Chapter 2

Literature Review

Kurzweg [2] conducted experiments in supersonic wind tunnels before 1951 for 3 years (N.A.C.A. and N.O.L.) show that the pressure at the base of bodies is essentially a function of parameters that govern the boundary layer. Hence, the base pressure is closely connected to surface friction and heat-transfer phenomenon. Experimental results obtained by him in the N.O.L. supersonic tunnels in a Mach range 1.5-5.0 on cylindrical bodies with and without boat-tails with conical heads under various systematic mechanical and thermodynamic variations of the boundary layer are presented and compared with theoretical results. Wick [4] studied experimentally for sonic flow. He conducted experiments for suddenly changing area. His main concern was to find the influence of boundary layer. Korst [6] wrote comment on the boundary layer effects. He wrote Comments on suddenly changing area of sonic condition. He compared his theoretical results which utilize a two-dimensional flow model. Wood [10] 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 stabilizes 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.

Heskestad [14] found that for one particular geometry, Reynolds number, and suction rate beyond critical value 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.
Roache [18] obtained a new method of implementing the re-compression 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. Chow et al. [21] studied the problem of transonic flow past boattails with the numerical relaxative schemes. They restricted preliminary calculations to a particular model configuration for boatailed afterbody. They learned that the small disturbance treatment of the inviscid part of the transonic flow is not adequate even though the model appears to be relatively slender, thus, the full potential equation must be employed for its study. They presented that the “strong interaction” character of these problems within the transonic flow regime will be fully illustrated from the results obtained from their study even though the flow has not been separated away from the boattailed afterbody.

Drewry [26] performed experimental studies to axi-symmetric, sudden expansion dump combustor configurations for integral rocket-ramjet missile under cold flow test conditions. These studies have included surface flow visualization, measurements of total and static pressures, and gas sampling within a representative combustor duct. Flow visualizations tests, using a surface oil flow technique, vividly demonstrated the complex nature of the flow recirculation region downstream of the dump station. Gas concentration measurements of simulated fuel-air mixing were made in the combustor duct using an on-line gas analysis system with a quadruple mass spectrometer. Combustor flow field studies were made for test configurations with and without mechanical flame holding devices. Liu and Chow [28] studied axi-symmetric 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 axi-symmetric configuration was reported. Hallet et al. [30] did experiments in sudden expansion on swirling air flow. Rathakrishnan [31] 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 suddenly changing
area. Chow [34] 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. Extension to cases with small angles of incidence was also discussed. Gharib [38] 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 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.

A simple momentum integral model for estimating the minimum or “critical” swirl intensity required to produce central recirculation in a swirling sudden expansion flow is presented by Hallet [45]. An explicit equation is given for the critical swirl. He presented i) expansion ratio & ii) profile shape of inlet velocity are the function of critical swirl. Adams and Eaton [46] 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. 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. Experiments have been made by Viswanath [49] to assess the effectiveness of several base modifications or passive devices for reducing base drag at transonic speeds. The modifications tested include base cavities, ventilated cavities, and two vertex suppression devices. Results show that, while appreciable drag reductions are possible with many of the devices examined, the net total drag reductions are relatively lower,
presumably because of the additional losses associated with the devices. Berbee and Ellzey [50] studied the effect of aspect ratio on the flow over a rearward-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 of 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. Isaacson et al. [52] 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 previous work instability profile with various values of steepness parameter. Reynolds shear-stress profiles suggest the presence of counterclockwise 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.

Selby [55] studied passive control of three-dimensional separated vortical 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. Gould et al. [58] investigated incompressible turbulent flowfield 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-ε 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. Fearn, Mullin and Cliffe [59] 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.

Flow through a rectangular Passage which is expanded suddenly into another rectangular duct of larger Cross-sectional area has been studied experimentally with stagnation Pressures from 3.5 atmospheres to 1.25 atmospheres by Rathakrishnan et al. [61]. The length to height ratio of the enlarged duct varied from 5.769 to 1.923 and three models with length to height ratios 5.769, 3.846, and 1.923 were studied. The influence of stagnation Pressures and length to height ratio of the enlarged duct on base pressure and flow field mean pressures in the enlarged duct is discussed. The results of the present investigation indicate that the oscillatory nature of the mean pressure flow field in the enlarged portion with rectangular cross-section is appreciably different from that for circular cross-section at similar flow conditions. Meyer, Dutton and Lucht [62] 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. Hwang et al. [63] investigated the base pressure of a sudden enlargement from a tapering nozzle and from their investigation which concerns the determination of the back-pressure-independent base pressure associated with the convergent flow accelerating device which followed with a sudden enlargement in cross-sectional area. The point of reattachment acts as a saddle point singularity for the system of equations explaining the viscous flow recompression. Combination with whole momentum balance, the base pressure and the position within the wake area
where recompression initiates can be determined. Experiments were conducted for sudden expansion for convergent nozzles for different area ratios and for various convergent angles. Tanner [68] 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. Bourdon and Dutton [69] 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.

Shaw et al. [71] 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. Viswanath [73] explored experimentally the zero-lift drag features of multi-step after-bodies that utilize the idea of controlled separated flows at transonic and supersonic speeds. The significant 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 per cent) compared to blunt bases; however, compared to axi-symmetric boattailed 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. Baoyu Guo, et al. [75] worked on three-dimensional, time-dependent calculations using the finite volume CFD code CFX4 and the VLES approach with standard k-e model to simulate the turbulent swirl flow in an axisymmetric sudden expansion with an expansion ratio of 5.0 for a Reynolds number of 105. This flow is unstable over the entire swirl number range considered between 0 and 0.48, and a large-scale coherent structure is found to precess about the centerline. Compared with
the unswirled case, inclusion of a slight inlet swirl (swirl number below 0.23) can reduce the precession speed, cause the precession to be against the mean swirl and suppress the flapping motion. Several modes of precession are predicted as the swirl intensity increases, in which the precession, as well as the spiral structure, reverses direction. Accompanying the transition between different modes, abrupt changes in precession frequency are also experienced. Grid sensitivity and comparison with smaller expansion ratio data are also discussed.

Khan and Rathakrishnan [76]-[80] did experimental examination to assess the effectiveness of micro jets for over, under, and correct expansion to control the base pressure in suddenly expanded ducts at moderate and high supersonic speeds. The result thus produced showed that the maximum gain in the base pressure is 152 percent for Mach number 2.58. The result also indicated that the micro jets do not augment the wall pressure field. They showed that micro jets can function as an effective controller raising the base suction to almost zero level for some special cases. Lovaraju et al. [81] conducted the experiments to investigate the effectiveness of passive controls in the form of small tabs and a cross-wire projecting normally into the flow at the nozzle exit, on the characteristics of an axi-symmetric sonic jet operated at three under expansion levels, from their studies on the effectiveness of cross-wire and tabs on the under expanded sonic jet shows that, both the passive controls are effective in reducing the supersonic core significantly. Also, both the controls render the symmetric shock-cell structures unsymmetrical and weaker, all along supersonic core. The cross-wire/tab controlled jets grow wider in the direction normal to the cross-wire/tab at all the operating conditions. However, the tabbed jets grow much wider compared to the cross-wire controlled jets. Farrukh Alvi et al. [83] obtained experimental investigation of the flow and acoustic properties of a supersonic impinging jet, with and without control. From their results they found that effectiveness of the control is strongly dependent on a number of geometric and flow parameters, such as the impingement plane distance, orientation of the micro jets and the main jet operating conditions. From their studies they concluded that activation of micro jets leads to a local thickening of the jet shear layer, near the nozzle exit, making it more stable and less receptive to disturbances. Furthermore, micro jets generate strong stream wise vorticity in the form of well organized, counter rotating vortex pairs.
E. Rathakrishnan [86] presented the physical reasons for the presence of waves in correctly expanded supersonic jets. Even though there is no pressure gradient at the nozzle exit, generating waves to take the exit pressure to the level of back pressure, the large space encountered by the jet makes it to relax. This relaxation at the nozzle leads to formation of an expansion fan at the exit for under flow at the nozzle exit and Mach waves at the nozzle lip for jets from correctly expanded nozzle. These expansion waves on reflection from the jet boundary form compression waves, thus causing the jet field to become wave dominated. C. Senthil Kumar et al. [88] presented the experimental results on the flow characteristics of a 150 slanted entry Convergent-Divergent (CD) nozzle with a design Mach number of 2.94 exposed to $M = 1.6$, 1.8 and 2.0 streams. The 150 slanted entry nozzle results are compared with the results of identical geometry straight entry nozzle. The objective is to check whether a slanted entry nozzle, kept in a supersonic flow, with a detached shock present at its mouth, can choke and deliver supersonic flow. The results show that the nozzle can choke and deliver supersonic flow. The present study also explores the flow separation inside a slanted entry supersonic nozzle when it is exposed to a supersonic stream. Vikram Roy et al. [90] carried the numerical analysis of the turbulent fluid flow through an axi-symmetric sudden expansion passage by using modified $k-\varepsilon$ model, taking into consideration the effects of the streamline curvature. It was observed that the size and strength of the re-circulation bubble decreases with increases in the Reynolds number. But if the expansion ratio was increased keeping the Reynolds number constant the size and strength of the re-circulation bubble increases. They concluded that these flow parameters are needed to be controlled for the generation of the re-circulation bubble as required for combustion or any other purposes like the chemical processes etc.