Studies on Suddenly Expanded Flow at Different Levels of Over Expansion for Area Ratio 3.24

Maughal Ahmed Ali Baig and Sher Afghan Khan

Abstract- The experiments are carried out to study the effect of different levels of over expansion on base pressure in a suddenly expanded axi-symmetric duct. Accordingly the experiments are conducted at two different levels of Over Expansions (I.e. $P_e/P_a = 0.277$ and 0.56). The area ratio of the present study is 3.24. The jet Mach numbers at the entry to the suddenly expanded duct, studied are 2.2 and 2.58. The length-to-diameter ratio of the suddenly expanded duct is varied from 10 to 1. Active control in the form of four micro jets of 1mm orifice diameter located at 90^0 intervals along a pitch circle diameter of 1.3 times the nozzle exit diameter in the base region are employed. In addition to base pressure, wall pressure field along the duct is also studied. From the present studies it is found that at a high level of over expansion micro jets are not effective. Further, it is found from wall pressure studies that the micro jets do not disturb the flow field in the enlarged duct.

Index Terms-Active Control, over expanded jet, Wall pressure distribution, Base Pressure

1. INTRODUCTION

The sudden expansion of flow in both subsonic and supersonic regimes of flow is an important problem with a wide range of applications. The use of a jet and a shroud configuration in the form of a supersonic parallel diffuser is an excellent application of sudden expansion problems. Another interesting application is found in the system used to simulate high altitude conditions in jet engine and rocket engine test cells; a jet discharging into a shroud and thus producing an effective discharge pressure which is sub atmospheric. A similar flow condition exists in the exhaust port of an internal combustion engine, the jet consisting of hot exhaust gases passes through the exhaust valve. Another relevant example is to be found in the flow around the base of a blunt edged projectile or missile in flight where the expansion of the flow is inward rather the outward as in the previous example. The experimental study of sudden expansion with internal flows has the enormous advantages over the external flows. The size of air supply needed is greatly reduced by eliminating the need for tunnel with large enough cross sections so that the wall interference will not disturb flow over the model.

Also complete static pressure and surface temperature measurements can be made not only along the entrance section to the expansion but also in the wake region.

Flow field of abrupt axi-symmetric expansion is a complex phenomenon characterized by flow separation, flow recirculation and reattachment. Such a flow field may be divided by a shear layer into two main regions, 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. The main feature of suddenly expanded flow field is illustrated in figure.1

M. Ahmed Ali Baig is currently a Research Scholar in Jawaharlal Nehru Technological University, Hyderabad, India and working in P.A. College of Engineering, Mangalore. E-mail Id: mabaig09@gmail.com

Sher Afghan Khan is a Research Supervisor and working in P. A. College of Engineering, Mangalore. E-mail Id: sakahn06@gmail.com

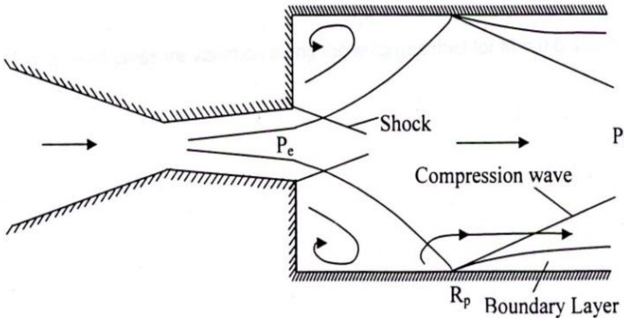

Fig. 1 Expansion of over expanded flow

2. LITERATURE REVIEW

The effect of boundary layer on sonic flow through an abrupt cross-sectional area was studied by Wick [1]. He observed experimentally that the pressure in the corner of expansion was related to the boundary layer type and thickness upstream of the expansion. He considered boundary layer as a source of fluid for the corner flow. Comment on the effects of boundary layer on sonic flow through an abrupt cross-sectional area change was studied by Korst [2]. He compared his theoretical results which utilizes a two-dimensional flow model considering the interaction between dissipative flow regions and the adjacent free stream with Wick [1] results and showed good agreement between theory and experiments. Hall and Orme [3] studied compressible flow through a sudden enlargement in a pipe both theoretically and experimentally. They developed a theory to predict the Mach number in a downstream location of sudden enlargement for known values of Mach number at the exit of the inlet tube, with incompressible flow assumption.

Anderson and Williams [4] 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 [5] 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. For an optimum performance of flow through pipes with sudden enlargement, it is not sufficient if the base pressure minimization alone is considered. The total pressure loss must also be taken into account. Raghunathan and Mabey [6] studied passive shock-wave/boundary layer control on a wall mounted model. They evaluated the effects of the orientation of holes on the passive shock wave/boundary layer control, incorporating three holes orientations; normal, forward facing and backward facing. Rathakrishnan, Ramanaraju and Padmanabhan [7] 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 effect of level of expansion in a suddenly expanded flow and the control effectiveness has been reported by Khan and Rathakrishnan [8]. 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. 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. Suddenly expanded flow with control seems to be of interest with many applications. Further, there seems to be complete vacuum as far as active control of base pressure field is concerned. It will be of immense help for various applications, if a mechanism is devised to control the base pressure, since the control of the base pressure will result in either increase or decrease of base pressure. This will help in minimizing the base pressure in the case of combustion chamber to maximize the mixing, and maximize the base pressure in case of rockets, projectiles, aircraft bombs and missiles to result in base drag reduction. Therefore, it is proposed to investigate the control of base pressure field with active control in the form of blowing.

3. EXPERIMENTAL SETUP

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 were conducted for Mach numbers 2.2 and 2.58 at a fixed level of over expansion of 0.56 & 0.277. From literature it is found that, the typical values of L/D (as shown in Fig. 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 were 10, 8, 6, 5, 4, 3, 2 and 1 and for each value of L/D ratio.

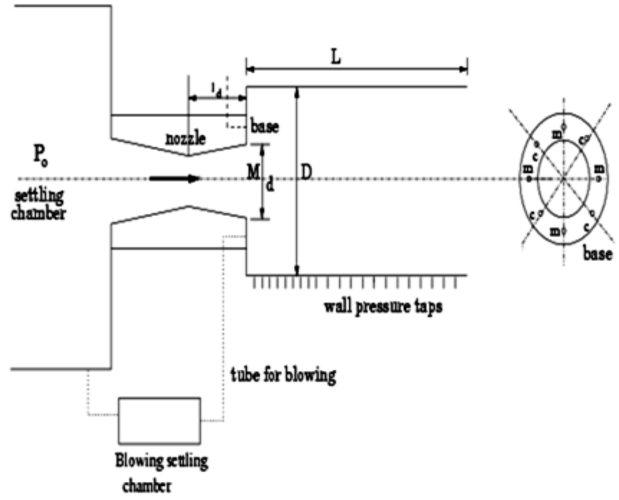

Fig 2 Experimental Set

4. 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 and a fixed level of over expansion (0.277 & 0.56). Area ratio reported in this paper is 3.24 and the control pressure ratio is same as the main settling chamber pressure ratio. This investigation focuses 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. In the present study the primary objective is to investigate the effectiveness of micro jets as a control mechanism for controlling the base pressure for over expanded conditions for Mach 2.2 and 2.58 at overexpansion level of 0.277 and 0.56 (i.e. P_e/P_a=0.277 and 0.56).

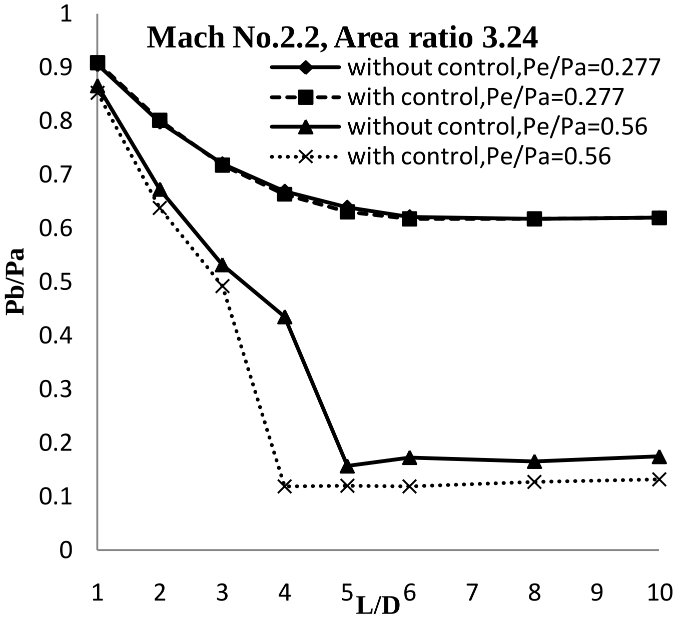

Fig. 3 Base pressure variation with L/D at M=2.2

Figure 3 presents result for Mach No. 2.2. As the level of over expansion decreases from 0.277 to 0.56 the base suction decreases and base pressure continues to decrease with L/D and attains a minimum at L/D = 6 for with control case at over expansion level of 0.56. The base pressure minimum at L/D = 6 is in agreement with the results of Rathakrishnan and Sreekanth [6], for subsonic and transonic flow. The control is only of marginal influence on the base pressure for all values of L/D for highest level of over expansion, i.e. at P_e/P_a= 0.277. Further, it is seen that when the level of over expansion decreases the trend is different, control results in decrease of base pressure. It becomes independent of L/D for L/D > 6. It is seen that, when the micro jets are activated the base pressure assumes considerably lower values compared to the corresponding cases without micro jets. It is evident from these results that, for P_e/P_a = 0.277 the control effectiveness is strongly influenced by the jet Mach number. The effectiveness increases with increase of Mach number. Also, the effectiveness is significant for L/D ranging from 3 to 6 compared to L/D range 6 to 10.

Figure 4 presents results for Mach number = 2.58. It is seen from the figure that there is slightly different behaviour compared to the behaviour at M = 2.2. Even for the lowest level of expansion the base pressure comes down with increase of L/D, showing a minimum at L/D = 6. The tendency of base pressure coming down with L/D becomes significant as the level of over expansion decreases. Here again the control is of marginal effect on base pressure. Further, like M = 2.2, for M = 2.58 also L/D more than 6 does not influence the base pressure significantly. However, at Mach 2.58 the control is more effective compare to at Mach 2.2.

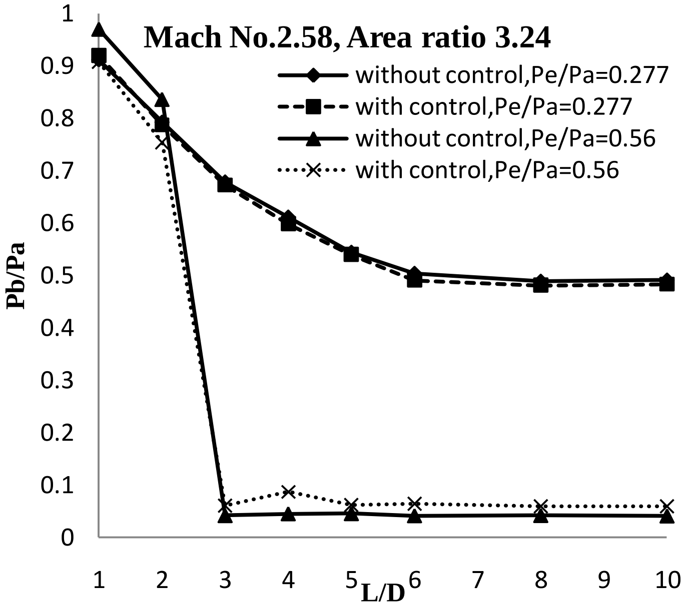

Fig. 4 Base pressure variation with L/D at M=2.58

It is seen that for same level of overexpansion, for a given area ratio, the reattachment length for higher Mach number will be higher. This will dictate base vortex strength. If the reattachment length is such that the vortex can be strong, this will result in large suction. From the above results it is found that these conditions are satisfied for Mach 2.2 and 2.58 for all level of expansion. Further, it is evident that, P_b/P_a is the lowest for Mach number 2.58 at the expansion level of 0.56. It decreases with decrease of level of expansion. When the micro jets are on, they entrain the mass from their vicinity. It should be noted that, the level of pressure at the base region depends on the shock strength at the nozzle exit for the present case of over expanded jets. However, it is the combined effect of jet Mach number, the shock strength and the location of the micro-jets, which will fix the base pressure level. This appears to be the cause for the control to become more effective at Mach 2.58 than Mach 2.2.

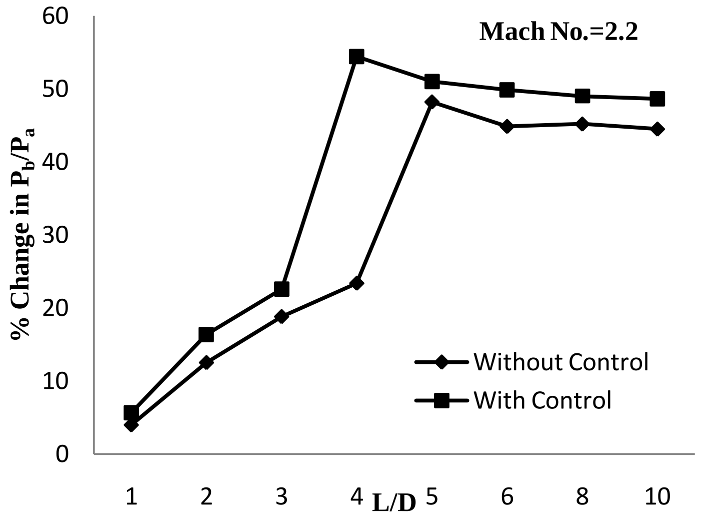

Fig. 5 Percentage Change in P_b/P_a at Mach 2.2

Figure 5 presents the results for Mach 2.2 and from the figure it is found that there is a 50 % increase in the base pressure when the value of level of overexpansion is decreased from 0.56 to 0.277. The physical reason for this increase is the strength of the oblique shock at these values of level of over expansion. Further, it is seen that up to L/D = 5 & 4 the percentage change in base pressure is independent of L/D then there is drastic decrease in the values and at L/D = 1 there is no change in the values. The reason for this may be that minimum L/D = 4 & 5 required for the flow to be attached with enlarged. Once the flow is detached from the duct wall the atmospheric pressure will influence the base pressure and the base pressure may achieve a value very close to atmospheric which is clearly seen in figures 3 and 4.

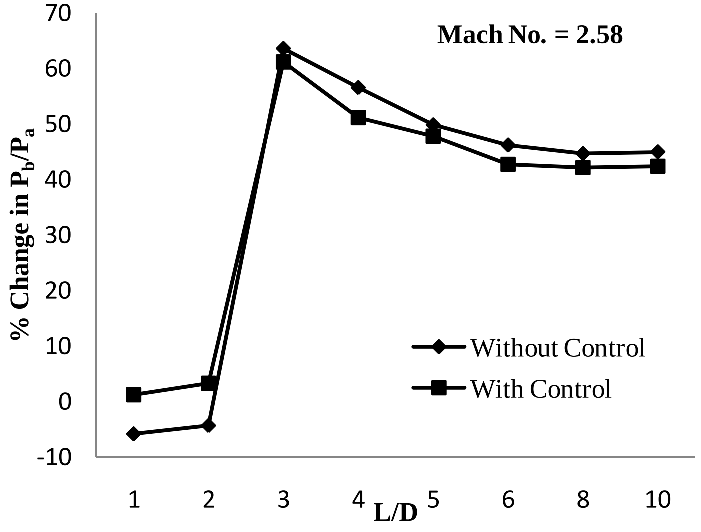

Fig. 6 Percentage Change in P_b/P_a at Mach 2.58

Figure 6 presents the results for Mach 2.58. In this case all the parameters are the same except the Mach number. As we know that with increase in Mach number, base pressure will increase. When the results are compared with and without control for two level of over expansion at Mach 2.58, it is found that the percentage change in base pressure is independent of L/D for L/D = 6 and above. Further, it is seen that the percentage increases with the decrease in L/D up to 3 and then there is steep drop in the value. This reconfirms the results as shown in figure 3 and 4. This clearly indicates that the flow is detached from the enlarged duct wall under these conditions when the micro jets are activated they flow freely as a free jet without any influence on the base pressure. From the figure 6 it is seen that as high as 65 percent change in the base pressure is observed which is quite significant in the application of external flow like flow over a blunt base which finds application in military and fuselage of the aircraft.

To understand one of the major problems associated with base flows i.e. oscillatory nature of pressure field in the enlarged duct just downstream of the base region, measurement of wall static pressure along the enlarged duct can be one of the best possible ways. To study this wall pressure distribution, tests were conducted with and without controls for both the Mach numbers and L/Ds. Fig 7 and fig 9 indicate the behaviour of wall pressure at over expansion level of 0.56 for Mach 2.58 and Mach 2.2 respectively and fig 8 and fig 10 indicate the behaviour of wall pressure at high level of over expansion i.e. 0.277.

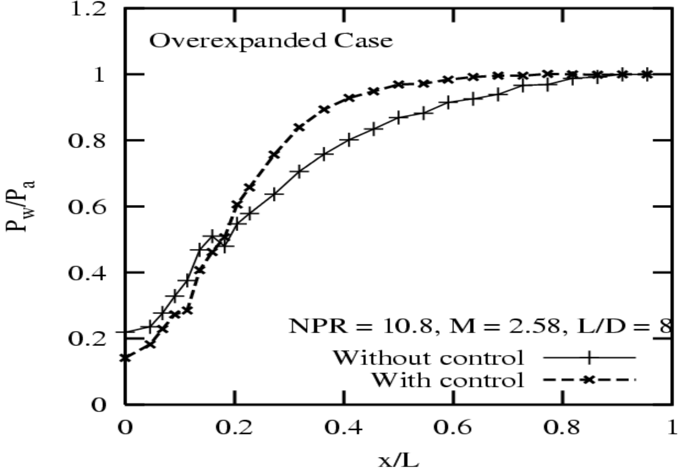

Fig 7 Wall Pressure Distribution at P_e/P_a= 0.56

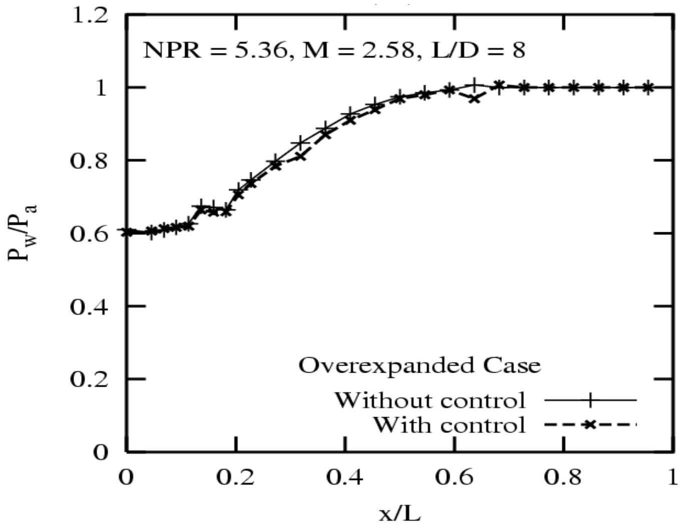

Fig. 8 Wall Pressure Distribution at P_e/P_a= 0.277

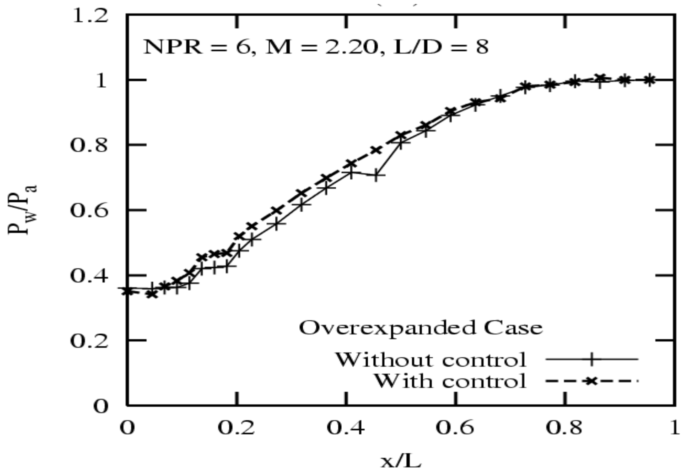

Fig. 9 Wall Pressure Distribution at P_e/P_a= 0.56

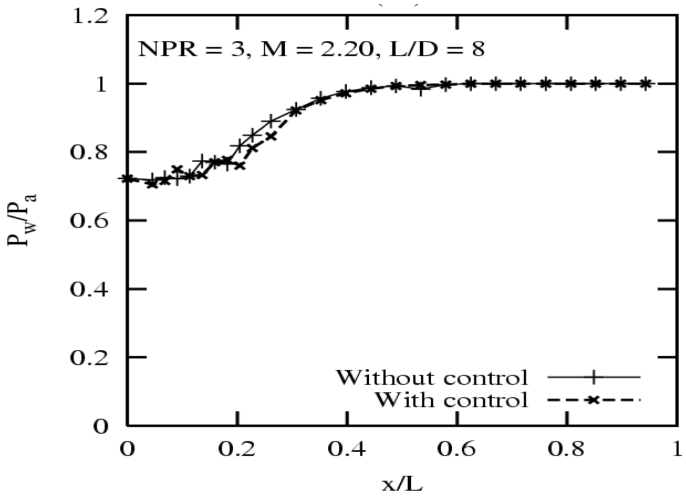

Fig. 10 Wall Pressure Distribution at P_e/P_a= 0.277

5. CONCLUSION

From the above results we can draw the following conclusions:

It is evident that, Mach 2.58 influences the base pressure more than the lower Mach number namely 2.2. Also, at Mach 2.58, the micro jets have a powerful influence on base pressure, taking its value to low levels compared to without control case. The minimum duct length required for Mach 2.2 and 2.58 are L/D = 6 for a level of over expansion of 0.277, whereas for the level of over expansion of 0.56 the said values are 3 and 4 respectively. The maximum gain in the base pressure at Mach 2.2 is around 60 percent when the level of over expansion is changed from 0.277 to 0.56 whereas the same becomes around 70 percent at Mach 2.58.This gain may be considered as one of the major advantage in case of exterior ballistics. It is also found that Microjets which are used as active method of controlling the base pressure; do not augment the wall pressure field in the expanded duct.

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