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Sonic Under Expanded Flow Control With Micro Jets

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ABSTRACT
This paper presents the results of experimental studies to control the base pressure from a convergent nozzle under the influence of favorable pressures gradient at sonic Mach number. An active control in the form of four micro jets of 1 mm orifice diameter located at 90^0 intervals along a pitch circle diameter of 1.3 times the nozzle exit diameter in the base region was employed to control the base pressure. The area ratio (ratio of area of suddenly expanded duct to nozzle exit area) studied are 2.56, 3.24, 4.84 and 6.25. The L/D ratio of the sudden expansion duct varies from 10 to 1. From the results, an important aspect to be noted here is that, unlike passive controls the favorable pressure gradient does not ensure augmentation of the control effectiveness for active control in the form of micro jets. To study the effect of micro jets on the quality of flow in the enlarged duct wall pressure was measured and it is found that the micro jets do not disturb the flow field in the duct rather the quality of flow has improved due to the presence of micro jets in some cases.
Keywords- Base pressure, Mach number, Micro jets, Sudden expansion, Wall pressure

I. INTRODUCTION

As a result of developments in space flights and missile technology, the base flows at high Reynolds numbers continue to be an important area of research. Following these, the interest shifted to the hypersonic speed regime from the point view of base heat transfer and near-wake structure. Our understanding of many features of base flows remains poor, due to inadequate knowledge of turbulence, particularly in the presence of strong pressure gradient. Triggered primarily by the requirements in technological developments, numerous research investigations have been reported in literature devoted to reducing the base drag penalty employing both energetic as well as passive techniques, these aim in manipulation/alteration of the near wake flow field for increasing the base pressure. Flow field of abrupt axi-symmetric expansion is a complex phenomenon characterized by flow separation, flow re-circulation and reattachment. A shear layer into two main regions may divide such a flow field, one being the flow recirculation region and the other the main flow region. The point at which the dividing streamline Strikes the wall is called the reattachment point and the features of sudden expansion flow field are shown in Fig. 1.

Vortex shedding in the wake of bluff bodies is an important flow phenomenon. At subsonic and transonic speeds, it has long been recognized that the wake behind an isolated two-dimensional section with a blunt trailing edge may break into a

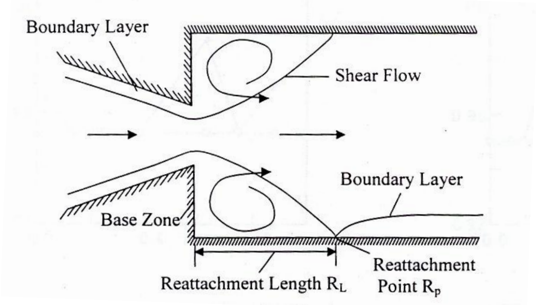


Fig. 1 Sudden Expansion flow field

vortex street. The direct result of this is an increase in drag, mainly as a result of reduced pressure. Further, the subject of base flows at high Reynolds numbers has been and continues to be an important area of research in view of its relevance in external aerodynamics. Base drag arising from flow separation at the blunt base of a body, can be sizeable fraction of total drag in the context of projectiles, mis-siles and after bodies of fighter aircraft; for example, the base drag component can be as high as 50 percent of the total drag for a missile with power off (i.e. with no jet flow at the base). Large-scale flow unsteadiness, often associated with a turbulent separated flow, can cause additional problems like base buffeting which are undesirable.

II. LITERATURE REVIEW

Wick [1] investigated experimentally the effect of boundary layer on sonic flow through an abrupt cross-sectional. He observed that the pressure in the expansion corner was related to the boundary layer type and thickness upstream of the expansion. He considered a boundary layer as a source of fluid for the corner flow. A two-dimensional configuration has been investigated in which air flows through a convergent nozzle and expands abruptly into a rectangular duct of larger cross-section which terminates in a plenum chamber. Anderson J. S. et al. [2] found that the most significant is the base-pressure type, where the variations in pressure are large. James A. Kidd et al. [3] conducted Free-flight tests of spin-stabilized projectiles and fin-stabilized missiles with various stepped, flat and bottailed bases at subsonic, transonic and supersonic Mach numbers. They got the results which indicate that sub sonically the addition of a stepped base can significantly reduce the aerodynamic drag over that a flat base. The shock structure present within under expanded gas jets issuing from rectangular and elliptical exits have been analyzed by means of numerical analysis by N. Menon and B. W. Skews [4]. The effect of the corners in the rectangular nozzles has a significant effect on the shock structure. The constant change in the azimuth of the elliptical nozzle results in a barrel shock attached to the nozzle exit. Viswanath P. R. [5] investigated experimentally the zero-lift drag characteristics of multi-step after-bodies that utilize the concept of controlled separated flows at transonic and supersonic speeds. The important geometrical parameters affecting the drag of such after-bodies were identified, and their effects were examined through a parametric study. Their results show that multi-step after-bodies can be design that provide significant total drag reduction (as high as 50 per cent) compared to (unmodified) 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. Khan and Rathakrishnan [6-10] done experimental investigation to study the effectiveness of micro jets under the influence of Over, Under, and Correct expansion to control the base pressure in suddenly expanded axi-symmetric ducts. They found that the maximum increase in base pressure is 152 percent for Mach number 2.58. Also they found that the micro jets do not adversely influence the wall pressure distribution. They showed that micro jets can serve as an effective controller raising the base suction to almost zero level for some combination for parameters. Further, it was concluded that the nozzle pressure ratio has a definite role to play in fixing the base pressure with and without control.

Jagannath et al. [11] 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. 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. An experimental study has been conducted by Lovaraju P. et al. [12] 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 underexpansion levels. The present investigation on the effectiveness of cross-wire and tabs on the underexpanded sonic jets shows that, both the passive controls are effective in reducing the axial extent of 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 S. Alvi et al. [15] obtained experimental investigation of the flow and acoustic properties of a supersonic impinging jet, with and without control. Pandey and Kumar [16] studied the base pressure in a suddenly expanded circular ducts using fuzzy set theory. From their analysis it was observed that L/D ratio is 6 for base pressure for Mach 1.58, 1.74, 2.06 and 2.23, which is in very close agreement with the experimental results. Vikram Roy et al. [17] carried the numerical analysis of the turbulent fluid flow through an axi-symmetric sudden expansion passage by using modified k-ε 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, 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. M. Ahmed Ali Baig et al. [18] conducted the experiments to assess the effect of Mach number on base pressure and control effectiveness in a suddenly expanded duct. From the experiments they found that for the given area ratio the base pressure increase with Mach number. Baig et al. [19] carried an experimental investigation to control the base pressure in a suddenly expanded axi- symmetric passage. The tests were conducted for Mach numbers 1.25, 1.3, 1.48, 1.6, 1.8, 2.0, 2.5 and 3.0. The area ratio of the study was 6.25. On the positive side the gain was 30 per cent whereas on the negative side the decrease in base pressure was 40 per cent. The effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts is studied experimentally by Syed Ashfaq et al. [20]. From the experimental results, it was found that the micro jets can serve as active controllers for base pressure. From the wall pressure distribution in the duct it found that the micro jets do not disturb the flow field in the enlarged duct.

III. EXPERIMENTAL METHOD

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 Fig. 2, four of which are (marked c) were used for blowing and the remaining four (marked m) were used for base pressure (P_b) measurement. Control of base pressure was achieved 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

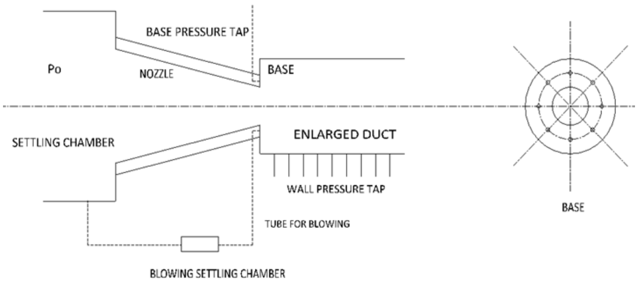


Fig. 2: Experimental Setup

made at an interval of 3 mm each and remaining was made at an interval 5 mm each. From literature it is found that, the typical L/D (as shown in Fig. 2) Resulting in P_b maximum is usually from 3 to 5 without controls. Since active controls are used in the present study, L/D ratios up to 10 have been employed.

The experimental setup of the present study consisted of an axi-symmetric nozzle followed by a concentric axi-symmetric duct of larger cross-sectional area. The exit diameter of the nozzle was kept constant and the area ratio of the model was 2.56, 3.24, 4.84, and 6.25 defined, as the ratio of the cross-sectional area of the enlarged duct to that of the nozzle exit, was achieved by changing the diameter of the enlarged duct. The suddenly expanded ducts were fabricated out of brass pipe. Model length was ten times the inlet diameter so that the duct has a maximum L/D = 10. The lower

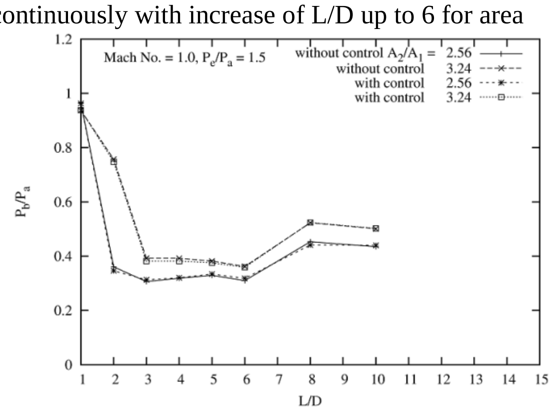
L/Ds were achieved by cutting the length after testing a particular L/D.

PSI model 9010 pressure transducer was used for measuring pressure at the base and the stagnation pressure in the settling chamber. It has 16 channels and pressure range is 0-300 psi. It averages 250 samples per second and displays the reading. The software provided by the manufacturer was used to interface the transducer with the computer. The user-friendly menu driven software acquires data and shows 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, etc. The transducer also has a facility to choose the number of samples to be averaged, by means of dipswitch settings. It could be operated in temperatures ranging from -20° to +60° and 95 per cent humidity.

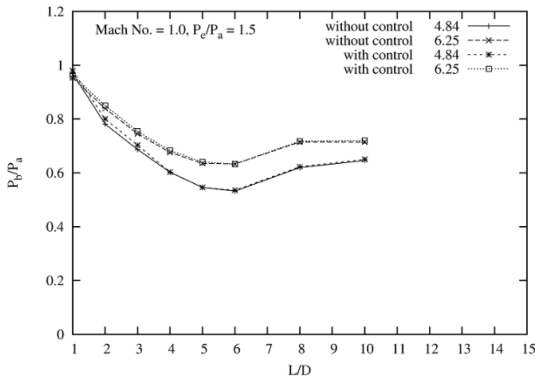
IV. RESULTS AND DISCUSSION

The measured data consists of base pressure (P_b); wall static pressure (P_w) along the duct and the nozzle pressure ratio (NPR) defined as the ratio of stagnation pressure (P_0) to the back pressure (P_{atm}). All the measured pressures will be non-dimensionalized by dividing them with the ambient pressure (i.e. the back pressure). In the present study the blow pressure will be the same as the NPR of the respective runs since we intend to draw the air from the main settling chamber. Hence, we don't need additional source of energy for micro jets as an active control. This is one of the major advantages otherwise the main concern for active control is from where we will get the source of energy. The results for sonic jets with an under expansion level of 1.5 ($P_e/P_a = 1.5$) are shown in Fig. 2 to 7. As the jets of the present studies are under expanded, for all these cases there will be an expansion fan positioned at the nozzle lip and the flow passes through this expansion fan before expansion into the duct. Thus, the flow becomes wave dominated in the vicinity of the base region where, expansion of the wave's recombination and reflection will take place. It is interesting to note that for this under expanded sonic jet L/D = 1 is not sufficient for the flow to attach with the duct wall even for the lowest area ratio of 2.56. This is because even though the Mach number at the nozzle exit is one, because of the under expansion level of 1.5 the equivalent local Mach number may be supersonic. This Mach number will result in deflecting away from the base region and in turn the reattachment length will increase. This higher inertia makes the flow to move without re-attaching with the duct wall even for the smallest area ratio.

From the Fig. 3 it is also seen that, for the under expanded sonic jet also the base pressure decreases continuously with increase of L/D up to 6 for area



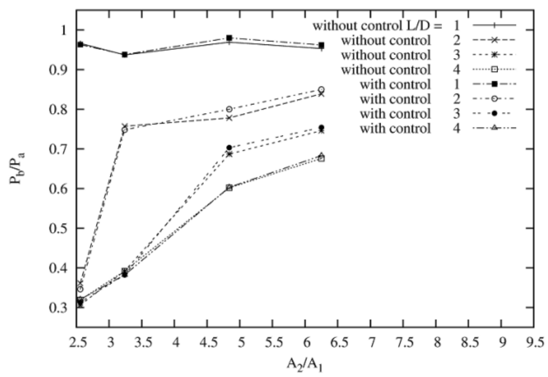
(a)



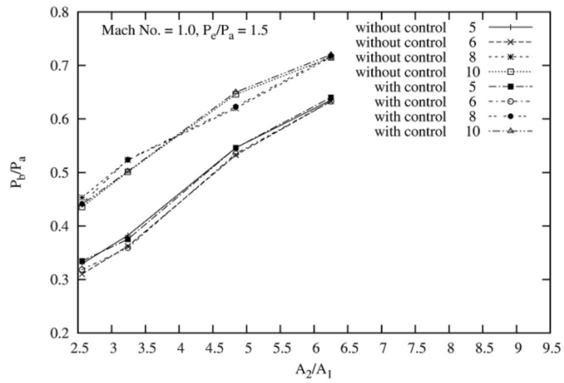
(b)

Fig. 3: Base Pressure Variation with L/D Ratio

ratios 4.84 and 6.25. But for higher L/Ds the base pressure increases with L/D. For area ratios 3.24 and 2.56, the base pressure assumes a minimum value at L/D 3 and 2, respectively and then shows only a marginal variation with L/D up to L/D = 6. For further increase of L/D the base pressure shows an increase with L/D from 6 to 8. But for L/D increase from 8 to 10 the variation is only marginal. For all the conditions of L/Ds and area ratios the control effectiveness is only marginal. This means that the minimum duct length required for the flow to be attached with the duct wall is L/D = 2 for area ratio 2.56, whereas for area ratio 3.24 this requirement is L/D = 3. However, for area ratio 4.84 and 6.25 the minimum requirement of the duct length is L/D = 6. The physical reason for this behavior may be due to the influence of the wave at the nozzle lip as well as the relief effect due to increase of area ratio also will influence the base pressure and with the increase in the enlarged duct area the reattachment length will increase which in turn weaken the base vortex and the base suction created by the base vortex will be reduced. This will result in low base pressure for lower area ratio and high value of base pressure for higher area ratio. Furthermore, it should be kept in mind that for area ratio 2.56, the micro jets at the base are located at mid pitch circle diameter (p. c. d.) of the base, whereas for area ratio 3.24 (and also for area ratios 4.84 and 6.25) the micro jets are closer to the nozzle exit (not in the middle of the base). This is because p. c. d. for micro jets is kept constant for all the area ratios. This may be the physical reasons for the different behavior of the base pressure at different for higher area ratio other than area ratio 2.56 as the location of the micro jets will also influence the flow field in the base region.



(a)



(b)

Fig. 4: Base Pressure Variation with Area Ratio A_2/A_1

The variation of base pressure with area ratio is presented in Fig. 4 (a) & (b). These results clearly show that at L/D = 1 the area ratio has got no effect on base pressure, but for all other L/Ds the base pressure increases with area ratio. The reasons for this trend of the base pressure for all the ratios at L/D = 1 is the insufficient length of the duct and the base flow is not attached with the duct rather the flow is exposed to the atmosphere. The same argument is true for L/D = 2 that at L/D = 2 the flow is attached with the wall for area ratio 2.56 whereas, for higher area ratio this length is not sufficient and the base pressure assumes higher values for the entire range of the area ratios of the present study except area ratio 2.56. The results presented in Fig. 4 (a) & (b) are nothing but the combined effect of L/D ratio, effect of back pressure on the base flows, and area ratio, since the Mach number and level of under expansion is kept constant in the present study.

The percentage variation of base pressure with L/D and area ratio is given, respectively in Figs. 5 and 6. From these results, it is seen that control results in both increase and decrease of base pressure for different combinations of parameters (Fig. 5).

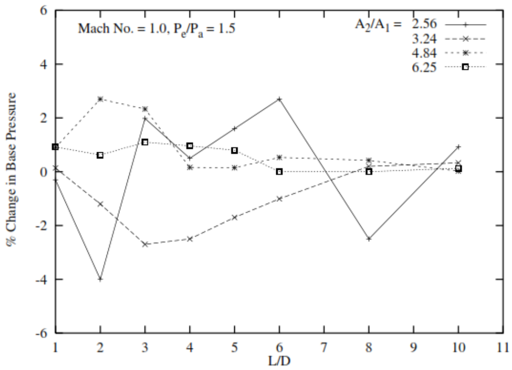
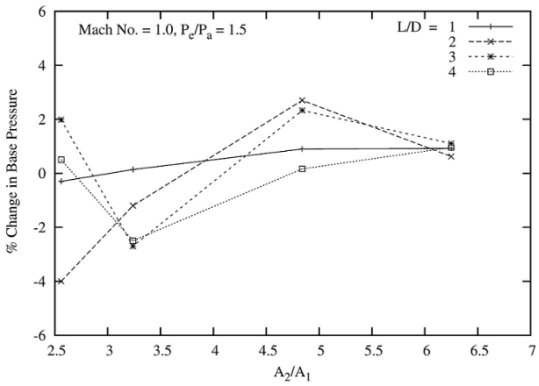
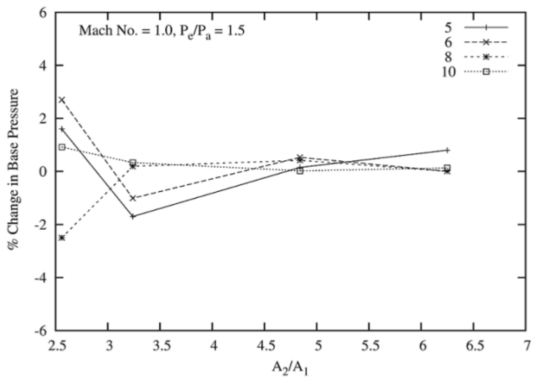


Fig. 5: Percentage Change in Base Pressure Variation with L/D

An important aspect to be noted here is that, unlike passive controls the favorable pressure gradient does not ensure augmentation of the control effectiveness for active control. It is seen that the maximum increase achieved is about only 3 per cent and the maximum decrease achieved is about 4 per cent in spite of the favorable pressure gradient. This once again emphasizes that wave dominated jets expanded into a duct is sensitive to area ratio, level of expansion, L/D and jet Mach number. It is well known that the reattachment length is a parameter strongly influencing the base vortex, the increase or decrease of reattachment length will modify the base pressure. With the increase in the area ratio the reattachment length will increase which will result in the larger flow area and the volume of the air available in the base region to interact with the base vortex. Hence, the vortex at the base will not be able to influence the base region very strongly thereby creating high value of suction for higher area ratio as compared to the lower area ratio. Since the Mach number is constant hence the strength of the vortex will remain the same for all the cases. From the Figs. 6 (a) & (b) it is evident that value of percentage change in base pressure is low for the lowest area ratio for the L/Ds tested and with increase of L/D the base pressure decreases for the all the area ratios tested. It is seen that the



(a)



(b)

Fig. 6: Percentage Change in Base Pressure Variation with Area Ratio A_2/A_1

minimum duct length required for the area ratio 2.56 is L/D = 2 whereas, for the area ratio 3.24 this requirement is L/D = 3. However, for the area ratio 4.84 and 6.25 the minimum duct length needed seems to L/D = 6. This is in agreement with the findings of Rathakrishnan & Sreekanth [13].The control effectiveness is only marginal. This is to be noted that when there is an expansion fan the shear layer exiting the nozzle will be deflected more towards the base thereby resulting in a decrease of reattachment length compared to a case without the expansion fan. The trend is wavy in nature and no definite conclusion can be drawn in view of the presence of waves at the nozzle lip which in turn will influence the base vortex and hence the base pressure.

Figs. 7 (a) to (h) presents the wall pressure distribution in the enlarged duct for area ratio 2.56. These measurements were taken to ascertain the influence of the micro jets on the quality of flow in the duct as well as the control effectiveness. From the results it is found that the control in the form of micro jets do not disturb the flow field or made oscillatory. It is also seen that for the lower L/D

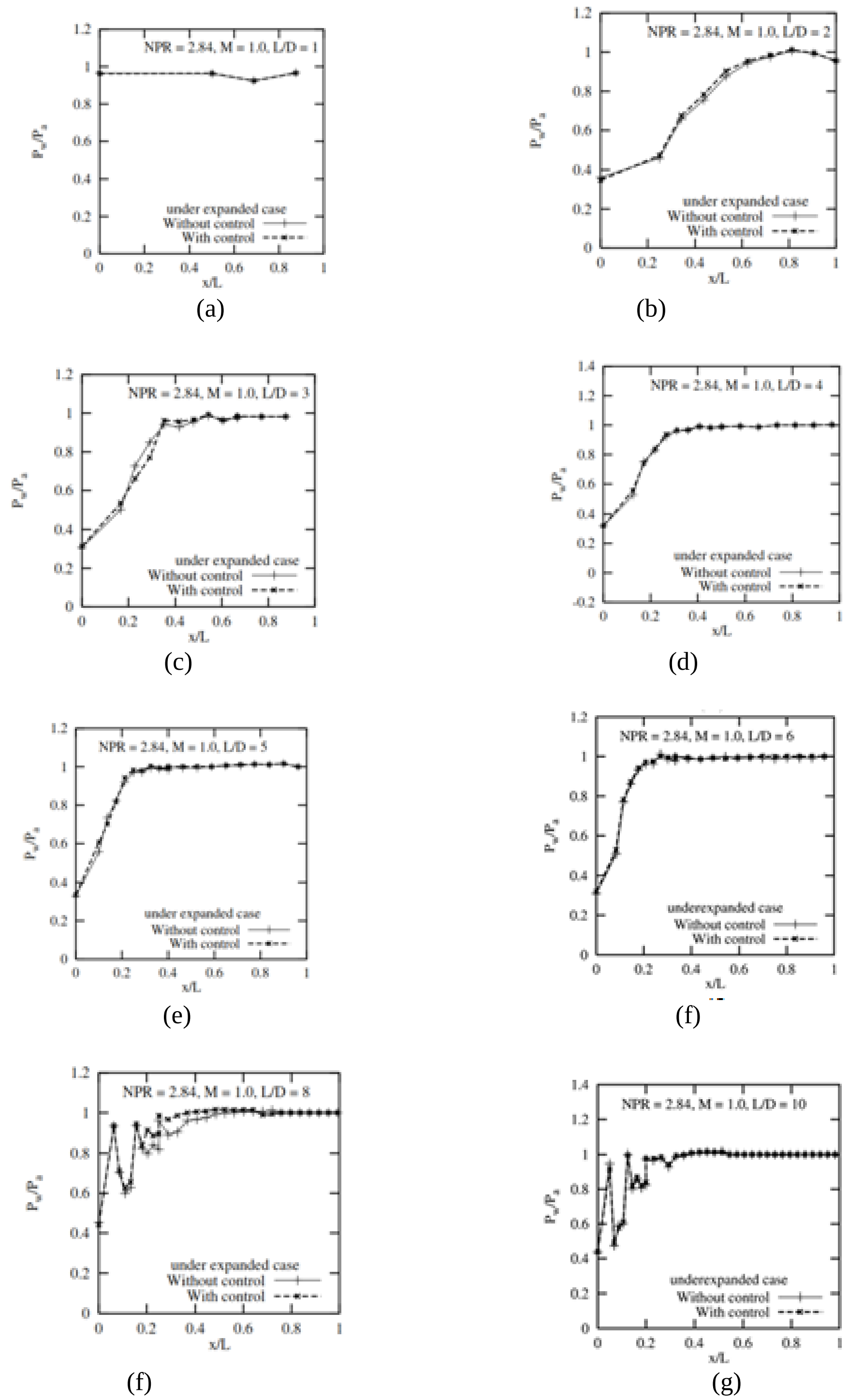


Fig. 7: Wall Pressure Distribution

ratio namely L/D = 1 and for due to the influence of the back pressure there is much varation in the values of the wall pressure. However, for higher L/D ratios namely L/D = 8 and 10 upto 40 percent of the initial length of the duct the flow is oscillatory. The reason for this behaviour may be due to the influence of the base vortex and this length is seems to be within the reattachemnt length.

V. CONCLUSIONS

From the above results it is found that the effectiveness of the Micro jets is marginal in controlling the base pressure even under the influence of favorable pressure gradient. An important aspect to be noted here is that, unlike passive controls the favorable pressure gradient does not ensure augmentation of the control effectiveness for active control in the form of micro jets.

Further, it is found that the minimum duct length required for the flow to be attached to the enlarged duct wall seems to be L/D = 2 for area ratio 2.56 and L/D = 3 for area ratio 3.24 of the present study. For area ratios 4.84 and 6.25 the minimum duct length required is L/D = 6.

From the wall pressure distribution in the duct it is found that the micro jets do not disturb the flow field in the enlarged duct. However, the wall pressure distribution in the duct indicates the waviness nature within the reattachment length and in the downstream the flow becomes smooth throughout for all the cases of the present study. The reason for this behaviour may be due to the influence of the base vortex and this region which is 30 percent of the duct length is within the reattachemnt length.

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

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