ACTIVE CONTROL OF BASE PRESSURE IN SUDDENLY EXPANDED FLOW FOR AREA RATIO 4.84

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Abstract:

Airflow from convergent-divergent axi-symmetric nozzles expanded suddenly into circular duct of larger cross-sectional area than that of nozzle exit area are studied experimentally, focusing attention on the base pressure and the flow development in the enlarged duct. Micro-jets of 1 mm orifice diameter located at 90^0 intervals along a pitch circle diameter (pcd) 1.3 times the nozzle exit diameter were employed as the controller of the base pressure. The tests are conducted for Mach numbers 1.87, 2.2 and 2.58. The area ratio of the present study is 4.84. The length-to-diameter ratio of the suddenly expanded duct is varied from 10 to 1 and nozzle pressure ratio (NPR) in the range 3 to 11. 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 and even do not augment the flow field in the duct. An increase of 45 percent in base pressure was achieved for certain combination of parameters of the present study.

Keywords: Nozzle Pressure Ratio, Wall Pressure, L/D Ratio, Micro jets.

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 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.

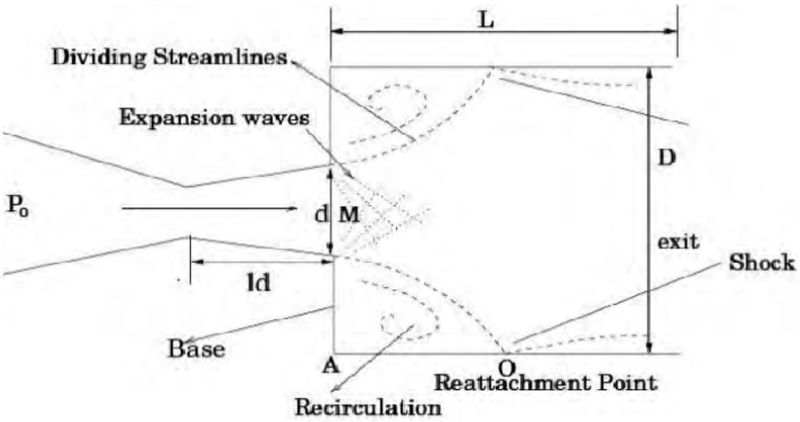

Fig 1: Sudden Expansion Flow field

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. Rathakrishnan and Sreekanth [2] studied flows in pipe with sudden enlargement. 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. 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. For a given nozzle and enlargement area ratio, the duct length must exceed a definite minimum value for minimum base pressure. Srikanth and Rathakrishnan [3] 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 [2].

Rathakrishnan et. al [4] 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. They studied air flow through a convergent axi-symmetric nozzle expanding suddenly into an annular parallel shroud with annular cavities experimentally. 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 [5]. 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.

The effect of level of expansion in a suddenly expanded flow and the control effectiveness has been reported by Khan and Rathakrishnan [7]. 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. This increase in base pressure is attributed to the relief available to the flow due to increase in the area ratio.

Jagannath et. al. [8] 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 [9] 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 [10] studied effect on base pressure due to active control in the form of Microjets at area ratio 2.56, and concluded that Microjets 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.

EXPERIMENTAL SETUP

The experiments were carried out using the experimental facility at the High Speed Aerodynamics Laboratory (HSAL), IIT, Kanpur. Fig. 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) were used for blowing and the remaining four (marked m) were used for base pressure (P_b) measurement. Control of the base pressure was 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. The area ratio of the present study is 4.84. For each Mach number, L/D ratios 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 is used for measuring pressure at the base. Mercury manometer was used for measurement of duct wall pressure distribution.

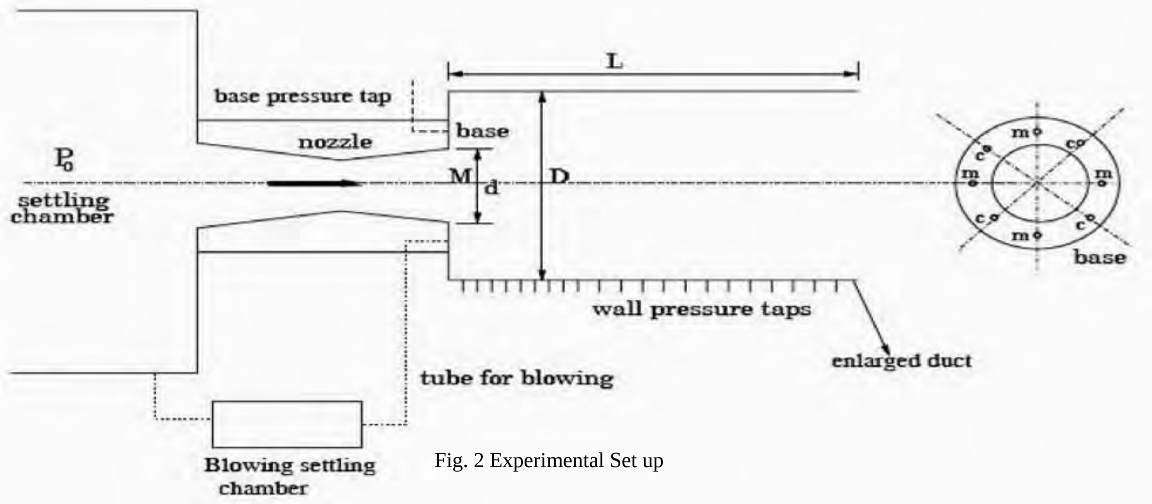

Fig. 2 Experimental Set up

RESULTS AND DISCUSSION

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 and L/D ratio of the enlarged duct. Area ratio reported in this paper is 4.84 and the control pressure ratio is same as the main settling chamber pressure ratio.

The primary objective of this investigation is to study the feasibility of employing blowing in the form of micro jets as a control mechanism for controlling the base pressure. The dependence of base pressure on Mach number and NPR in the range of 3 to 11 for area ratio 4.84 is shown in Fig. 3(a) for L/D = 10. Results of base pressure with and without control are compared. It is seen from the results that in supersonic regime the Mach number has got very strong influence on the base pressure. Also, it is seen that with increase in NPR the control becomes more effective in increasing the base pressure for Mach 1.87. But for higher Mach numbers the control results in decrease of base pressure compared to without control case as seen for Mach number range 2.2 to 2.58 for NPR 5, 7, 9 and 11. 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 which encounters the mass flow injected by the micro jets. However, for Mach numbers 1.87 and 2.2, NPR 11 results increase of base pressure compared to the without control case. This may be because as the NPR increases the level of overexpansion comes down; hence the oblique shock at the nozzle exit becomes weaker than those at lower NPRs. Therefore the turning away tendency of the incoming flow decreases leaving the vortex almost intact. At this situation when 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 case. It is to be noted that in addition to influence of shock or expansion wave at the nozzle lip, the relief effect due to increase of area ratio also will influence 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. 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 [6], who reported that the effectiveness of passive control in the form of tabs in enhancing the mixing increases with increase of favorable pressure gradient. At NPR 3 the control effectiveness is almost insignificant and the effectiveness increases with increase of NPR. The value of NPR for correct expansion for Mach 1.87 is 6.4. Therefore, upto 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 establishing favorable pressure gradient the control becomes progressively more effective with increase of favorable pressure gradient. For mach 2.2 initially at NPR 3 the control results in increase of base pressure, control reversal takes place at NPR 5 and further increase n NPR results in decrease of base pressure up to NPR 9 then again at NPR 11 control tends to increase the base pressure. However, for Mach 2.58 control results in decrease of base pressure for all the NPRs tested. Base pressure results for L/D = 8 are shown in Fig. 3(b). For this L/D the behaviour is same as that for L/D = 10.

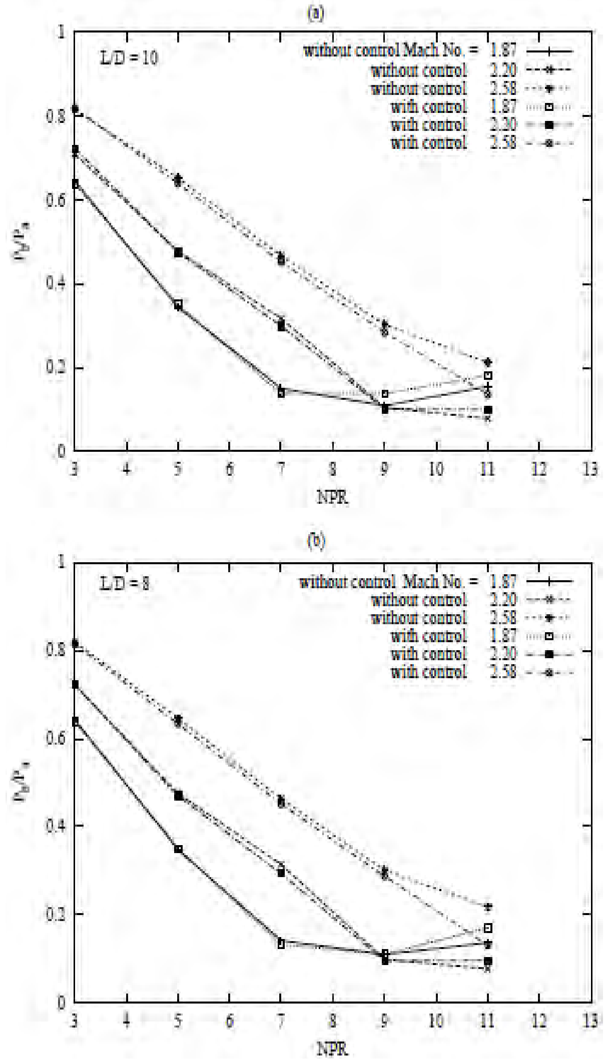

Fig. 3 Base pressure variation with NPR

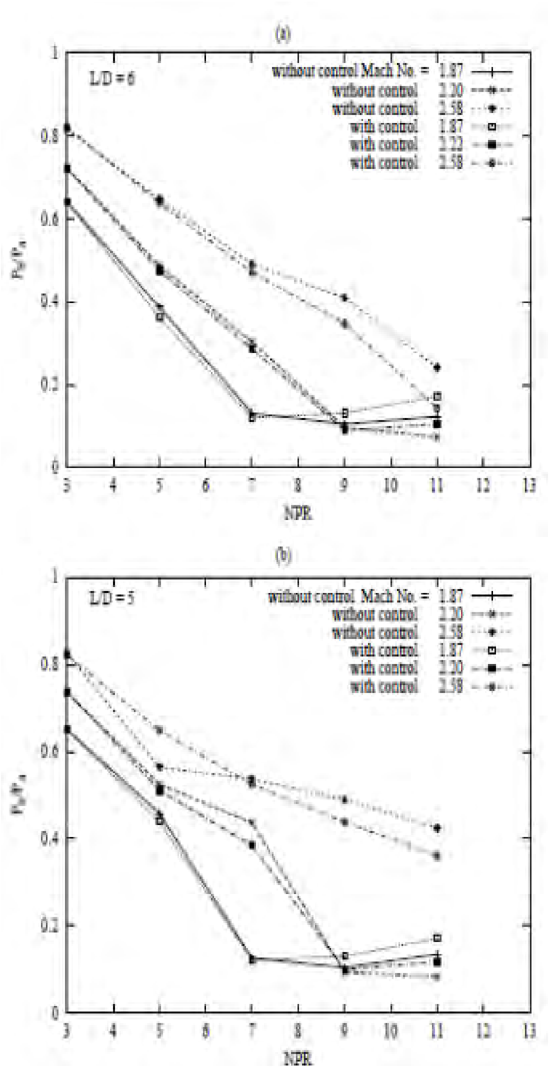

Fig. 4 Base pressure variation with NPR

Results for L/D = 6 are shown in Fig. 4(a). Here at NPR 3 the control is not effective for all the Mach numbers. For Mach 1.87 the control results in decrease of base pressure up to NPR 7.5. But for higher NPRs the control is able to reduce the base suction. For Mach 2.2 control results in decrease of base pressure up to NPR 9.5 and then control results in increase of base pressure. For Mach 2.58 the control results in decreasing the base pressure for all the NPRs. Fig. 4(b) shows results for L/D = 5. For Mach 1.87 the base pressure decreases up to NPR 7.5 and then starts increasing with and without control. For Mach 2.2 base pressure decreases up to NPR 9 without control and then remains almost constant, but control results in decreasing the base pressure up to NPR 9 and then increases. For Mach 2.58 when control is activated it results in increasing the base pressure up to NPR 6.8, at higher NPRs 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 level of pressure at the base region. It is seen from the figures that the location of base pressure increase gets shifted to higher NPR with increase of Mach number.

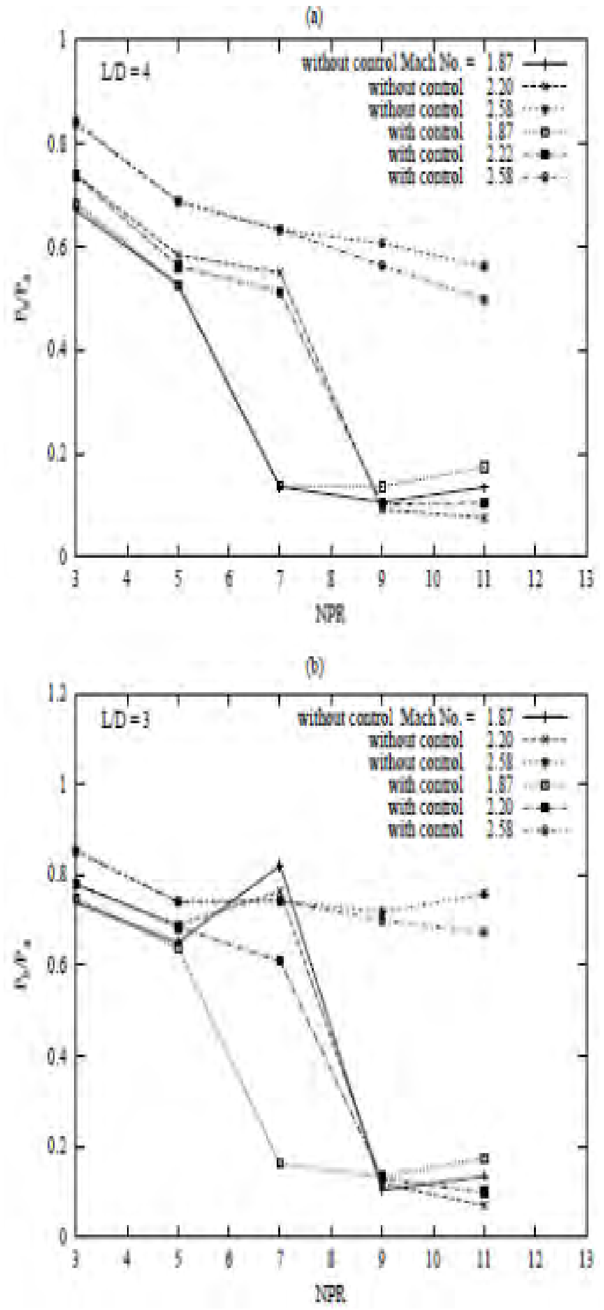

Fig. 5 Base pressure variation with NPR

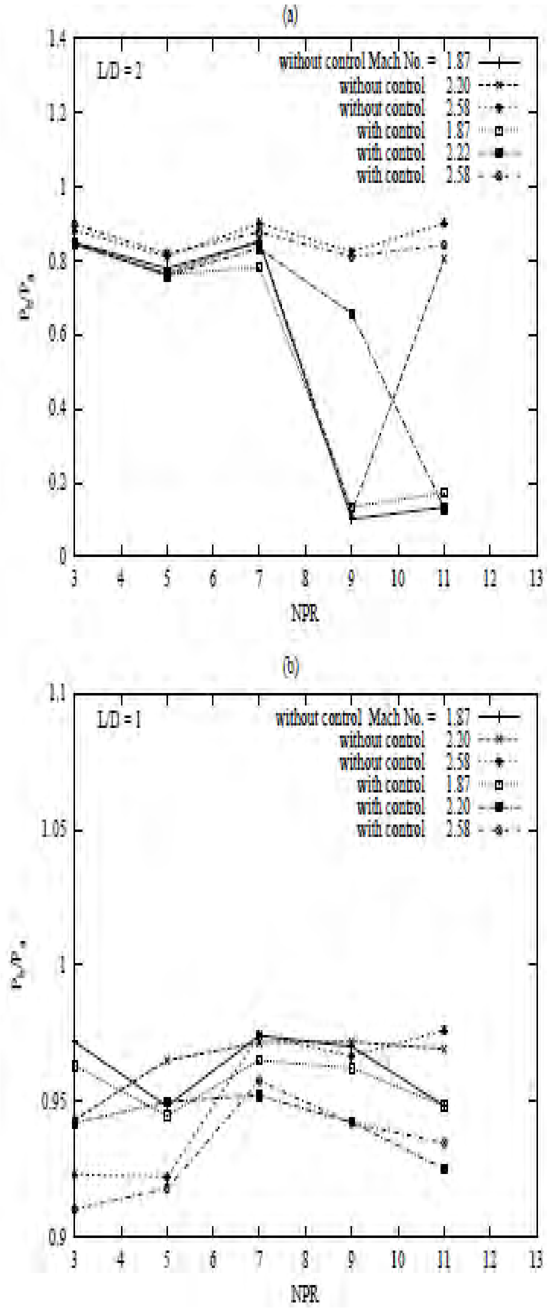

Fig. 6 Base pressure variation with NPR

Results for L/D = 4 are shown in Fig. 5(a). For Mach 1.87 and 2.2 the trend is similar as that for higher L/Ds without control. Control results in decrease of base pressure upto NPR 7 for Mach 1.87 and up to NPR 9 for Mach 2.2. For Mach 2.58 the trend is totally different. It is seen that up to NPR 7 control is ineffectiveness and for higher NPRs the control results in decreasing the base pressure. Fig. 5(b) shows results for L/D = 3. It is seen that for Mach 2.58 the behaviour is on the similar line as that of for L/D = 4. However, this behaviour at M = 1.87 and 2.2 is completely different. Initially control results in decrease of base pressure up to NPR 9 then control results in increase of base pressure. At NPR 7 very high values of base pressure are seen for Mach 1.87 and 2.2, this peculiar behaviour may be because of the shock structures at the nozzle exit, location of reattachment length, effect of the back pressure, interaction of the base vortex and the influence of the shear layer.

Results for L/D = 2 and 1 are shown in Figures 6(a) to (b). Here the behaviour is different from those of at higher L/Ds. In Fig. 6(a) it is seen that for all the Mach numbers and the NPRs in the range 3 to 7 the flow is not attached with enlarged duct wall. For Mach 1.87 and 2.2 at NPRs 9 and 11 the control results in increase of base pressure. Whereas for Mach 2.58 it assumes very high value of base pressure and control results in decrease of base pressure. Fig. 6 (b) shows the results for L/D =1, it is evident from the figure that this length is not sufficient for the flow to be attached with the wall.

It is evident from these results that, the L/D has a defined role 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 [18] 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 [2] were up to sonic Mach number and at a maximum NPR of 3, whereas, in the present study the Mach numbers as well as the Nozzle Pressure Ratio are in the higher range. It is found that the flow is attached with the enlarged duct for L/D = 2.

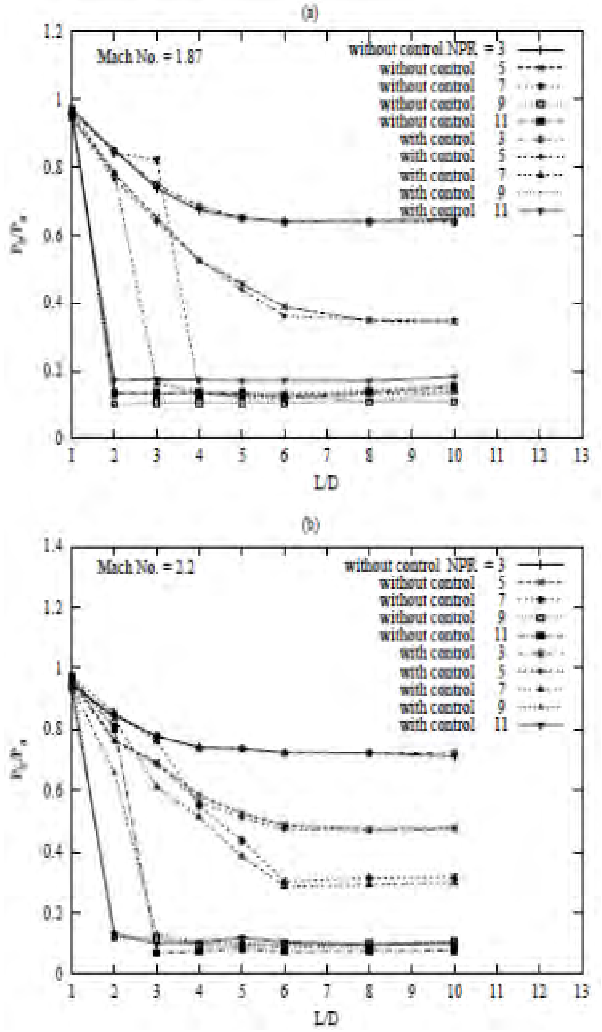

Fig 7 Base pressure variation with L/D ratio

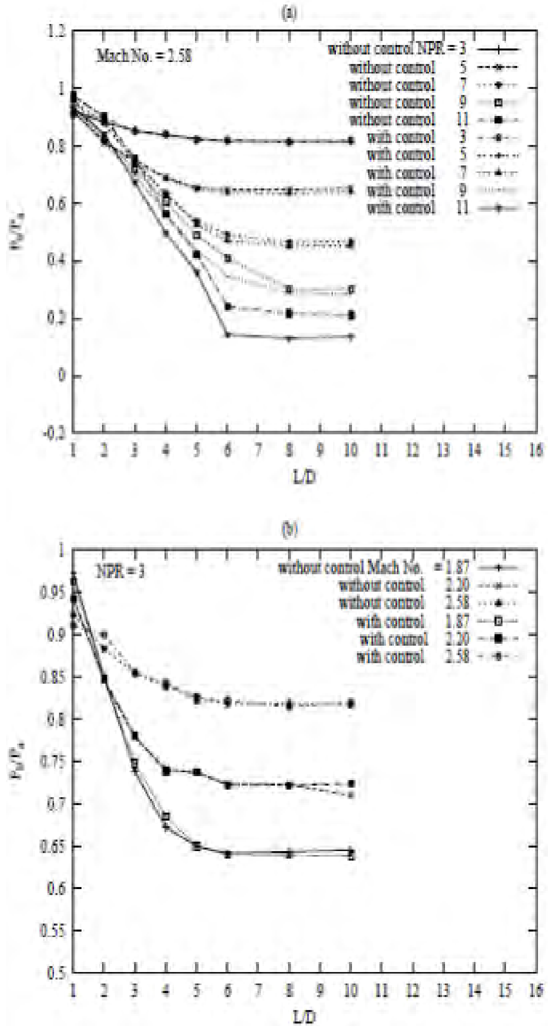

Fig 8 Base pressure variation with L/D ratio

It is important to note that the NPR range in the present study is such that jet exiting the nozzle experiences correct, over and under expansion. It is well known that weak wave, oblique shock or expansion fan will be positioned at the nozzle lip for correct, over and under expanded conditions, respectively. To understand the influence of level of expansion on the base pressure with and without control the base pressure variation as function of Mach number, NPR and L/D are presented in Figs. 7(a) to 8(a). For mach 1.87 it is found that for NPRs above 7, 9 and 11 the micro jets favourably influence (i.e., increase of P_b in the present study is considered as favourable) the base pressure, for Mach numbers 1.87 and at NPRs 3 and 5 the control is ineffective and the minimum duct length required for the attached flow of L/D for the flow to be is L/D = 6, whereas the requirement for NPR 7, 9 and 11 are L/D = 4, 3 and 2. Similarly for Mach 2.2 also, for NPR 3 and 5 the control effectiveness is marginal. It is found that at NPR 7, 9 and 11 the control results in decrease of base pressure for all the L/Ds and the minimum duct length needed for the flow to be attached is L/D = 6 for NPRs 3, 5, 7 and for 9 and 11 it is L/D = 3 and 2 respectively. For Mach 2.58 it is visualized that for NPRs 3 and 5 the control is marginally effective and for remaining NPRs the control results in decrease of base pressure and the minimum duct required is L/D = 6 for all the NPRs tested. It is well known that, if there is an oblique shock at the nozzle exit, the shear layer coming out of the nozzle will be deflected towards the nozzle centre line by the shock. This will delay the reattachment and will result in a longer reattachment length compared to a case without shock. It is well known that the reattachment is parameter strongly influencing the base vortex, the increase or decrease of reattachment length will modify the base pressure. Similarly, when there is an expansion fan the shear layer exiting the nozzle will be deflected more towards the base thereby resulting in decrease of reattachment length compared to a case without expansion fan. 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 as shown in Figs. 8 (b) and it can be that the control effectiveness of micro jets get reversed with the change in the L/D from 3 to 6 and from 4 to 8 for Mach 1.87 and minimum duct length required is L/D = 6.

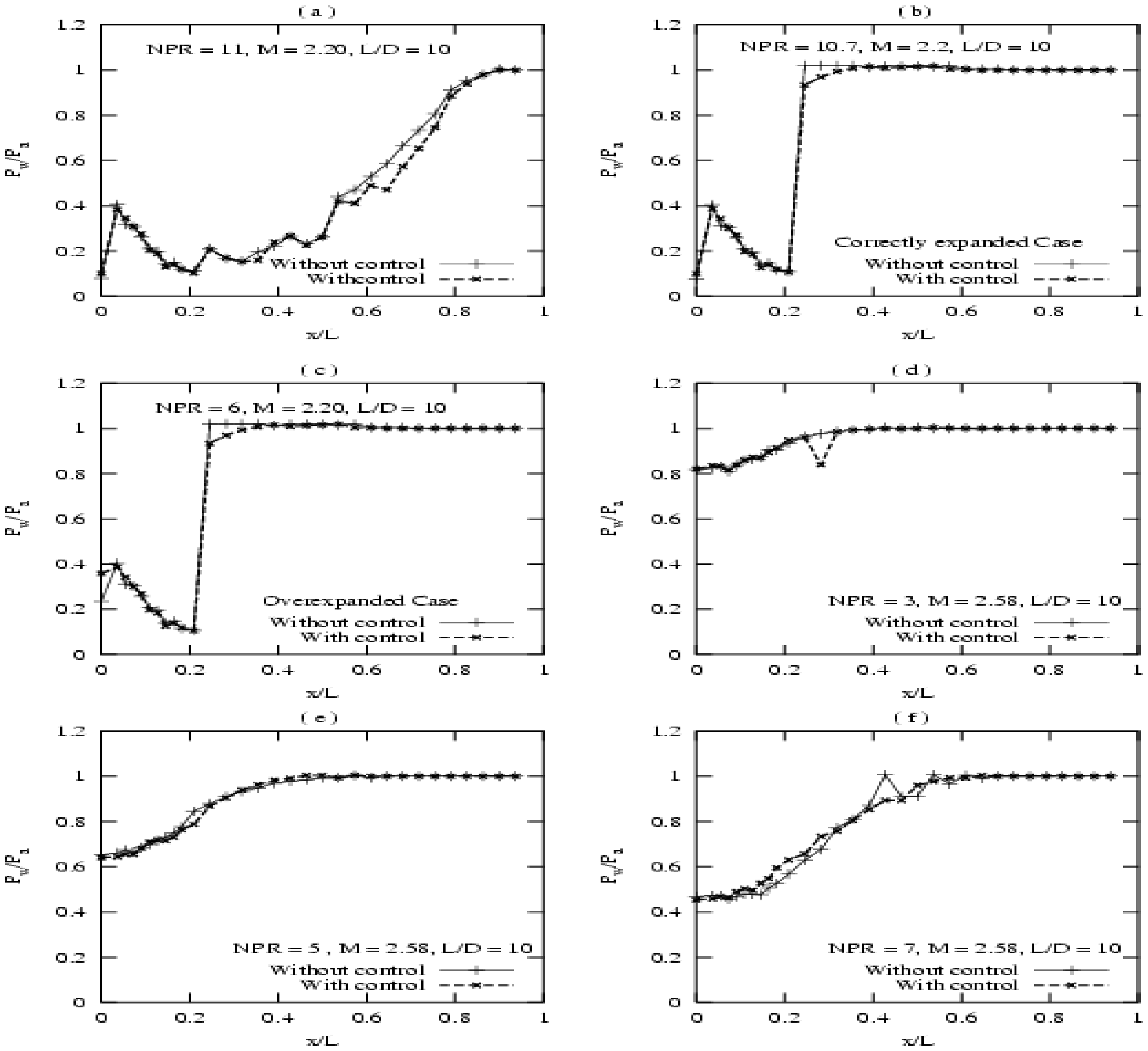

Fig 9. Wall pressure distribution

One of the major problems associated with base flows is the oscillatory nature of pressure field in the enlarged duct just downstream of the base region. This can be understood by scanning the wall static pressure along the enlarged duct. In the present investigation also, attention was focused to study the effect of the active control on the enlarged duct wall pressure field. To study this wall pressure distribution, tests were conducted with and without controls for all the Mach numbers and L/Ds.

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, 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 exit plane total 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 they are L/D = 4, 3 and 2. For Mach 2.2 minimum L/D required is 6 for NPRs 3, 5 and 7 however it is 3 and 2 for NPRs 9 and 11. For Mach 2.58 the minimum L/D required is 6 for all the NPRs. It is found from these results that the micro jets can serve as active controls for an effective control of base pressure. There is no adverse effect of the active control on the enlarged duct flow field, as evidenced by the identical behaviour of the wall pressure distribution with and without control. The nozzle pressure ratio has a definite role to play in fixing the level of base pressure with and without control at supersonic jet Mach numbers.

Uncertainty in Base Pressure

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

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