Nusselt to determine the factors governing the base pressure.
The effect of boundary layer on sonic flow through an abrupt cross-sectional area was studied experimentally by Wick (1953). He observed that the pressure in the corner of expansion was related to the boundary layer type and thickness upstream of the expansion. He considered boundary layer as a source of fluid for the corner flow. But in the view of Hoerner (1950) the boundary layer was an insulating layer that reduces the effectiveness of the jet as a pump. The base corner was thought of as a sump with two supplies of mass. The first was the boundary layer flow around the corner and the second source was the back flow in the boundary layer along the wall of expanded section. This back flow occurred because of the pressure difference across the shock wave originating where the jet strikes the wall. He concluded that the mechanism of internal and external flow was principally the same and base pressure phenomenon in external flow could be studied relatively easily by experiments with internal flow.

Korst (1954) wrote comment on the effects of boundary layer on sonic flow through an abrupt cross-sectional area change. He compared his theoretical result which utilizes a two-dimensional flow model considering the interaction between dissipative flow regions and adjacent free stream with Wick’s result and showed good agreement between theory and experiments.

Korst (1956) investigated the problem of base pressure in transonic and supersonic flow for cases in which the flow approaching the base is sonic or supersonic after the wake. He devised a physical flow model based on the concepts of interaction between the dissipative shear flow and the adjacent free stream and the conservation of mass in the weak. His results agreed closely with the experimental data of Wick.

Badrinarayanan (1961) investigated experimentally the base flows at supersonic speeds. Detailed measurements in the wake flow behind blunt
based two-dimensional and three-dimensional bodies were made at $M = 2$. The results throw some light on the behavior of separated flow and indicates the importance of flow reversal. The effect of air injection at the base shows that the base pressure increases significantly with air injection.

Wood (1964) studied the effect of base bleed on a periodic wake. He concluded that Base bleed reduces the drag of an aerofoil, by delaying the onset of instability in the separated shear layers. The proportion of vorticity which actually enters the vortex sheet after being shed from the model falls from an initial value of about 0.5 as the shear layers increase in length. In his experiment, the optimum bleed was given by a bleed coefficient of 0.125. This gives a drag reduction equal to that produced by a long splitter plate and it was thought that little further improvement is possible by any method of wake interference. No attempt was made by Wood to explain either how base bleed stabilize the shear layer or why very small bleed quantities appear to have the reverse effect. The method used by the Wood to determine the properties of the vortex street was an indirect one, based on the assumed validity of the VON KARMAN vortex street.

2.2 EXPERIMENTAL AND ANALYTICAL STUDIES

Hall and Orme (1956) studied compressible flow through sudden enlargement in a pipe, both theoretically and experimentally, and showed a good agreement between theoretical and experimental results. They developed a theory to predict the Mach number in a downstream location of sudden enlargement for known values and Mach number at the exit of the inlet tube, with incompressible flow assumption. They also assumed that the pressure across the face of the enlargement was equal to the static pressure in the small tube just before the enlargement. But this assumption is far away from reality, it is a well established fact that the pressure across the face in the recirculation region, namely the base pressure is very much different from the pressure in the smaller tube just before the enlargement. They used a nozzle and tube
arrangement for the experiments and studied the problem with a range of throat Mach Numbers from 0.0 to 1.0

Benedict (1962-1976) with various other investigators analyzed the sudden enlargement problem in an elaborate manner both theoretically and experimentally.

Heskestad (1968-1970) in his experiments applied a suction scheme to flow through sudden enlargement. He concluded that for fixed geometry and Reynolds number, gradual increase in suction rate from zero caused progressively more rapid expansion into the larger pipe diameter, a process which accelerated toward a critical suction rate and then continued slowly. With one particular geometry, Reynolds number, and suction rate beyond critical, the initial border to the remaining pocket of separated flow behind the step appeared common to expansion ratios greater than a certain minimum. On the other hand, turbulence was found to propagate increasingly faster into the potential core of the flow as expansion ratio increased.

Nicoll and Ramaprian (1970) investigated performance of conical diffuser with annular injection at inlet. The effects of injection rate and diffuser geometry on the pressure recovery and stall were discussed. Results indicate that the improvement in diffuser performance is significant even at moderate rates of injection. An analytical method based on the solution of the boundary layer equations by the Patankar-Spalding finite difference methods was used to obtain predications of pressure recovery with inlet injections. The predications compare well with the experimental results.

Bar-Haim and Weihs (1985) studied boundary-layer controls as a means of reducing drag on fully submerged bodies of revolution. He concluded that the drag of axisymmetric bodies can be reduced by boundary-
layer suction, which delays transition and can control separation. The boundary-layer transition was delayed by applying a distributed suction technique. Optimization calculations were performed to define the minimal drag bodies at Reynolds numbers of $10^7$ and $10^8$. The reduction in drag relative to optimal bodies with non-controlled boundary-layer was 18 and 78 per cent, at Reynolds numbers of $10^7$ and $10^8$

Ackeret (1967) studied special features of internal flow. He concluded that there is a pre-dominant role played by the equation of continuity, especially if compressibility is involved and in aeronautics big deflection of the air streams are avoided as far as possible but in ducted flow, they may be quite common. If the width of the duct is not growing too fast, along its length, separation is followed by re-attachment. He observed that, in case of internal flow also, three-dimensional boundary layers can appear as in external flow. He presented the article on the aspects of internal flow covering different types of internal flows describing some of the aspects of separation, re-attachment and pressure fluctuations that are associated with sudden enlargement flows.

Anderson and Williams (1968) worked on base pressure and noise produced by the abrupt expansion of air in a cylindrical duct. They used stagnation pressure ratios of the forcing jet from atmospheric to six times atmosphere for various lengths to diameter ratios. With an attached flow the base pressure was having minimum value which depend mainly on the duct to nozzle area ratio and on the geometry of the nozzle. The plot of overall noise showed a minimum at a jet pressure approximately equal to that required to produce minimum base pressure.

Muller (1968) studied analytically the determination of turbulent base pressure in supersonic axisymmetric flow. As per their analysis the
axisymmetric base pressure may be classified as assuming either rising or constant pressure along the jet mixing region. A modification in the re-compression component of the basic pressure rise flow model plus an accurate computers solution of the nonlinear equations for axisymmetric mixing produces base pressure results that agree well with data were suggested. Extension of this method and the constant pressure method to include the effect of specific heat ratio exhibit proper trends. A determination of the plug base pressure of an ideal shroud contour expansion deflection nozzle was presented as a result of the analytical procedures developed.

Mueller et al (1970) studied analytically the influence of initial flow direction on the turbulent base pressure in supersonic axisymmetric flow. His results show excellent agreement between analytical results for \( \gamma = 1.4, \frac{T_b}{T_\infty} = 1, M_j = 2.0 \) and \( \frac{r_b}{r_c} = 0.58 \), and the experimental data of Reid and Hastings (1959).

Durst et al. (1974) studied low-Reynolds number flow over a plane symmetric sudden ex-pansion. The flow was depending totally on Reynolds number and the nature was strongly three-dimensional. At higher Reynolds number the flow become less stable and periodicity became increasingly important in the main stream, accompanied by a highly disturbed fluid motion in the separation zones as the flow tended towards turbulent. They reported flow visualization and laser anemometry measurements. At Reynolds number of 56 the separation region behind each step were of equal length for each step but at Reynolds number of 114, the two separation regions were having different lengths leading to asymmetrical velocity profiles. At Reynolds number of 252, a third separation zone was found on one wall There were substantial three-dimensional effects in the vicinity of the separation regions.
Roache (1973) obtained a new method of implementing the recompression condition which improves convergence properties for base bleed. A Criterion for selection of the wake radius ratio was included in the flow model, thus eliminating all empirical parameters except the Jet spread parameter (eddy viscosity). Calculations were made for base pressure, with and without base bleed, on cylinders, sharp cones, and on blunted cones.

Cherdon et al (1978) studied asymmetric flows and instabilities in symmetric ducts with sudden expansion. Asymmetric flows were caused by the disturbances generated at the edge of the expansion and amplified in the shear layers. The Spectral distribution of the fluctuation in velocity are quantitatively related to the dimensions of the two unequal regions of flow recirculation. They showed that the intensity of fluctuating energy in the low Reynolds number flow can be larger than that in corresponding turbulent flow.

Durst et al (1974) demonstrated that symmetric flows can exist in two-dimensional plane symmetric sudden-expansion ducts for only a limited range of Reynolds numbers. At higher Reynolds numbers, the small disturbances generated at the tip of the sudden expansion are amplified in the shear layers formed between the main flow and the recirculation flow in the corners. The result was a shedding of eddy-like patterns which alternated from one side to the other with consequent asymmetry of the mean flow, particularly of the dimensions of the two regions of recirculation. Although the flow were three-dimensional, its major feature could be understood by considering the interaction of two-dimensional shear layers.

Brady and Acrivos (1982) studied closed-cavity laminar flows at moderate Reynolds numbers. They suggested that similarity solutions should
be viewed with caution because they might represent a real flow once a critical Reynolds number was exceeded.

The flow field in a suddenly enlarged combustion chamber was studied experimentally by Yang and Yu (1983). The combustion chamber consisted of Plexiglas circular duct with a suddenly enlarged section followed by a nozzle. The Reynolds number based on the inlet duct diameter and center-line Velocity was $6.4 \times 10^4$. The wall pressure measurements were carried out with a laser-Doppler anemometer. Detailed profiles of mean velocities, turbulent intensities, turbulent shear stresses and wall pressure distribution were developed. The dividing streamline, the re-attachment point and the magnitudes of the mean kinetic energy and turbulent kinetic energy were also determined. They observed that the laser-Doppler anemometer with a frequency shifter was an useful instrument for measuring reverse flow fields, especially for the highly turbulent flow field encountered in the study. Measurements from a conventional hot-wire anemometer might present considerable errors.

Koh (1971) suggested a new wind-tunnel technique for providing simulation of flight base flow. He concluded that, the dimensionless base pressure in subsonic and supersonic flow is governed by two parameters: the Mach number and the boundary layer thickness. He suggested the use of long cylindrical body and boundary layer suction in place of conventional mountings for base pressure models. The cylindrical body was extended and supported far upstream so that there is no strut to interfere with the flow. The boundary layer thickness was controlled by use of suction ahead of the base pressure model. His scheme was successfully demonstrated for the case of subsonic and transonic flows.
Anderson et al. (1977) studied flow oscillations in a duct with a rectangular cross-section. They investigated a two-dimensional configuration in which air flows through a convergent nozzle and expands abruptly into a rectangular duct of larger cross-section which terminates in a plenum chamber. Three different types of oscillation have been observed in the downstream duct. At low plenum-chamber pressures oscillation occurs towards the exit of the duct as the boundary layer of the flow becomes alternately separated and attached. At increasing plenum pressure a shock-pattern oscillation takes place in which a change from a normal shock to oblique shocks occurs during a cycle. At still greater plenum pressure a base pressures oscillation occurs which influences the entire duct flow downstream of the abrupt change in cross-section. The amplitudes of the oscillations can be as high as 10 per cent of the rest state, and the frequency of the base pressure oscillations can be predicated approximately from one-dimensional gas-dynamic theory.

Tang and Fenn (1978) studied experimentally discharge coefficients for critical flow nozzles for hydrogen, helium, nitrogen and argon over a Reynolds number range from $10^2$ to $10^4$. For Reynolds number above 200, the measured coefficients were in excellent agreement with those predicted by a straight forward application of boundary-layer theory. The results suggest that in many cases experimental calibration of metering nozzles must be avoided.

Liu (1979) studied axisymmetric transonic turbulent base pressure. It was stipulated that the inviscid flow field can be produced from an equivalent body and the inviscid flow so established guide; the viscous flow processes of mixing and re-compression along the wake. The viscous-inviscid interaction is manifested by the fact that the characteristic parameters required to establish the corresponding inviscid flow were determined through viscous-flow considerations. Extension of this approach to study the base pressure of
transonic flow past a backward facing step in axisymmetric configuration was reported.

Howe (1981) studied the influence of mean shear on unsteady aperture flow, with application to acoustical diffraction and self-sustained cavity oscillations. He used linearized theory of unsteady flow through a two-dimensional aperture in a thin plate in the presence of a grazing mean flow on one side of the plate. The mean shear layer was modeled by a vortex sheet, and it was predicted that at low mean-flow Mach numbers there is a transfer of energy from the mean flow to the disturbed motion of the vortex sheet provided (i) the Kutta condition is imposed at the leading edge, and (ii) the width of the aperture $2s$ satisfies $1/2 < 2s/\lambda < 1.1$, where $\lambda$ is the hydrodynamic wavelength of the disturbance on the vortex sheet within the aperture. The theory was used to examine the effect of mean shear on the diffraction of sound by a perforated screen, and to predict the spontaneous excitation and suppression of self-sustained oscillations in a wall-cavity beneath a nominally steady mean flow.

Eaton and Johnston (1981) wrote a review paper on research of subsonic turbulent reattachment. They described the general features of backward-facing step flow. Five principal independent parameters on reattachment length. 1) Initial boundary-layer state, 2) initial boundary-layer thickness, 3) freestream turbulence, 4) pressure gradient, 5) aspect ratio were discussed in the review.

2.3 FLOW CONTROL BY PASSIVE AND ACTIVE TECHNIQUES

Rathakrishnan and Sreekanth (1984) studied flows in pipe with sudden enlargement. In their experiments, the flow of air from a plenum chamber to a circular cross-section constant area tube was made to expand suddenly by having an abrupt change in cross-sectional area. The pressure
ratios covered ranged from 1.1 to 3.0 and the area ratio of the expansion was varied from 2.78 to 8.38. Length–to-diameter ratio was varied from 1 to 10. Total head pressure at the axis of symmetry at the plane of enlargement and the static pressure variation along the wall of duct were measured. They concluded that the non-dimensionalized base pressure is a strong function of the expansion area ratios, the overall pressure ratios and the duct length-to-diameter ratios. Further, they showed that for a given overall pressure ratio and a given area ratio, it is possible to identify an optimal length-to-diameter ratio of the enlargement that will result in maximum exit plane total pressure at the nozzle exit on the symmetry axis (i.e. minimum pressure loss in the nozzle) and in a minimum base pressure at the sudden enlargement plane. The separation and re-attachment seemed to be strongly dependent on the area ratio of the inlet to enlargement. For a given nozzle and enlargement area ratio, the duct length must exceed a definite minimum value for minimum base pressure. For an optimum performance of flow through pipes with sudden enlargement, it is not sufficient if the base pressure minimization alone is considered. The total pressure loss must also be taken into account.


Selby (1989) studied passive control of three-dimensional separated vertical flow associated with swept rearward facing steps. Results have indicated that geometric modifications in the region downstream of the step where the spanwise vortex is formed has little effect on the extent of the separated flow, while “conical-lip” and “vortex-trough” base modifications lead to significant reduction in reattachment distances. “The conical-lip” modification involves a step lip with variable radius and the “vortex-trough”
are grooves in the surface upstream of the step which produces longitudinal vortices.

Fearn et al (1990) studied nonlinear flow phenomena in a symmetric sudden expansion. Their results show that the asymmetry arises at a symmetry-breaking bifurcation and good agreement between the experiment and numerical calculations was obtained. At higher Reynolds number the flow becomes time-dependent and there is experimental evidence that this is associated with three-dimensional effects.

Rathakrishnan et al (1991) studied flow through rectangular passage which was expanded suddenly into rectangular duct with stagnation pressure ratios from 3.5 to 1.25. The length-to-height ratio of the enlarged duct varied from 5.769 to 1.923 and three models with length-to-height-ratios of 5.789, 3.846 and 1.923 were studied. The influence of nozzle pressure ratios and length-to-height ratios of the enlarged duct on base pressure and flow field in the rectangular enlarged duct were appreciably different from that for circular cross-section at similar flow conditions, indicating that the passage cross-section is an important parameter in these studies.

Iwamoto and Deckker (1985) studied the Hartmann-Springer tube using the hydraulic analogy. They conclude from their experiments that although the hydraulic analogue is two-dimensional, it has been shown to reproduce the main features of the stable oscillatory flow in the cavity of a Hartmann-Springer tube. Patterns of the distribution of water depths at nodal points in a grid of square cells of 5mm side covering a field of half width 90 mm and 250mm long have been obtained during steady flow and at selected times during the oscillatory flow. In particular, it has been possible to establish qualitatively that there is a threshold of low-pressure near the cavity entrance which is a necessary condition for stable oscillatory flow.
Stiffler and Baksh (1986) studied a subsonic air jet impinging upon a cavity to explain the resultant heating phenomenon. Flow visualization within the cavity showed a large central vortex dominating the flow pattern. Velocity measurements inside the cavity were made using a hot-wire anemometer. Temperature was measured with a copper-constantan thermocouple. The velocity field within the cavity was described by a modified Rankine combined vortex. An uncommon form of the energy equation was used to account for turbulent heating in adverse pressure gradients. A theoretical solution was developed to model the temperature field in the cavity. There was a good agreement between the calculated and measured temperatures.

Anasu and Rathakrishnan (1987) investigated experimentally the influence of cavity on flow through sudden enlargement. Air jet issuing out of a convergent nozzle was made to expand suddenly into an axisymmetric pipe of larger diameter with annular cavities at fixed intervals in the enlarged ducts. The nozzle pressure ratio was varied from 3.0 to 1.2. The corresponding Mach number at the entry to enlarged duct with area ratio 2.4 and 10 were tested and the length-to-diameter ratio of the duct was varied form 2 to 10 for each area ratio and each enlarged duct had five cavities when the L/D was 10. They concluded that, for the inlet Mach numbers in the range of 0.1 to 0.8, the area ratio of the enlarged duct strongly influences the base pressure as well as flow development in the enlarged duct. The introduction of secondary circulation by the cavities reduces the oscillatory nature of the flow in the enlarged duct, thereby helping the flow to develop smoothly from the base pressure value to the atmospheric level. Duct L/D ratio upto six only is of significant effect in reducing the base pressure. This behavior is similar to that for passages without cavities Ref (1984).
Gharib (1987) studied influence of externally forced initial flow conditions on axisymmetric cavity shear layer. A sinusoidally heated strip upstream of the cavity excited Tollmein Schlichting waves that, after amplification by the boundary layer, were introduced to the cavity shear layer. It was shown that by selecting a forcing frequency, which satisfies a phase difference criterion between two corners of the cavity and has an amplitude that is above the threshold amplitude, it is possible to excite a naturally non-oscillating shear layer. It was also shown that the frequency and amplitude of the oscillation in the self sustained mode can be controlled through external forcing. By using a feed-back control scheme, upto 40 per cent reduction of the velocity fluctuation level could be obtained.

Ghoniem and Sethian (1987) studied the structure of the recirculating zone forming behind a rear-ward-facing step in a channel for Reynolds number in the 50-5000 range, using random vortex method. Results are analyzed in terms of instantaneous streamlines, average velocity profiles, and turbulence statistics. Four distinct flow regimes were identified. At very low Reynolds numbers, the flow is viscous, and the recirculation zone is formed of one stationary eddy at the corner of the step. As the Reynolds number increases, an eddy may detach and decay as it moves downstream. At moderate values, the flow reaches a state of transition, with eddy shedding at the step. At high Reynolds numbers, the flow exhibits turbulent behavior with a continuous process of eddy formation and pairing. The recirculation zone length increases with Reynolds number, reaching a maximum, at transition and then decays to a shorter length in the turbulent range.

Raghunathan and Mabey (1987) studied passive shock-wave/boundary layer control on a wall-mounted model. They evaluated the effects of orientation of holes on passive shock-wave/boundary layer control, incorporating three hole orientations; normal, forward facing and backward
facing. The porosity used was 1.6 per cent. Their measurements include static and dynamic pressures on the model surface, and wake traverses. They visualized the field with shadowgraph. The forward facing holes located around shock position showed an appreciable decrease in drag compared to solid surface model.

Raghunathan (1987a) studied pressure fluctuations measurements with passive shock/boundary layer control experimentally. He concluded that, passive shock/boundary layer control in transonic flow could reduce pressure fluctuations in the region of shock/boundary layer interaction and hence could suppress buffeting.

Raghunathan (1987b) also studied the effect of porosity strength on passive shock-wave/boundary layer-control and found that the forward-facing holes configuration with a porosity of 1 to 2 per cent produces maximum drag reduction.

Hallet and Gunther (1984) studied mixing of swirling flow in a sudden expansion and their experiments revealed that at the highest swirl tested a central recirculation zone was formed. While at swirl intensities below the critical value required for central back flow a precession of the flow was discovered in which the flow entering the expansion was deflected away from the axis of symmetry and caused to precess around it. The effect of these flow patterns on the mixing of a tracer gas with the main flow was studied by measuring both time-mean values and turbulent fluctuations of the concentration. The time-mean measurements indicated mixing at all swirl levels to be about equally fast, but measurements of fluctuation intensities showed a much higher unmixedness at low swirl, corresponding to the large-scale motions of the precessing flow.
Gharib and Roshko (1987) studied the effect of flow oscillations on cavity drag. Their results showed that self-sustained, periodic oscillations of the cavity shear layer are associated with low cavity drag. In this low-drag mode the flow regulates itself to fix the mean-shear-layer stagnation point at the downstream corner. Above a critical value of the cavity width-to-depth ratio there is an abrupt and large increase of drag due to the onset of the “wake mode” of instability. It was also shown by the measurement of the momentum balance how the drag of the cavity is related to the state of the shear layer, as defined by the momentum transport and Reynolds stress, and how these are related to the amplifying oscillations in the shear layer. The cavity shear layer was found to be different, in several respects, from a free shear layer.

Adams and Eaton (1988) from their experimental results concluded that velocity bias was not a major problem. A small amount of velocity bias less than 4 per cent was measurable in particle averages. Their LDA results for the backward-facing step flow indicate the importance of upstream initial conditions on the development of the free shear layer. A thick boundary layer causes a lower pressure rise to reattachment and a lower pressure gradient at reattachment than cases with thinner initial separating boundary layers. The skin-friction results have strong similarities to the results of others in the separated regions, despite the large differences in expansion ratio and initial shear-layer thickness.

Wilcox (1988) studied the passive venting system for modifying cavity flow field at supersonic speeds. Experimentally he showed that a passive venting system could be employed to control cavity flow-fields at supersonic speeds specifically the passive venting system had been used to extend the 1/h value before the onset of high drag-producing closed cavity flow. In his experiments the porous floor eliminated the large drag increase
for \( h \geq 12 \). The increase in \( C_D \) is comparatively very less with the floor having less diameters.

Tanner (1988) studied the influence of base cavity at angles of incidence on the base pressure. He concluded that a base cavity could increase the base pressure and thus decrease the base drag in axi-symmetric flow. He varied the angle of incidence from 0 to \( 25^\circ \). At \( \alpha=2^\circ \), he found the maximum drag reduction.

Berbee and Ellzey (1989) studied the effect of aspect ratio on the flow over a rear-ward-facing step. From their experimental results they concluded that the mean velocity and turbulence intensity profiles are constant across the width of the test-section for either of the Reynolds numbers tested for aspect ratios 10 and 4. At a distance greater than three step height downstream of the step, the peak turbulence intensity is greater for a higher aspect ratio and is relatively insensitive to Reynolds number. The peak frequency is lower and the spectrum is narrower for a higher aspect ratio in the region near the step.

Isaac son et al (1989) studied unstable vortices in the near region of an internal flow cavity. Experimental data were taken in the forward region of a separated internal free shear layer produced in an internal cavity flow field. It was found that in the region very near the forward restrictor, experimental velocity profiles agree closely with the exact Stuart (1967) instability profile with various values of steepness parameter, Reynolds shear-stress profiles suggest the presence of counter-rotating longitudinal vortices. Spectral analysis by the maximum entropy method of the time samples within the vortices indicates sub harmonic and harmonic components of the fundamental frequency, with a weak indication of the fundamental frequency itself.
Chow (1985) studied an equivalent body concept to examine the base pressure problem of a transonic flow past a blunt-based projectile. The strong inviscid-viscous interaction was clearly illustrated from the method of approach to the problem. A definition of the base pressure that is compatible with that for the supersonic flow regimes was developed for transonic flow regime. An analysis of the asymptotic far-wake condition relates a needed parameter to the total drag experienced by the projectile. Results were obtained for transonic (both subsonic and supersonic) approaching flow conditions and were also compared with the available experimental data. Extension to cases with small angles of incidence was also discussed.

Rathakrishanan et al (1989) studied the influence of cavities on suddenly expanded subsonic flow-field. They studied air flow through a convergent axisymmetric nozzle expanding suddenly into an annular parallel shroud with annular cavities experimentally. They concluded that the smoothening effect by the cavities on the main flow-field in the enlarged duct was well pronounced for large ducts and the cavity aspect ratio had significant effect on the flow-field as well as on the base pressure. From their results it is seen that increase in aspect ratio from 2 to 3 results in decrease of base pressure but for increase in aspect ratio from 3 to 4 the base pressure goes up.

The effectiveness of passive devices for axi-symmetric base drag reduction at Mach 2 was studied by Viswanath and Patil (1990). The devices examined included primarily base cavities and ventilated cavities. Their results showed that the ventilated cavities offered significant base-drag reduction. They found 50 per cent increase in base pressure and 3 to 5 percent net drag reduction at supersonic Mach numbers for a body of revolution.

Gould et al (1990) investigated incompressible turbulent flow field following an axisymmetric sudden expansion with two-component laser
velocimeter measurements. Mean velocities, Reynolds stresses, and triple products were measured and presented at axial positions ranging from $x/H = 0.2 – 14$. A balance of the turbulent kinetic energy in the flow was performed. The production, convection, and diffusion of turbulent kinetic energy were computed directly from the experimental data using central differencing. A specially designed correction lens was employed to correct for optical aberrations introduced by the circular tube. This lens system allowed the accurate simultaneous measurements of axial and radial velocities in the test-section. The experimental measurements were compared to predictions generated by a code that employed k-$\epsilon$ model. Agreement was good for mean axial velocities, turbulent kinetic energy, and turbulent shear stresses. However, the modeled turbulent normal stresses were in poor agreement with the measured values. The modeled diffusion of the turbulent kinetic energy was under-predicted in the region between the shear layer and the centerline of the flow giving lower values of turbulent kinetic energy downstream of the potential core than measured.

Kruiswyk and Dutton (1990) studied effects of base cavity on subsonic near-wake flow. They experimentally investigated the effects of base cavity on the near-wake flow-field of a slender tow-dimensional body in the subsonic speed range. Three basic configurations were investigated and compared they are a blunt base, a shallow rectangular cavity base of depth equal to one half of the base height and a deep rectangular cavity base of depth equal to the base height. Schlieren photographs revealed that the base qualitative structure of the vortex street was unmodified by the presence of the base cavity. The weaker vortex street yielded higher pressures in the near-wake for the cavity bases, and increases the base pressure coefficients in the order of 10 to 14 per cent, and increases in the shedding frequencies of the order of 4 to 6 per cent relative to the blunt-based configuration.
Pandey (1994) studied sudden expansion flow from nozzles with cavities in subsonic and supersonic flows. The cavity aspect ratio (the width to depth of the cavity) used were 1 and 2. His experimental results revealed that the base pressure is strongly influenced by the parameters viz, the nozzle exit Mach number, primary pressure ratio, the area ratio and the duct L/D ratio. The base pressure was found to be oscillatory for flow from straight convergent-divergent nozzles, whereas for flow from Laval nozzles the oscillations are insignificant. The base pressure increases with increase in Mach number in the supersonic range, whereas in the subsonic range it decreases with increase of Mach number. The annular cavities were found to increase the base pressure with increase in their aspect ratio. The length to diameter ratio beyond 6 is of no significant influence on the base pressure. The effect of cavity on wall pressure development in the enlarged duct is significant for subsonic Mach numbers, whereas for supersonic Mach numbers the effect is only marginal. The total pressure loss increases with increase of Mach number, primary pressure ratio and L/D ratio. Pressure loss was more for convergent-divergent nozzles compared to Laval nozzles. For a given primary pressure ratio and area ratio there exists a definite critical length of the enlarged duct giving a maximum secondary vacuum at the base and a minimum pressure loss.

Herrin and Dutton (1994) studied supersonic base flows in the near wake of a cylindrical after-body at Mach 2.5. They aimed to gain a better understanding of the complex fluid dynamic processes of the supersonic base flow fields including separation, shear layer development, reattachment along the axis of symmetry, and subsequent development of the wake. Their results indicate relatively large reverse velocities and uniform turbulence levels with a strong peak in the inner, subsonic region which eventually decays through reattachment as the wake develops. A global maximum in turbulent kinetic energy and Reynolds shear stress was found upstream of the reattachment
point, which is in contrast to data from the reattachment of a supersonic shear layer onto a solid wall. Mean static pressure measurements were used to assess the radial dependence of the base pressure and the mean pressure field approaching separation. In addition, two-component laser Doppler velocimeter (LDV) measurements were obtained throughout the near-wake including the large separation region downstream of the base.

Herrin and Dutton (1994) studied supersonic near wake after-body boat—tailing effects on axisymmetric bodies. The after-body investigated is typical of those for conventional boat-tailed missiles and projectiles in UN-powered flight. Results indicate that a net after-body drag reduction of 21 per cent was achieved with boat-tailed after-body for a freestream Mach number of 2.46. The shear layer growth rate, and therefore mass entrainment from the recirculation region behind the base was significantly reduced by after-body boat-tailing due to the reduction in turbulence level throughout the near wake as compared to the cylindrical after-body at Mach 2.5. They aimed at gaining a better understanding of the complex fluid dynamic processes present in supersonic base flow fields including separation, shear layer development, reattachment along the axis of symmetry, and subsequent development of the wake. Their results indicate relatively large reverse velocities and uniform turbulence levels with a strong peak in the inner, subsonic region which eventually decays through reattachment as the wake develops. A global maximum in turbulent kinetic energy and Reynolds shear stress was found upstream of the reattachment point, which is in contrast to data from the reattachment of a supersonic shear layer onto a solid wall.

Viswanath (1995) reviewed the flow management techniques for base and after-body drag reduction of the problem of turbulent base flows and drag associated with it. This review presents the development that have taken place on the use of passive techniques or devices for axisymmetric base and
net after-body drag reduction in the absence of jet flow at the base. In particular, the paper discusses the effectiveness of cavities, ventilated cavities, locked vortex after-bodies, multi-step after-bodies and after-bodies employing a non-axisymmetric boat-tailing concept for base and net drag reduction in different speed regimes. The broad features of the flow and the likely fluid-dynamical mechanism associated with the devices leading to base drag reduction were highlighted. Flight-test results assessing the effectiveness of some of the devices were compared with data from wind tunnels. This review indicates that base and net after-body drag reduction of considerable engineering significance in aerospace applications can be achieved by various passive devices even when the (UN-manipulated) base flow is not characterized by vortex shedding.

Mathur and Dutton (1996) studied the effect of base bleed on the near wake flow field of a cylindrical after-body in a Mach 2.5 flow. Their results indicate relatively uniform radial pressure profiles across the base plane. With increasing bleed flow rate, the average base pressure was found to increase initially, attain a peak near an injection parameter of I=0.0148, and then decrease with further increase of I. The optimum bleed condition near I=0.0148 is also characterized by a weak corner expansion, a minimum value of free-shear layer angle, and the near-disappearance of the recirculation region (reverse velocity) along the centerline of the near wake.

Mathur and Dutton (1996) studied velocity and turbulence measurements in a supersonic base flow with mass bleed. The bleed flow provides at least some of the fluid required for shear layer entrainment and shields the base annulus from the outer shear layer and the primary recirculation region, leading to an increase in base pressure. There is an overall reduction in turbulence level throughout the base bleed flow fields relative to the near-wake flow fields of blunt-based and boat-tailed after-
bodies. With increasing bleed the formation of a strong bleed jet shear layer and secondary recirculation region near the base annulus offsets the benefits of base bleed, leading to a drop in the base pressure. The net benefits of base bleed are maximized at the optimum bleed condition, which corresponds to the highest base pressure, the disappearance of the primary recirculation region, and the lowest turbulence levels in the near-wake flow filed. They concluded that increased benefits from base bleed could be achieved by injecting the bleed fluid at the lowest possible velocity though the use of larger bleed orifices, porous bases, or bleed orifices located along the outer base annulus.

Rathakrishnan (1997) investigated the effect of Ribs on suddenly expanded axisymmetric flows laying emphasis on the base pressure reduction and enlarged duct pressure field. Annular ribs with aspect ratio 3:1 was found to be optimum and the do not introduce any oscillations to the wall pressure field of the enlarged duct, at the same time the increase in pressure loss compared to plain duct was also less than six percent. Even for the case with passive control the duct L/D in the range 3 to 5 experiences the minimum base pressure, as in the case of plain ducts. He established quantitatively that annular rib with aspect ratios 3:2 and 3:3 results in increase of base pressure beyond some L/D of the enlarged duct and also they introduce oscillations to the duct pressure filed. Hence, he concluded that there is a threshold of the control rib aspect ratio which is necessary for obtaining maximum suction at the base along with minimum pressure loss and non-oscillatory flow development in the enlarged duct.

Tanner (1998) published a review paper on theories for base pressure in incompressible steady base flow. He described general features of 2-D steady base flow derived from the theory and experiments. Experimental and theoretical results are in closed agreement.
Choudhary and Amit (1999) studied active control of base pressure in suddenly expanded flows. He concluded that at some combination of flow and geometrical parameters, an increase in the base pressure to a maximum of 6.6 percent is possible. The effect of the active control on the enlarged duct wall pressure field is only marginal. Their studies were limited up to sonic speed only.

Bourdon and Dutton (1999) investigated the spatial evolution of large scale turbulent structures in the shear layer of an axisymmetric, supersonic separated flows. The experimental diagnostic used were planar visualization of condensed ethanol droplets that were suspended in the supersonic free stream. Spatial correlation analysis of large ensembles of images show that the mean side-view structure is highly strained and elliptical in shape and is inclined toward the local free stream direction. Also, the effect of lateral streamline convergence for this axisymmetric case causes a reduction in side-view structure are wedge shaped, wider on the free-stream side than on the recirculation region or developing wake side. It was concluded that, the wedge shape is caused by the axisymmetric confinement of the shear layer as it approaches the wake centerline.

Meyer et al (1991) investigated vortex formation and merging in the near field of axisymmetric jet. Their results indicate that there are several phases of the pairing event with distinct mixing characteristics, including vortex roll-up interaction and re-entrainment.

Shaw et al (1999) did conditional analysis of wall pressure fluctuations in plume-induced separated flow fields. The Separation process in plume-induced, boundary layer separated flow fields was found to be unsteady.
Rathakrishnan (1999) studied the effect of splitter plate on bluff body drag. It was concluded from his experimental results that, for a plate at the center, a backward plate results in a significant increase of base pressure when compared to a forward plate, for all 1/h tested. This is because the backward splitter plate divides the wake into two parts, thereby preventing the formation of strong vortices at the base and resulting in a significant increase of the base pressure. For the splitter plate as the symmetrical plane there exists a critical 1/h beyond which the effect of 1/h on \(C_{pb}\) is insignificant. For Reynolds number \(0.98 \times 10^5\) the critical 1/h is about 1.0. Further, Reynolds number \(0.58 \times 10^5\) the forward splitter plate located at h/4 from the top is more effective in increasing the base pressure when compared to other locations. Also, the plate located at the rear h/4 also results in a significant increase in base pressure compared to the plated position at forward center though this increase is much smaller compared to that of the forward position at h/4. Hence, 1/h > 1 is also effective in reducing base suction, even though the effect is very small compared to that for l/h<1.

2.4 FLOW VISUALIZATION AND VELOCITY MEASUREMENT

Viswanath (2001) investigated experimentally the zero-lift drag characteristics of multi- step after-bodies that utilize the concepts of controlled separated flows at transonic and supersonic speeds. The important geometrical parameters affecting the drag of such after bodies were identified, and their effects were examined through a parametric study. Their results show that multi-step after-bodies can be designed that provide significant total drag reduction (as high as 50 percent) compared to (unmodified) blunt bases; however, compared to axisymmetric boat-tailed after-bodies of a given base area, the multi-step after bodies have relatively higher drag. Finally, the certain flow features involving separation and reattachment on multi-step after-bodies were discussed based on flow visualization studies.
Boswell and Dutton (2001) investigated experimentally the flow along the after-body and in the base region of a circular cylinder with a length-to-radius ratio 3.0 aligned at a $10^0$ angle of attack and a free stream Mach number 2.5. The objective was to understand the mechanisms that control base flow for supersonic bodies with a nonzero-angle-of-attack orientation. Laser Doppler Velocimetry measurements were conducted in the incoming boundary layer to quantify the initial conditions at the onset of three-dimensional behavior.

Schileren and Mie scattering visualizations were obtained to discern governing flow features and to image the large-scale turbulent structures of this separated flow. Surface oil-streak visualizations were obtained to determine the three dimensionality of the after-body surface flow and to deduce the base surface flow field. Pressure-sensitive paint measurements were done to determine the spatial evolution of surface pressure along the cylindrical body at angle of attack and to determine the change in base pressure caused by inclination of the body. Their results provide evidence of expected mean-flow features, including base-corner expansions, separated shear layer development, re-compression shocks and a turbulent wake. No evidence of lee-side flow separation was detected along the after-body. However, a strong secondary circumferential flow, which develops along the after-body due to pressure gradients on its surface, results in the entertainment of fluid into the base region from the leeward portion of the flow. The average base pressure ratio measured for the angle of attack case was 48.4 per cent lower than that measured for zero angle of attack, resulting in a significant increase in base drag for cylindrical objects inclined at angle of attack.
The above review reveals that there is a large quantum of literature available on the problem of sudden expansion and both active and passive control of such flow fields. Earlier researchers working on passive control of suddenly expanded flow fields have mostly employed cavities or ribs as passive control devices. In almost all these studies the position of cavities or ribs was fixed. The effect of varying position of the ribs or cavities may have a profound effect on the suddenly enlarging flow field. With this idea it is proposed to investigate the effect of rib position and geometry on the flowfield. To have a complete understanding of the control effectiveness, the problem is studied with a wide range of Mach numbers starting from subsonic to supersonic Mach numbers.