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Combined Effect of Nozzle Pressure Ratio and Screech Prone Supersonic Mach Number in a Suddenly Expanded Flow

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ABSTRACT
This paper presents the results of an experimental study to evaluate the effectiveness of the micro jets to control the base pressure in a suddenly expanded flow at supersonic Mach numbers. Four micro jets of 1mm orifice diameter located at 90° intervals along a pitch circle diameter of 1.3 times the nozzle exit diameter in the base region were employed as active controls. The Mach numbers of the present study were 1.8 and 2.0. The jets were expanded suddenly into an axi-symmetric circular tube with cross-sectional area 2.56, 3.24, 4.84 and 6.25 times that of the nozzle exit area. The Length to Diameter ratio of the suddenly expanded duct was varied from 10 to 1 and experiment were conducted for Nozzle Pressure Ratio (NPR) from 3 to 11. Jets were over, under, and correctly expanded depending upon the NPR of the respective runs. When flow from the nozzle was over expanded or under expanded an oblique shock or expansion fan will be positioned at the nozzle lip, which in turn will result in increase or decrease of the base pressure. From the results it was observed that at NPRs 3 the control was not effective, however, at NPR 5, 7, 9, and 11 a significant change in the base pressure for all the area ratios was seen. From the results it was concluded that the level of expansion, Mach number, length-to-diameter ratio, and area ratio played an important role to fix the value of the base pressure and the control effectiveness by the micro jets.

Keywords: Base pressure, Active Control, Abrupt Expansion, Nozzle Pressure ratio.

1. Introduction

The discipline of "Base Flow Aerodynamics" has attracteda lot of attention in the past few years. The examination of base flow behind aerodynamic vehicles such as missiles, rockets, aircraft bodies and projectiles as well as re-entry vehicles is essential to understand the flow separation phenomenon, which leads to the formation of a low-pressure circulation region near the base. The interaction between the rocket exhaust, and the transonic/supersonic external flow deteriorates the performance of launchers and projectiles, and base flow is the trigger. Talking about the advanced future nozzle mechanics, such as the plug nozzle, the performance becomes more relative to the external flow, and therefore, the base flow plays even greater role. In order to comprehend the parameters of the base flow aerodynamics, more experiments are carried out and new applications are chosen. In the case of flow separation, the pressure in this region is usually substantially lower than the free stream atmospheric pressure. This notable difference in pressures can be up to two-thirds of the total drag on the body of revolution at Transonic Mach numbers. Nevertheless, the base drag at supersonic speeds is around one-third of the total drag and has decreased in this stream. Whereas, the base drag is 10 per cent of the skin-friction drag in the sub-sonic flow as the wave drag will not be there. To further increase of the base pressure, which decreases the base drag, one can think of different geometrical modifications, like boat tails, additional cavities, sting and discs, or application of base bleed and base combustion. However, the studies of base drag reduction with active control has not been studied much, therefore, an attempt has been made to study the problem with an internal flow. The experimental study of an internal flow apparatus has a number of distinct advantages over usual ballistics test procedures. Huge volume of air supply is required for tunnels with test-section large enough so that wall interference, etc., will not disturb flow over the model. `Stings' and other support mechanism required for external flow tests are also eliminated in the internal flows. The most important advantage of an internal flow apparatus is that complete static pressure and surface temperature measurements can be made not only along the entrance section to the expansion(analogous to a body of the projectile), but also in the wake region These measurements are particularly valuable if one needs to test the theoretical prediction adequately.

As stated, numerous techniques have been analyzed to control the flow separation; hence, base drag shall either by preventing it or by reducing its effects. Many researchers have adopted the passive methods like splitter plate, ribs at the base region of the enlarged duct, acoustic excitation, step body, locked vortex, but very few efforts have been made on active control strategies. Therefore, in the present work, an effort is made to examine the base pressure manipulation with active control with the help of micro jets under the effect of favorable, unfavorable pressure gradient and for ideally expanded cases; at high supersonic Mach numbers with micro jets.

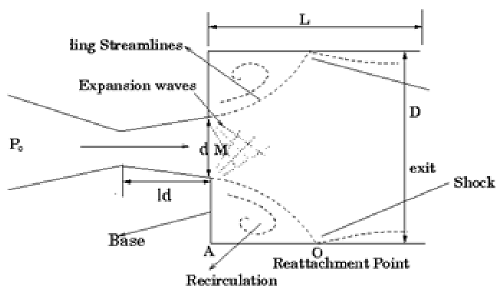


Fig.1: Sudden expansion flow field

2. Literature Review

In base flow aerodynamics, the aerodynamic forces are mainly loaded by separation over the rear slant, a torus on the base and two longitudinal vortices created on the side edges (Ahmed et al. 1984; Spohn and Gillie´ron 2002; Roume´as et al. 2008) [1-3]. The abrupt expansion of air in a duct results in the base pressure and noise was studied by Anderson and Williams. When the flow remains attached, the base pressure showed minimum value, which depends mainly on the duct to nozzle area ratio and on the geometry of the nozzle. Various jet flow models for fuel injection into a combustion chamber and dispersion of effluents into rivers through a diffuser were studied by Green 1995[4]. A specific configuration of jet flow had found applications as a combustion burner in many industries (Nathan et al. 2006) [5]. Rathakrishnan and Sreekanth [6] studied flows in pipe with sudden enlargement. They concluded that the non-dimensional base pressure was a strong function of the expansion area ratios, the overall pressure ratios and the duct length-to-diameter ratios. They showed that for a given overall pressure ratio and a given area ratio, it was possible to identify an optimal length-to-diameter ratio of the enlargement that will result in the 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 reattachment seemed to be strongly dependent on the area ratio of the inlet to enlargement. For a given nozzle and duct area ratio, the duct length must exceed a definite minimum value for minimum base pressure. The effectiveness of passive devices for axi-symmetric base drag reduction at Mach 2 was studied by Vishwanath and Patil [7]. The devices examined included primarily base cavities and ventilated cavities. Their results indicated that the ventilated cavities offered significant base drag reduction. They found a 50 per cent increase in base pressure and 3 to 5 per cent net drag reduction at supersonic Mach numbers for body of revolution.

The effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts was studied experimentally by Khan et al. [8]-[15]. From the experimental results, it was found that the micro jets can serve as active controllers for the base pressure. From the wall pressure distribution in the duct it was found that the micro jets do not disturb the flow field in the enlarged duct. Ashfaq Syed Ashfaq et al. [16]-[27] studied the effect of area ratio, nozzle pressure ratio, length to diameter ratio and control effectiveness for various area ratios for correctly and under expanded jets. From their result they found that the control in the form of the micro jets was very effective. One of the reason for this behaviour could be due the lowest area ratio, the space available for the flow to create the suction was the lowest and the vortex sitting at the base whose strength was constant was able to influence the base region very effectively leading to very low level of base pressure and also the wall pressure was found to be low and oscillatory in nature. This trend of the wall pressure having waviness was observed for all the NPRs and Length to Diameter ratio and it was also observed that this waviness nature was very strong at the higher NPRs as compared to the lower NPRs. They presented the results of experimental studies to control the base pressure from a convergent nozzle under the influence of favourable pressures gradient at sonic Mach number. The area ratio (ratio of area of suddenly expanded duct to nozzle exit area) studied were2.56, 3.24, 4.84 and 6.25. It was found that many techniques can be used to reduce or even suppress two or three dimensional separation. These techniques include blowing or suction of air flow through slots (Lehugeur et al. 2010; Wassen and Thiele 2007, 2008; Muminovic et al. 2008) [28-30] or holes (Favier et al. 2007; Roume´as et al. 2008) [31-32], use of array(s) of unsteady (synthetic or pulsed) jets (Leclerc 2008), actuators (Boucinha et al. 2008a, b; Moreau 2007) [33-35] and others. All of these techniques come with pros and cons, as the steady blowing or suction through orifices normal to freestream flow and located close downstream of the separation line had been revealed to be effective in reattaching the flow, but such devices need a continuous supply of mass flow through such orifices. In the case of slots, the mass flow rate had been shown to be very high in order to effect the requisite control. On the other hand, range of steady microjets had proven much efficient in comparison to single slit in terms of the flow rate needed, while being very effective in controlling the separation. This being the physical mechanisms behind this 'discrete' or 'segmented' control differ from the use of (quasi) two-dimensional or high aspect ratio slots. Steady microjets act as 3D disturbances, which generate distinct 3D vertical structures that offer some advantages in terms of mixing and re-energizing the separating boundary layer. To date, separation control using microjets had primarily been examined in canonical flows such as a modified backward facing ramp (Kumar and Alvi 2006, 2009) [36-37] and for aircraft-related applications for two-dimensional (at least geometrically) airfoils (Bourgois et al. 2005; Favier et al. 2007; Kreth et al. 2010) [38-40].

In this study, we examine the use of microjet based control in a suddenly expanded axi-symmetric duct, especially, the aim is to control the base pressure in the transonic/supersonic regime, which appears to be very promising. We will evaluate the microjet efficiency to reduce the base drag and to gain some insight in the mechanism behind this approach.

3. Experimental Setup

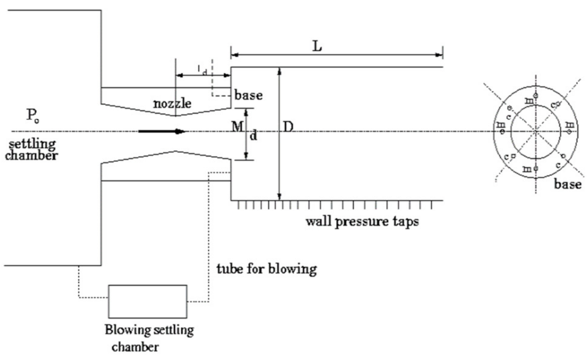


Fig. 2: Experimental setup

The Fig. 2 shows the experimental setup, which was used for the present study. At the exit periphery of the nozzle there were eight holes as shown in the figure, four of which were (marked c) were used for blowing and the remaining four (marked m) were used for the base pressure (P_b) measurement. Control of base pressure was carried out by blowing through the control holes (c), using pressure from a settling chamber by employing a tube connecting the settling chamber and the control holes (c). Wall pressure taps were provided on the duct to measure wall pressure distribution. First nine holes were made at an interval of 3mm each and the remaining was made at an interval 5mm each. From the literature it was found that, the typical Length to Diameter (as shown in Fig. 2) resulting in P_b maximum was usually from 3 to 5 without controls. Since active controls were used in the present study, Length to Diameter ratios up to 10 had been employed. For each Mach number, and Length to Diameter ratios used were 10, 8, 6, 5, 4, 3, 2, and 1 and for each value of Length to Diameter ratio NPRs used were 3, 5, 7, 9, and 11.

PSI model 9010 pressure transducer was used for measuring pressure at the base, the stagnation pressure in the main settling chamber and the pressure in the control chamber. It has 16 channels and pressure range was 0-300 psi. On average 250 samples per second displayed reading was achieved. The software provided by the manufacturer was used to interface the transducer with the computer. The user-friendly menu driven software acquires data and showed the pressure readings from all the 16 channels simultaneously in a window type display on the computer screen. The software can be used to choose the units of pressure from a list of available units, perform a re-zero/full calibration, and other transducer could also facilitate the chosen number of samples to be averaged, by means of dipswitch settings. It could be operated in temperatures ranging from -20° to +60° Celsius and 95 per cent humidity.

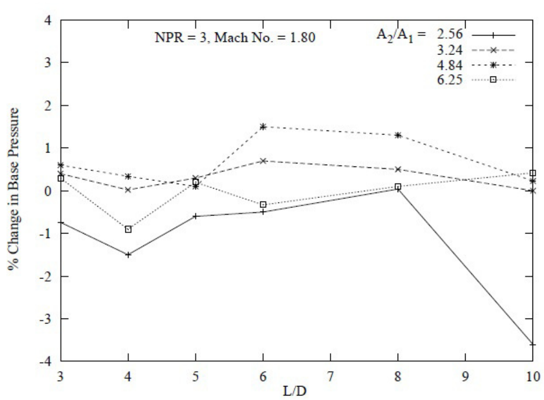
4. Results and Discussion

The obtained values consist of base pressure (P_b); wall static pressure (P_w) along the length of the duct, and the NPR i.e. stagnation pressure (P_0) to back pressure (P_{atm}) ratio. The obtained pressures were made non-dimensional by dividing them with the atmospheric pressure/back pressure. This investigation focus the attention on the effectiveness of active control in the form of micro jets, located at the base region of suddenly expanded axi-symmetric ducts, to modify the base pressure at supersonic Mach number, which was more prone to screech. The parameters considered in the present study were the area ratio of the enlarged duct, L/D ratio of the suddenly expanded duct, the jet Mach number and the level of expansion (NPR).

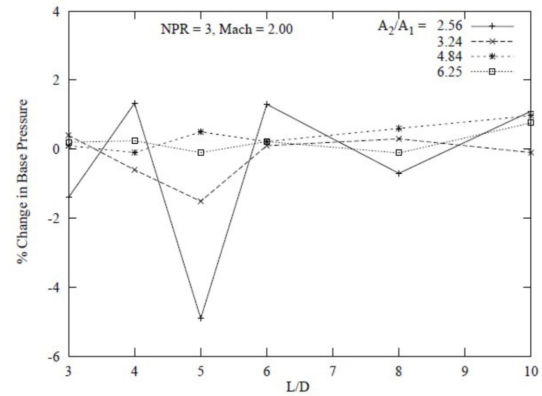
The dependence of base pressure on Mach number, four area ratios namely 2.56, 3.24, 4.84, and 6.25 for NPRs from 3 to 11 were given in the Figs. 3((a) to (j)). Results of the base pressure with and without control were compared. It was seen from these results that in supersonic regime the Mach number had a very strong influence on the base pressure. For a given Mach number the nozzle pressure ratio (NPR), which dictates the level of expansion, has a strong role to play on the control effectiveness of the micro jets. Also, it was seen that with increase of NPR, the control becomes more effective in increasing the base pressure for Mach numbers in the range from 1.8 to 2.0. The physical reason for this may be the influence of the shock at nozzle exit, which turns the flow away from the base region, thereby weakening the vortex positioned at the base. This results in increase of base pressure since the weakened vortex at the base encounters the mass flow injected by the micro-jets. However, NPR11 results in continuous increase of base pressure compared to the without control case for the present range of Mach number tested namely, 1.8 and 2.0. This may be due to the NPR increases the level of overexpansion decreasing Hence, the oblique shock at the nozzle exit becomes weaker than those at lower NPRs. Therefore, the turning away tendency of incoming flow comes down leaving the vortex almost intact. At this situation when the micro jets are introduced they may propagate without any deflecting tendency, thereby entraining some mass from the standing vortex and convecting it away from the base causing the base pressure to assume higher values than those for without control. It was well known from literature that passive controls perform better in the presence of favorable pressure gradient. In the present study the combined effect of favorable pressure gradient and the relief due to area ratio on the active control effectiveness is investigated.

The percentage change in base pressure as a function of length to diameter ratio and area ratio are presented for NPR =3, 5, 7, 9, and 11.

The NPR range in the present study was such that jet exiting the nozzle experiences correct, over and under expansion. It was well known that oblique shock or expansion fan will be positioned at the nozzle lip for over and under expanded conditions, respectively. To understand the influence of level of expansion on the base pressure with and without control the percentage change in base pressure variation as a function of Mach number, L/D and NPR were presented here. The effect of area ratio with Mach number and NPR being shown in the Figs. 3 ((a) to (j)). The results for NPR 3 as in the Fig. 3 ((a) to (b)) for Mach numbers 1.8 and 2.0, contain the base pressure with L/D for over expanded jets. The NPR required for ideally expanded jets were5.8 and 7.8, respectively, for Mach 1.8 and 2.0. When the flow was exiting from the nozzle at NPR 3, the jets were over expanded and hence, there will be an oblique shock at the nozzle exit and the shear layer coming out of the nozzle will be deflected towards the nozzle center line by the shock. This delayed the reattachment and will result in a longer reattachment length as compared to a case without a shock. It was also known that the reattachment length being a parameter strongly influencing the base vortex, the increase or decrease of reattachment length will modify the base pressure. From the figure it was seen that control effectiveness was only marginal and the reason for this trend was mainly due to the level of over expansion.



(a)



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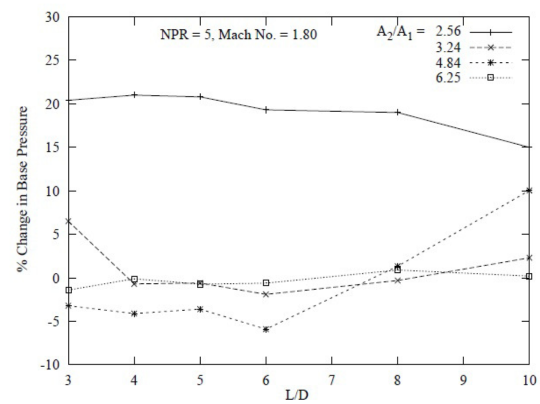
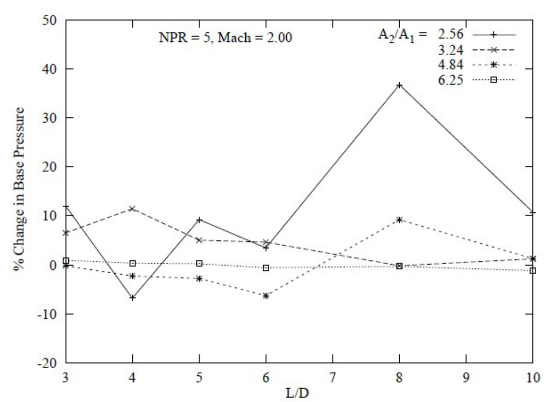


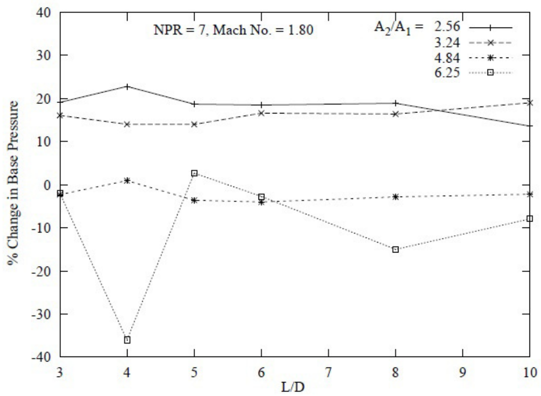
(c)



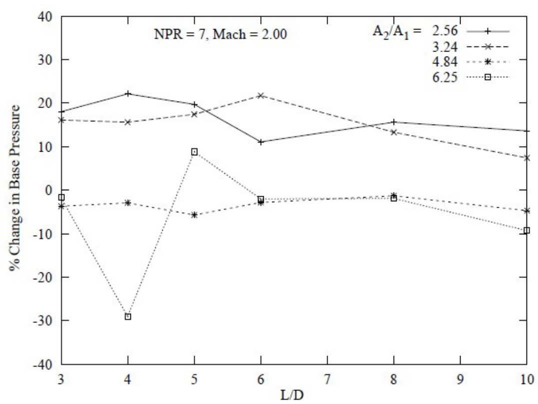
(d)

Results for NPR = 5 being as shown in the figs. 3 (c) to (d)). Due to the increase in NPR the level of over expansion had reduced. In the case of Mach 1.8, this NPR was very close to become ideally expanded and there was appreciable gain in the base pressure in the range from fifteen to twenty percent. This happens only for lowest area ratio namely 2.56, because of the area ratio at the micro jets are located at the middle position ofthe base region. For all the remaining area ratio at

Mach 1.8 and 2.0, the effectiveness of the micro jets were only marginal Fig. 3 ((c) to (d)).



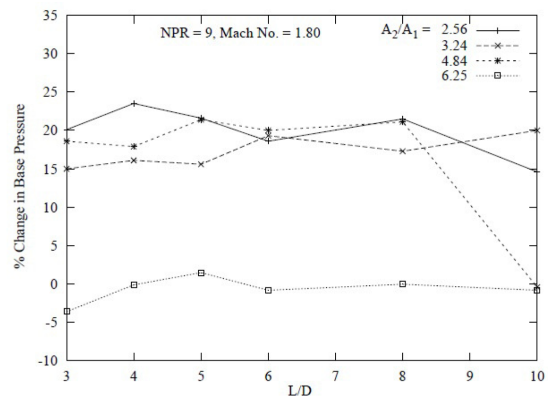
(e)



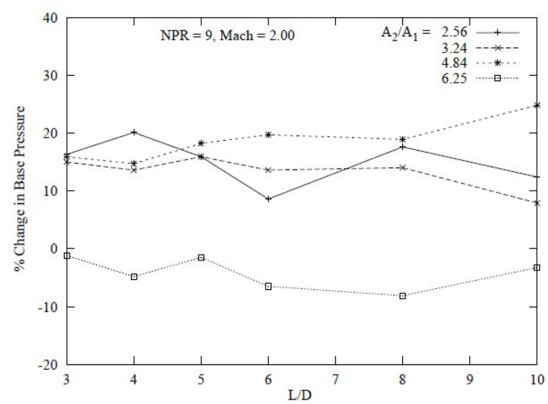
(f)

Base pressure results for NPR 7 were obtained as in the Figs. 3(e)-(f) for Mach numbers1.8 and 2. Here, for the Mach number 1.8, the jet were under expanded and Mach number 2 are over expanded. Due to the change in the expansion level, the change in the base pressure values were observed. For lower area ratios, the increase in the base pressure is considerable, which was around twenty five percent and for area ratio 4.84 the micro jets were not effective. In the results for area ratio 6.25, it was found that at L/D = 4 for both the Mach numbers, the jets become quite and the phenomena was observed by the Anderson and Williams had shown up during this test, which indicates that the base pressure was having a minimum value, depends mainly on the duct to nozzle area ratio and on the geometry of the nozzle. The plot for the overall noise showed a minimum at a jet pressure approximately equal to that required producing the minimum base pressure. We too had also observed this phenomenon when micro jets were activated, the jets were silent.

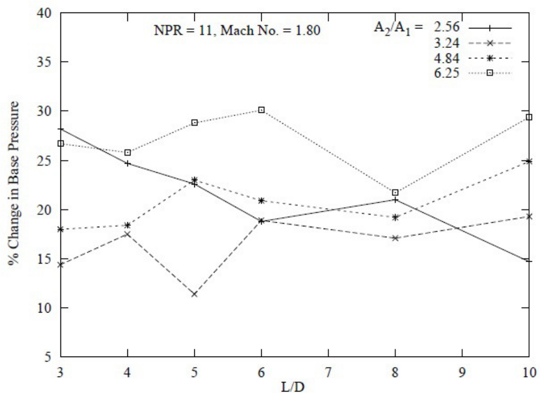
Results for NPR 9 were shown as in the Figs. 3((g)-(h)). Here both the Mach numbers were under expanded, there is an expansion fan at the nozzle exit due to increase in NPR. This expansion fan had a control over the base pressure depending on the relaxation it enjoys due to the area ratio effect. From the results it was found that for all the area ratios the control had become effective except for area ratio 6.25 where the control effectiveness was marginal for both Mach numbers. This observation was in good agreement with those reported by Ratha Krishnan and Sreekanth [2] for subsonic and transonic case without control. These results reiterate the fact that a definite L/D was necessary for the flow to re-attach after sudden expansion for a given set of parameters. If the length was less than this minimum limit, the flow will proceed without re-attaching with the duct.



(g)

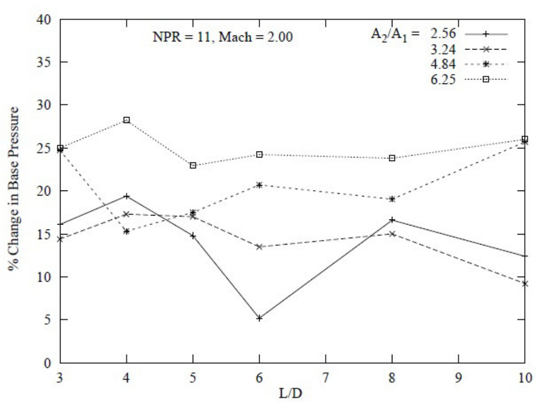


(h)



(i)

Results for the NPR 11 being shown as in the fig. 3 ((i) to (j)). An important point to be observed, that unlike passive controls the favorable pressure gradient need not yield the desired results for active control in the form of micro jets. However, for higher values of the NPRs namely 11, the active control by micro jets results in increase of base pressure for all the values of the area ratios of the present study. It was interesting to note that, irrespective of the relief due to the area ratio the control effectiveness was significant at high supersonic Mach numbers under the influence of favorable pressure gradient.



(j)

Fig. 3: Percentage change in base pressure with L/D ratio

It wasevident that increase in relief to the flow simply indicate that relaxation space existing for the flow was increasing. This sort of relief will make the shock/expansion waves at the nozzle lip to spread relatively more freely with increase of relief at the lip of nozzle/area ratio.

For lower area ratio, there was significant increase of base pressure for most of the cases, but it should be emphasized that some combination of parameters results in decrease of base pressure when control was employed. Therefore, one had to identify the proper combination of parameters to achieve the control of base pressure resulting in increase or decrease of base pressure depending on the need of the application. For example, for base drag reduction one can aim at increasing the base pressure to a maximum and for mixing enhancement in the combustion chamber one can aim to decrease the base pressure to as a low value as possible.

5. Conclusions

From the above results, control with the help of micro jets to control base pressure had been established. The flow field in the duct remains unaltered when jets were highly over expanded. With the increase in the NPR, the control in the form of micro jets becomes for effective for all NPR > 5 and above. The flow field was dominated by the presence of the waves both strong as well as the weak ones. The reflection of the waves from the wall, recompression and recombination's are taking place in the base region as well as partially in the duct wall, thereby making the flow oscillatory. The micro jets can be used as effective controllers, increasing the base suction to appreciable level for some combination of parameters. The nozzle pressure ratio plays a key role in deciding the magnitude of base pressure with and without control, in the high supersonic jet Mach number regime too.

All the non-dimensional wall pressure values exhibited in this paper were within an uncertainty band of ± 2.6%. All the investigation results were within the range of± 3 per cent.

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