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CONTROL OF BASE FLOWS WITH MICRO JET FOR AREA RATIO OF 6.25

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ABSTRACT

Suddenly expanded flow with active controls in the form of micro jets has been investigated experimentally, laying emphasis on the effectiveness of micro jets on the base pressure and enlarged duct pressure field. Air injection at four locations at the base, symmetric to the nozzle axis is used as the active control. The jet Mach numbers of the present studies are 1.87, 2.2 and 2.58. The area ratio of present study is 6.25. The length-to-diameter ratio of the suddenly expanded duct and the Nozzle Pressure Ratio (NPR) are varied from 10 to 1 and 3 to 11. In addition to base pressure, wall pressure field along the duct was also studied. It is found that the active control in the form of blowing through small orifices (micro jets) are effective in controlling the base pressure field. Micro jets do not augment the flow field in the duct. As high as 55 percent, increase in base pressure was achieved for certain combination of parameters of the present study.

Keywords: micro jets, base flow, settling chamber, control chamber, L/D ratio.

1. INTRODUCTION

Flow separation at the base of aerodynamic vehicles such as missiles, rockets, and projectiles leads to the formation of a low-pressure recirculation region near the base. The pressure in this region is generally significantly lower than the free stream atmospheric pressure. Base drag, caused by this difference in pressures, can be up to two-thirds of the total drag on a body of revolution at Transonic Mach numbers. However, the base drag will decrease at Supersonic speeds and is around one-third of the total drag. 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. Techniques such as boattailing, base burning, and base bleed have been used traditionally to reduce base drag. However, very few studies have been carried with active control.

Here 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 main features of suddenly expanded flow field are illustrated in Figure-1.

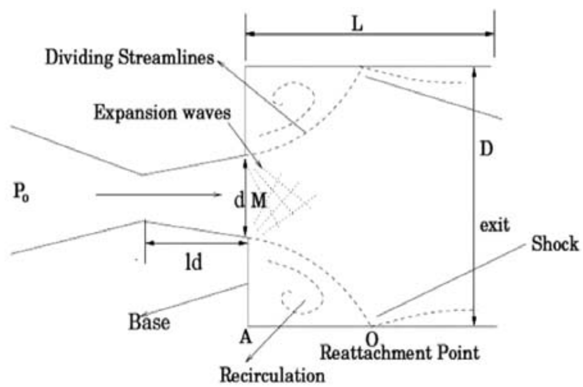

Figure-1. Sudden expansion flow field.

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 wants to test theoretical prediction adequately.

2. LITERATURE REVIEW

Anderson and Williams [1] worked on base pressure and noise produced by the abrupt expansion of air in a cylindrical duct. With an attached flow the base pressure was having minimum value which depends 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.

Bar-Haim and Weihs [2] studied boundary layer control as a means of reducing drag on fully submerged bodies of revolution. He concluded that the drag of axi-symmetric bodies can be reduced by boundary layer suction, which delays transition and can control separation.

Rathakrishnan and Sreekanth [3] studied flows in pipe with sudden enlargement. They concluded that the non-dimensionalized base pressure is a strong function of the expansion area ratio, the overall pressure ratio and the duct length-to-diameter ratio. 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 reattachment seemed to be strongly dependent on the area ratio of the inlet to enlargement.

Srikanth and Rathakrishnan [4] developed an empirical relation for base pressure as a function of nozzle pressure ratio, area ratio and length-to-diameter ratio of the enlarged duct, using the experimental data of Rathakrishnan and Srekanth [3]. Tanner [5] studied base cavity at angles of incidence. 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^{o}C. At α = 2^{o}C, he found the maximum drag decrease.

Rathakrishnan *et al*., [6] studied the influence of cavities on suddenly expanded subsonic flow field. 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 in 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 [7]. 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 per cent net drag reduction at supersonic Mach numbers for a body of revolution.

Viswanath [8] reviewed the flow management techniques for base and after-body drag reduction the problem of turbulent base flows and drag associated with it. The paper discusses the effectiveness of cavities, ventilated cavities, locked vortex after-bodies, multi-step after-bodies and after-bodies employing a non-axi-symmetric boat-tailing concept for base and net drag reduction in different speed regimes. His 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 base flow is not characterized by vortex shedding.

Effects of base cavity on subsonic near-wake flow were studied by Kruiswyk and Dutton [9]. They experimentally investigated the effects of the base cavity on the near-wake flow field of a slender two 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 in the base pressure coefficients of 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.

Mathur and Dutton [10] 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.

Rathakrishnan [11] investigated the effect of Ribs on suddenly expanded axi-symmetric flows laying emphasis on the base pressure reduction and enlarged duct pressure field. Annular ribs with aspect ratio 3:1 was found to be the optimum and they 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 was also less than six per cent. 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 ribs 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 field. 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.

Khan and Rathakrishnan [13] studied the control of suddenly expanded flow from over expanded nozzles with micro jets for high supersonic Mach number. The aim of their study was to access the effectiveness of the micro jets under the influence of adverse pressure gradient.

Khan and Rathakrishnan [14] conducted the experiments for under expanded case for Mach numbers 1.25, 1.3, 1.48, 1.6, 1.8, 2.0. All the experiments were conducted for a fixed value of level of under expansion (P_e/P_a = 1.5). They found from their studies that the micro jets are very effective whenever nozzles are under expanded. As reported in the literature that whenever favorable pressure gradient exist the effectiveness of the control will be at its best whether it is active control or passive control.

Khan and Rathakrishnan [15] studied the control of suddenly expanded flows for correctly expanded case. They found from their studies that the micro jets are not very effective for correctly expanded case for Mach numbers 1.25, 1.3, 1.48, 1.6, 1.8, 2.0. There is a marginal change in the values of the base pressure. The physical reasons for this phenomenon may be due to the presence of a weak wave at the nozzle lip. When micro jets are activated they are not able to modify the base pressure in the presence of a weak wave. Another important phenomenon observed was that even for the correctly expanded flow case the flow is dominated by the waves. Earlier it was believed that the correctly expanded flow is free from waves.

The effect of level of expansion in a suddenly expanded flow and the control effectiveness has been reported by Khan and Rathakrishnan [16]. In their study they considered correct, under, and over expanded nozzles for four area ratio for the Mach numbers 1.25, 1.3, 1.48, 1.6, 1.8, 2.0, 2.5, and 3.0. They conducted the tests for the NPRs in the range 3 to 11. From their results it was found that for a given Mach number, length-to-diameter ratio, and the nozzle pressure ratio the value of base pressure increases with the area ratio. Jagannath *et al*., [17] studied the pressure loss in a suddenly expanded duct with the help of Fuzzy Logic. They observed that minimum pressure loss takes place when the length to diameter ratio is one and further it was observed that the results given by fuzzy logic are very logical and can be used for qualitative analysis of fluid flow through nozzles in sudden expansion.

Pandey and Kumar [18] studied the flow through nozzle in sudden expansion for area ratio 2.89 at Mach 2.4 using fuzzy set theory. From their analysis it was observed that L/D = 4 is sufficient for smooth development of flow keeping in view all the three parameters like base pressure, wall static pressure and total pressure loss. The above review reveals that even though there is a large quantum of literature available on the problem of sudden expansion, vast majority of them are studies without control. Even among the available literature on investigation of base flows with control, most of them, use only passive control by means of grooves, cavities and ribs. Only very few studies report base flow investigation with active control.

M. A. Baig and S. A. Khan [19] studied effect on base pressure due to active control in the form of micro jets at area ratio 2.56, and concluded that micro jets do not disturb flow field and base pressure increases for certain combinations of parameters of study.

Therefore, a closer look at the effectiveness of active control of base flows with micro-jets, especially in the supersonic flow regime will be of high value, since such flow field finds application in many problems of applied gas dynamics, such as the base drag reduction for missiles and launch vehicles, base heating control for launch vehicles, etc. With this aim the present work investigates the base pressure control with active control in the form of micro jets.

The experiments are carried out using the experimental facility at the High Speed Aerodynamics Laboratory (HSAL), IIT, Kanpur. Figure-2 shows the experimental setup used for the present study. At the exit periphery of the nozzle there are eight holes as shown in the Figure, four of which (marked c) are used for blowing and the remaining four (marked m) are used for base pressure (P_b) measurement. Control of the base pressure is done, by blowing through the control holes (c), using the pressure from the blowing chamber by employing a tube connecting the chamber and the control holes (c). Pressure taps are provided on the enlarged duct wall to measure wall pressure distribution in the duct. First nine holes are made at an interval of 4 mm each and remaining is made at an interval of 8 mm each. Experiments are conducted for Mach numbers 1.87, 2.2 and 2.58. From literature it is found that, the typical values of L/D (as shown in Figure-2) resulting in base pressure maximum are usually 3 to 5 without controls. Since active control is employed in the present study, L/D ratios up to 10 had been tested. For each Mach number, L/D ratios to be tested are 10, 8, 6, 5, 4, 3, 2 and 1 and for each value of L/D ratio NPR employed are 3, 5, 7, 9, and 11.

Pressure transducer of the make PSI System 2000 was used for measuring pressure at the base. It has 16 channels and pressure range is 0-300 psi. It averages 250 samples per second and displays the reading. Mercury manometer is used for measurement of duct wall pressure distribution.

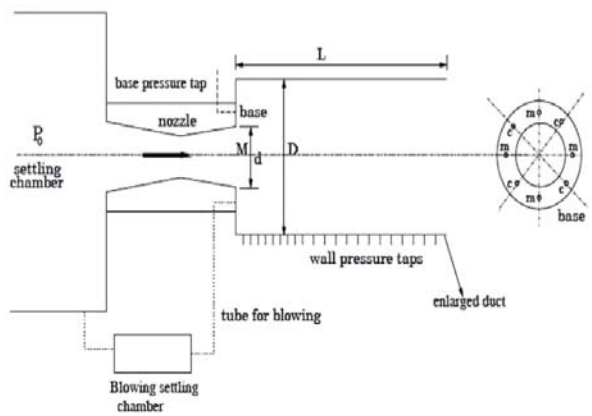

Figure-2. Experimental setup.

4. RESULTS AND DISCUSSIONS

This investigation focuses attention on the effectiveness of active control of micro jets at the base region of a suddenly expanded axi-symmetric duct to modify the base pressure. The measured data consists of the base pressure (P_b) wall static pressure (P_w) distribution along the length of enlarged duct and nozzle pressure ratio (NPR) defined as the ratio of stagnation pressure (P_0) to back pressure (P_{atm}). All measured pressures were non-dimensionalized with the ambient atmospheric pressure (i.e., back pressure). In addition to the above pressures, other parameters of the present study are the jet Mach number (M), area ratio (enlarged duct cross sectional area/nozzle exit area), length to diameter ratio of the enlarged duct (L/D). Area ratio used is 6.25 and the blow pressure ratio is same as the NPR of respective runs.

Non-dimensionalized base pressure variation with NPR for duct L/D = 10 at Mach 1.87, 2.2 and 2.58 for the cases of flow with and without control are compared in Figure-3 (a). It is clearly seen that the functional dependence of base pressure with NPR is unaltered by the control. However, the control tends to modify the base pressure level at all NPRs. Also, the control effectiveness in modifying the level of base pressure gets enhanced with increase of NPR. This agrees well with the findings of Navin Kumar Singh and Rathakrishnan [12], who reported that the effectiveness of passive control in the form of tabs in enhancing the mixing increases with increase of favorable pressure gradient. For the NPRs in the range of 3 to 5 the control effectiveness is almost insignificant and the effectiveness increases with increase of NPR. For Mach 1.87, the NPR for correct expansion is 6.4. Therefore, up to NPR 6.4 the flow at nozzle exit is over expanded and hence adverse pressure gradient is present when the flow enters the enlarged duct. For NPR larger than 6.4 favorable pressure gradient exists at the nozzle exit. For NPR < 6.4, in the presence of adverse pressure gradient the control effectiveness is only marginal. Also, as the NPR increases from 3, i.e., as the level of adverse pressure gradient decreases, the control effectiveness increases. For the NPRs in the range from 5 to 9.5 the control results in decrease of base pressure whereas, for NPRs beyond 9.5 controls tend to increase the base pressure. Furthermore, it is seen that the control results in decrease of base pressure compared to without control case, upto certain NPR and then increases the base pressure to stay above that for without control case. For Mach 2.2 the value of NPR for correct expansion is 11. This is clearly seen that for NPRs in the range 3 to 7 the control is marginally effective and it becomes effective for higher NPRs in the range 7 to 11, but control results in decrease of base pressure. The reason for this behavior is due to the presence of adverse pressure gradient. For Mach 2.58 the value of NPR for correct expansion is 19. As discussed above that the control is ineffective as long as adverse pressure gradient exits. Similar results are seen at this Mach number and the control reversal takes place at NPR 8. This peculiar behavior is due to the level of over expansion. A closer look at the flow process at the base of the duct will explain the reason for this behaviour. The base pressure level is dictated by the expansion level at the nozzle exit and the duct L/D, for a given area ratio. There will be an expansion fan and oblique shock at the nozzle lip, for under and over expanded flows, respectively. Thus, the wave at the nozzle lip has a dominant influence on the base pressure level. This causes the control to become more effective at higher NPR for higher Mach numbers, compared to lower Mach numbers. The above discussed behavior of base pressure with NPR for the cases of with and without control is clearly seen in Figure-3 (a). It is to be noted that in addition to influence of shock wave or expansion fan at the nozzle lip, the relief effect due to increase of area ratio also will influence the base pressure. Further, it is to be noted that for area ratio 2.56, the micro jets at the base were located at mid pitch circle diameter (pcd) of the base [19], whereas for area ratio 6.25 the micro jets are closer to the nozzle exit (not at the middle of the base). This is because pcd for micro jets was kept constant in the present study.

Base pressure results for L/D = 8 are shown in Figure-3 (b). For Mach 1.87 the micro jets are ineffective till NPR 5. However, for higher NPR in the range 5 to 9 initially the control results in increase of the base suction and for NPR > 9.3 the control results in decrease of base suction and the control reversal takes place at NPR 9.3 The results for Mach 2.2 are on the similar lines, as that of at L/D = 10, as the jets remain over expanded for the all the NPRs in the present test. It is seen that at Mach 2.58 at NPR 3 the control results in increase of base pressure and the control reversal takes place at NPR 4.5 and 7 as compared to NPR 8 for L/D = 10. This shift in the behavior may be due to the reduction in the length of the enlarged duct and the effect of the back pressure.

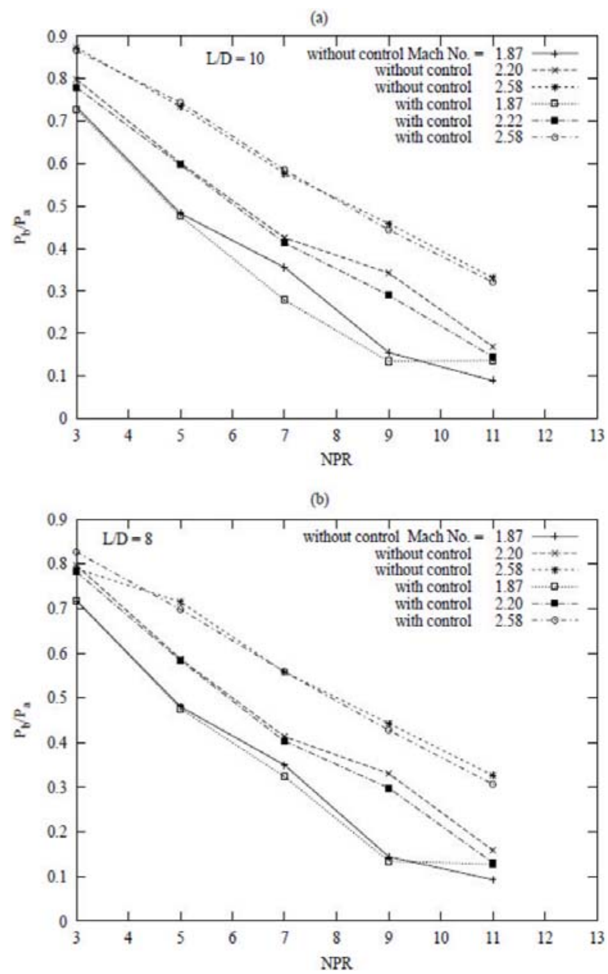

Figure-3. Base pressure variation with NPR.

Results for L/D = 6 are shown in Figure-4 (a). As discussed earlier control is marginally effective for Mach 1.87, control reversal takes place at NPR 9.2. For Mach 2.2 the control reversal takes place at NPR 5 and 9 and control results in decrease of base pressure for all the NPRs.

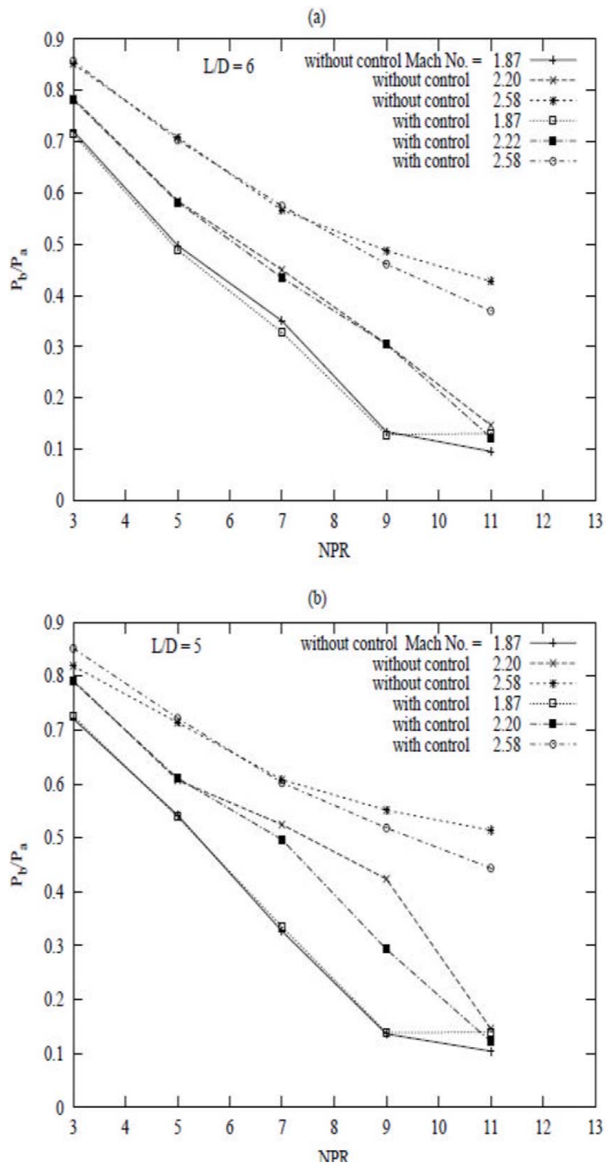

Figure-4. Base pressure variation with NPR.

For Mach 2.58 the Micro jets are ineffective up to NPR 8 and then control results in decrease of base pressure. Figure-4 (b) presents results for L/D = 5. It is seen that for Mach 1.87 there is no effect of control up to NPR 9, however, at NPR 11 control results in increase of base pressure. For Mach 2.2 control results in decrease of base pressure for NPRs 5 onwards. For Mach 2.58 control results in increase of base pressure for NPRs 3 to 5, control reversal takes place at NPR 7 and from NPR 7 onwards control results in decrease of base pressure. This implies that the level of overexpansion plays an important role in dictating the base pressure, there is an oblique shock generated at the nozzle exit, since for Mach 1.87 flow is over expanded upto NPR 6.4, for Mach 2.2 flow is over expanded upto NPR 11, and for Mach 2.58 flow is over expanded upto NPR 19. Flow through the oblique shock experiences a pressure increase, but the vortex at the base tries to establish a low-pressure at the base region. Thus, the low-pressure caused by the vortex and the flow with the pressure behind the oblique shock have to coexist at the base, before getting mixed up with the main flow. This process dictates the magnitude of pressure at the base region. It can be expected that the location of base pressure increase gets shifted to higher NPR with increase of Mach number.

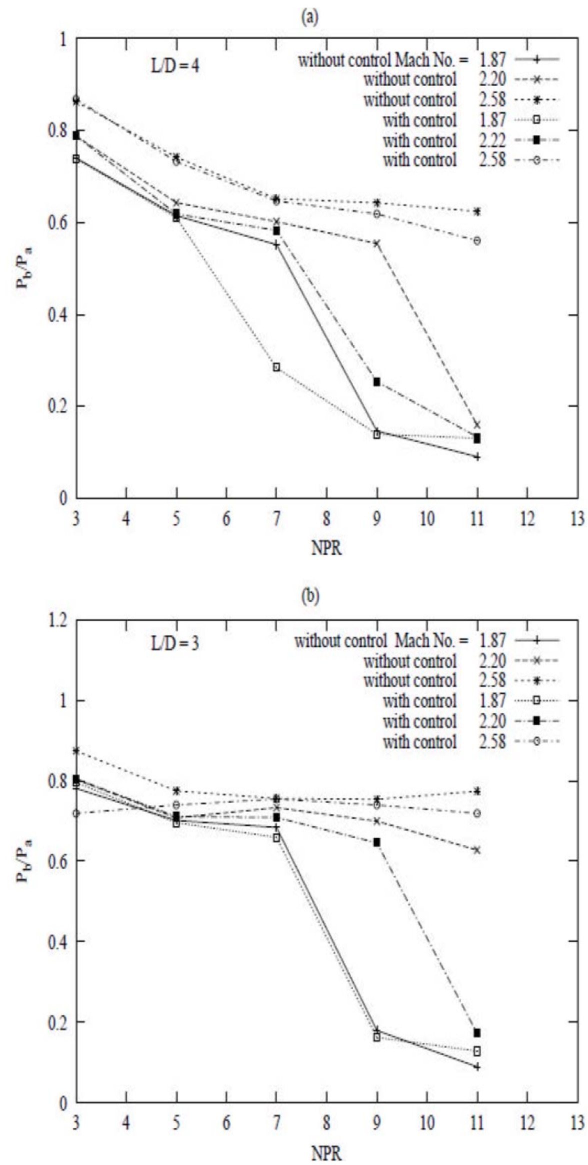

Figure-5. Base pressure variation with NPR.

Results for L/D = 4 are shown in Figure-5 (a). For Mach numbers 1.87 and 2.2 the trend are similar as that for higher L/Ds without control. Control results in decrease of base pressure up to NPR 9 for Mach 1.87 and for Mach 2.2 base pressure decreases for all the NPRs. For Mach 2.58 the control effectiveness is marginal, however, it decreases progressively from NPR 7 onwards.

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Figure-5 (b) shows results for L/D = 3. For Mach 2.2 and 2.58, the base pressure assumes very high value up to NPR 9. Control effectiveness is marginal for Mach 2.58, but for Mach 2.2 at NPR 11 there is drastic reduction base pressure. However, this behavior at M = 1.87 is totally different. Initially base pressure assumes high value up to NPR 7 then with the increase in NPR base pressure decreases throughout; however, control reversal takes place at NPR 5 and 9.5. Control results in decrease of base pressure up to NPR 9.5 then beyond NPR 9.5 the micro jets are able to reduce the suction. This behavior is due to the level over expansion, L/D ratio, Mach number and NPR. Flow is attached with the enlarged duct for Mach 1.87 only, for the remaining Mach numbers the flow is detached with the duct.

Results for L/D = 2 are shown in Figure-6 (a). Here it is seen that, the trend is similar to that of for higher L/Ds for Mach 2.2 and 2.58 and control is not effective. However, for Mach 2.2 NPRs in the range 7 to 11, control results in decrease of base pressure. This behavior may be due to decrease in the level over expansion. But at Mach 1.87 the behavior is different as seen from Figure, the base pressure assumes very high value up to NPR 7 then there is decrease in base pressure up to NPR 9 and then again there is a marginal increase in base pressure. The control reversal takes place at NPR 9.

Results for L/D = 1 are shown in Figure-6 (b). It is evident from the figure that the duct length is not sufficient for the shear layer to attach with the duct wall for all the Mach numbers tested.

It is evident from these results that, the L/D has a definite role to play in the control of base pressure achieved with micro jets. It can be stated that, the base pressure due to the re-circulating flow at the base is dictated by the reattachment length, which is the distance from the beginning of the enlargement to the point where the free shear layer from the nozzle attaches with the duct wall. For this to take place the duct should have a definite length. It has been proved by Rathakrishnan and Sreekanth [5] that this minimum length is L/D = 3, for subsonic and sonic flows. It is in disagreement of the above findings. This may be because the experiments by Rathakrishnan and Sreekanth [5] were up to sonic Mach number and at a maximum NPR of 3, whereas, in the present study the Mach numbers as well as Nozzle Pressure Ratio are in the higher range. Hence, even L/D = 2 results in increase of base pressure for Mach 1.87 and flow is attached with the duct.

It is important to realize that, even though it appears as if the base pressure increases at minimum value of NPR 5, 7, and 9 for Mach numbers 1.87, 2.2, and 2.58, respectively, tests with close steps of NPR will be helpful in identifying the minimum value of NPR at which this increase begins. However in the present study such tests are not conducted. It is interesting to note that after the limiting NPR, increase in NPR results in increase of base pressure for all Mach numbers. However, the rate of increase becomes a function of nozzle expansion level. Once the flow becomes under expanded the magnitude of increment becomes larger. Further, the micro jets become effective in enhancing the base pressure when the nozzle is under expanded.

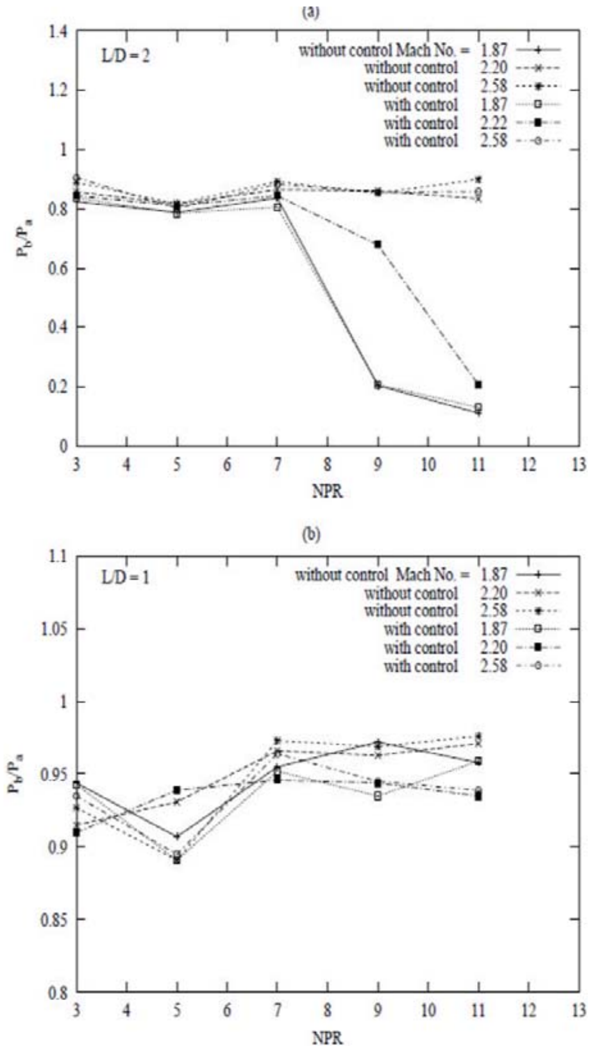

Figure-6. Base pressure variation with NPR.

From Figures 7 (a) to 8 (a) it is seen that for NPRs above 7 and 9 the micro jets favorably influence (i.e., increase of P_b in the present study is considered as favorable) the base pressure, for Mach numbers 1.87, 2.2, and 2.58, respectively. This can be considered as a great advantage since for vehicles like missiles flying at supersonic Mach numbers, the base drag can be as high as 30 per cent of the total drag, but in transonic flow it could be as high as 50 per cent of the total drag. Therefore, even a small increase in base pressure will result in significant reduction of drag.

Results of base pressure for Mach 1.87 as a function of L/D are presented in Figure-7(a). It is seen that for NPRs in the range 3 and 5 the base pressure decreases with L/D, the control is not effective and the minimum duct length required for the attached flow is L/D = 6. Since at NPR 3 and 5 the jets are over expanded, hence, the trend is the same and only the magnitude differs for different values of NPR.

At NPR 7 the base pressure variation is oscillatory in nature and control results in decrease of base pressure. The nature of the behavior at NPRs 9 and 11 is different compared to at lower NPRs namely 3, 5, and 7. At these NPRs the base pressure assumes a very low value, control results in decrease of base pressure at all the L/Ds. For the NPRs in the range 7 to 11 the jets are under expanded and only the level of under expansion is different, this can be clearly seen in the Figure-7(a), especially for NPR 9 and 11. At these NPRs the flow is under expanded and there will be an expansion fan at the nozzle lip which will deflect the flow inward resulting in reduction of reattachment length which will continue to decrease with increase in NPR.

Figure-7 (b) presents results for Mach 2.2. The trends are on the similar line as discussed for Mach 1.87 for NPRs 3 and 5; here the same trend has been extended up to NPR 7. The fluctuating nature is observed at NPR 9 and at NPR 11 the base pressure assumes minimum value. The minimum duct length required is L/D = 6 for NPR 3 to 9 and L/D = 4 for NPR 11.

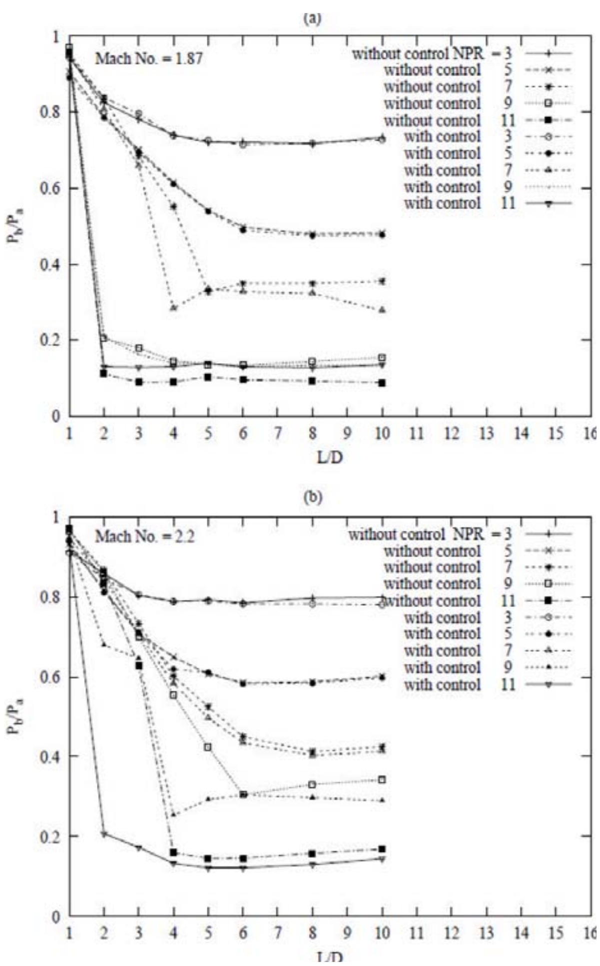

Figure-7. Base pressure variation with L/D.

The results for M = 2.58 are shown in Figure-8(a). The base pressure is decreasing for all the NPR and L/Ds and control results in decrease of base pressure. This is because as these flows are highly over expanded, the shock will deflect away towards the shear layer resulting in larger reattachment length, interacting with the main jet without influencing the base flow. Therefore, these shocks have larger shock angle and hence the flow deflection angles are smaller. The flow behind oblique shocks even though experience larger increase of pressure, are not in a position to influence the base region. Hence, the base pressure is dictated by the re-circulating flow rather than the flow behind the shock. Therefore, one has to consider these waves while analyzing the base flows with supersonic Mach numbers.

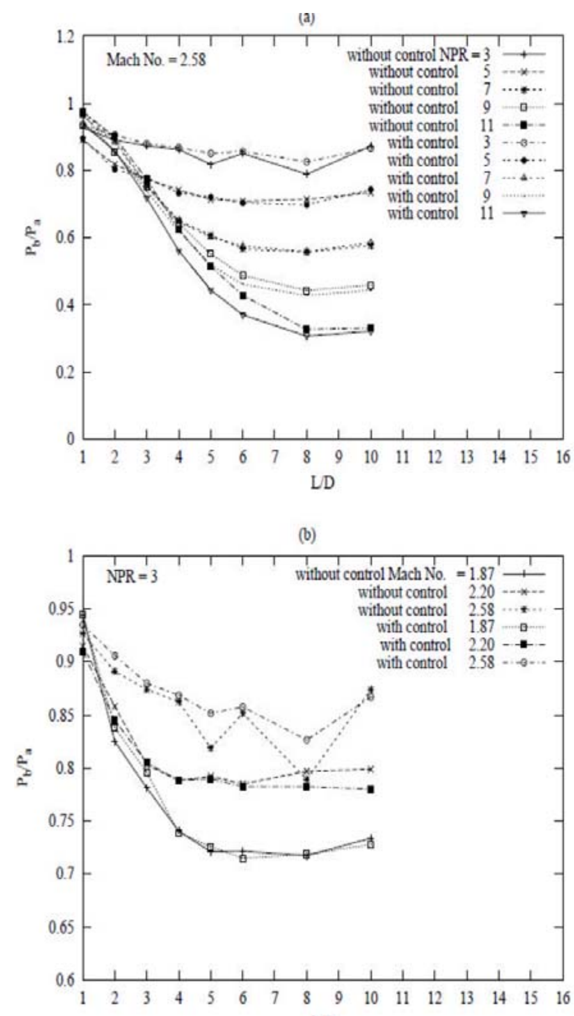

Figure-8. Base pressure variation with L/D.

To study the effect of NPR and L/D on base pressure the same representative results of P_b/P_a variation with L/D are shown in Figures 8(b) to 10(b). Figure-8(b) shows the results for NPR 3, it is interesting to note that the control effectiveness of micro jets get reversed with the change in the L/D from 4 to 5 for Mach 1.87. For Mach 2.2 and 2.58 base pressure decreases with L/D continuously and it becomes independent of L/D beyond L/D = 6.

Results for NPR 5 for all the Mach numbers are shown in Figure-9(a). The results are on the similar lines as discussed for NPR 3. Figure-9(b) shows results for NPR 7, it is seen that base pressure is influenced by the L/D for with and without control case for Mach 1.87 and 2.2 and control is effective for all the values of L/D. But for Mach 2.58 base pressure decreases with L/D throughout and the minima is around L/D = 6 which also happens to be the minimum L/D required for the flow to be attached with the duct.

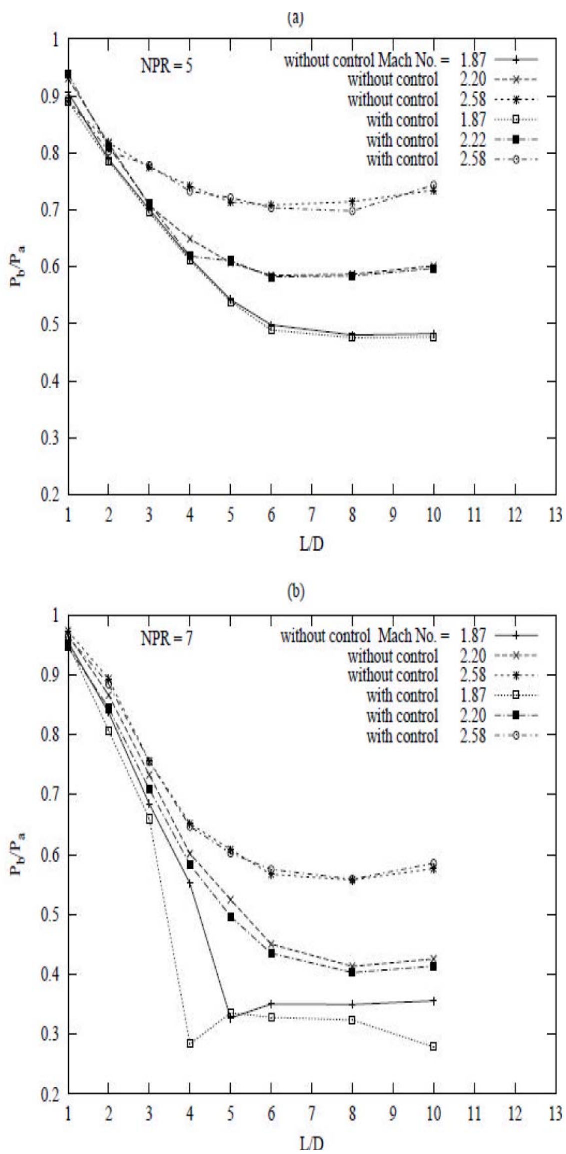

Figure-9. Base pressure variation with L/D.

Results for NPR 9 and 11 are shown in Figure-10(a)-(b). From Figure-10(a) at NPR 9 for Mach 2.58 there is a drastic decrease in base pressure for L/D from 1 to 8 for Mach 2.58 and control results in decrease of base pressure. However, for Mach 1.87 and 2.2 base pressures are independent of L/D from L/D = 2 and 6 respectively and control is effective for all the values of L/D. This again is due to the wave influence on the flow at the base.

Results for NPR 11 are shown in Figure-10 (b). It is seen that the results of Mach 2.58 are on the similar line as those for NPR 9. For 1.87 and 2.2 there is a further decrease in pressure compared to the case for NPR 9 and the minimum duct length required for the flow to remain attached with the duct is L/D = 2 and 4, respectively.

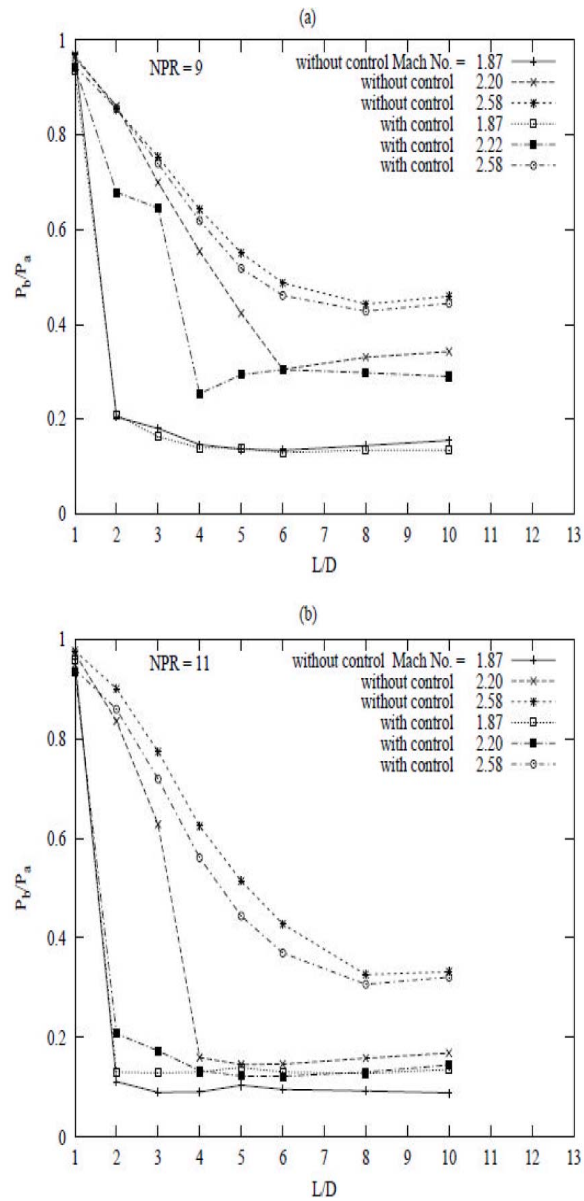

Figure-10. Base pressure variation with L/D.

Figures 11 to 13 present base pressure results as a function of Mach number for NPR 3 to 11 for different L/Ds. In Figure-11 ((a) to (b)), it is seen that for L/D = 10

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at NPR = 3 the shock wave at the nozzle lip is very powerful resulting in very high level of base pressure, further its magnitude continued to increase for higher Mach numbers namely 2.2 and 2.58 as the flow becomes highly over expanded. It is found that for NPR 3 the control results in decrease of base pressure at Mach 2.2 and no such trends are observed for other Mach numbers. The control is not effective at NPR 5. At NPR 7 for Mach 1.87 the control results in decrease of base pressure, however, at NPRs 9 and 11 control results in increase of base pressure. But for Mach 2.2 control results in decrease of base pressure. Similar results are seen in Figure-12 for L/D = 6 and 5. From Figure-13 ((a) to (b)) it seen that the duct length is not sufficient and hence, the flow is not attached with the duct wall.

(a)

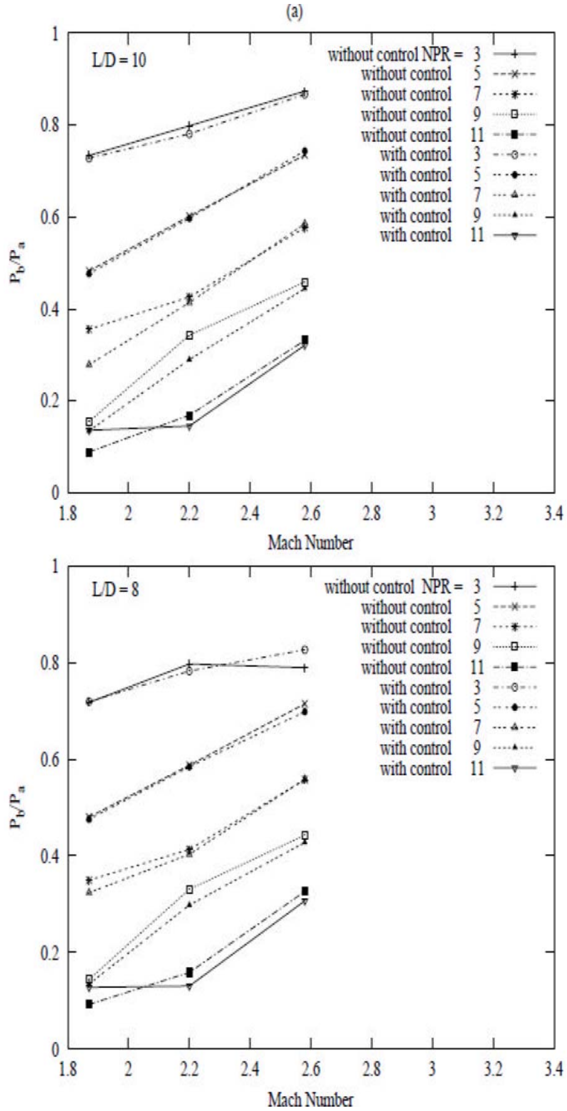

Figure-11. Base pressure variation with Mach number.

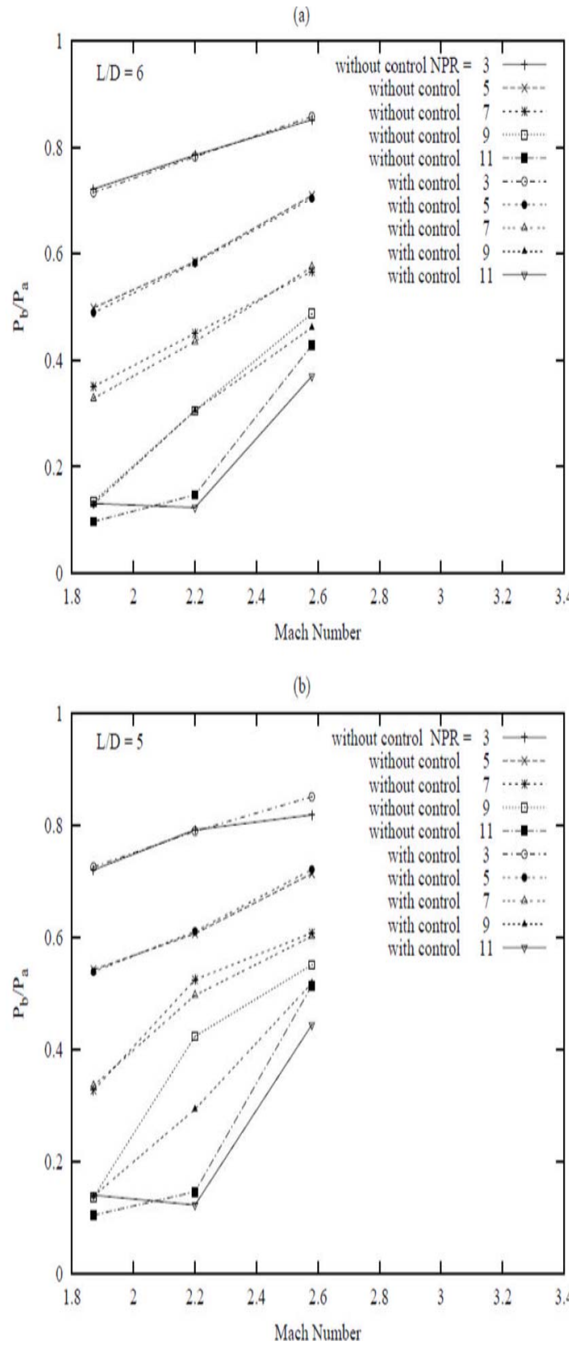

Figure-12. Base pressure variation with Mach number.

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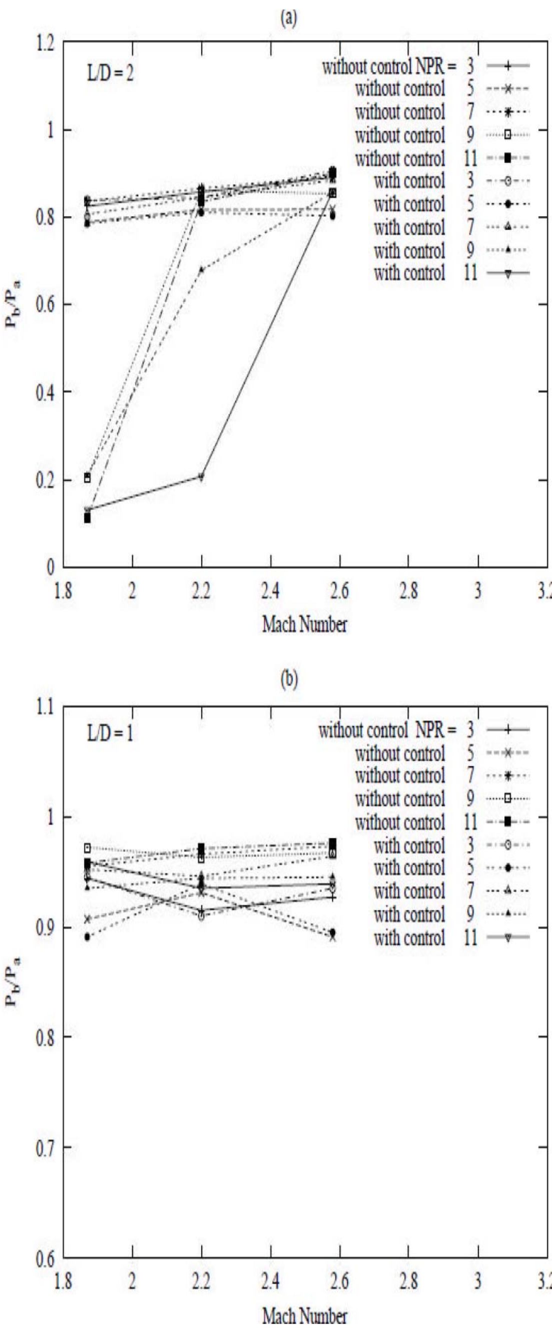

Figure-13. Base pressure variation with Mach number.

CONCLUSIONS

From the above results we can draw the following conclusions. The base pressure is a strong function of the area ratio, the nozzle pressure ratio (NPR), Mach number, and the duct length-to-diameter ratio. For a given area ratio, Mach number, and nozzle pressure ratio it is possible to identify an optimum L/D ratio of the duct that will result in maximum or minimum base pressure at the nozzle exit. The requirement of minimum duct length for the attached flow, separation and reattachment seemed to be strongly dependent on the area ratio, the Mach number, and nozzle pressure ratio. For Mach 1.87 the minimum duct length required is 6 for NPR 3 and 5 where as for NPR 7, 9, and 11 it is L/D = 4 and 2. For Mach 2.2 minimum L/D required is 6 for NPRs 3 to 9 however it is 4 for NPR 11. For Mach 2.58 the minimum L/D required is 6 for all the NPRs tested. It is found that the control results in decrease of base pressure for all the NPRs tested and high value of the minimum length for the flow to attach, since for this area ratio the maximum relief is available for the shear layer to relax resulting in maximum reattachment length and hence unable to influence the vortex at the base. The micro jets are not very effective for Mach 2.58; however they are effective for Mach numbers 1.87 and 2.2. The nozzle pressure ratio has a definite role to play in fixing the level of base pressure with and without control.

Uncertainty in base pressure

All the non-dimensional base pressure presented is within an uncertainty band of ± 2.6 per cent. All the results are repeatable within ± 3 per cent.

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