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Effect of Mach number In a Suddenly Expanded Flow for Area Ratio 4.84

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ABSTRACT

The experiments were carried out to assess the effect of Mach number on base pressure and control effectiveness in a suddenly expanded duct. In the present study the Mach number at the nozzle exit and the nozzle pressure ratio (NPR) are the flow parameters considered. The area ratio (i.e. ratio between cross sectional area of the sudden expansion duct and the nozzle exit area) and the length-to-diameter ratio of the duct are the geometrical parameters considered. The jet Mach numbers at the entry to the suddenly expanded duct, studied are 1.87, 2.2 and 2.58. The nozzle pressure ratio (NPR) used is from 3 to 11, in steps of 2 and experiments are conducted for NPR 3, 5, 7, 9, and 11 for all the Mach numbers. The area ratio of the present study is 4.84. The L/D ratio of the 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 for the given area ratio the base pressure increase with Mach number. When the flow is over expanded the base pressure assumes very high value due the presence of oblique shock at the nozzle lip. It is also found from wall pressure studies that the micro jets do not disturb the flow field in the enlarged duct.

Keywords: ***Axi-symmetric duct, Base Pressure, Mach number, Micro jets.***

I. INTRODUCTION

The diverse nature of applicability of jets demands that they be made suitable for a specific application by controlling them. Hence control may be defined as the ability to modify the jet flow mixing characteristics to achieve engineering efficiency, the technological ease, economy, adherence to standards and so on. All types of jet control methods can be broadly classified into active and passive controls. In active control, an auxiliary power source is used to control the jet characteristics. In passive control the controlling energy is drawn directly from the flow to be controlled. Both active and passive controls mainly aim at modifying the flow and noise characteristics. 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 boat tailing, 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.

II. LITERATURE REVIEW

The effect of boundary layer on sonic flow through an abrupt cross-sectional area was studied experimentally by Wick [1]. He observed that the pressure in the corner of expansion was related to the type and thickness of boundary layer upstream of the expansion. He considered boundary layer as a source of fluid for the corner flow. But in view of Hoerner [2] the boundary layer was an insulating air that reduces the effectiveness of the jet as a pump. The base corner was thought of as a sump with two supplies of mass. The first was the boundary layer flow around the corner and the second source was back flow in the boundary layer along expanded section wall. This back flow occurred because of the pressure difference across the shock wave originating where the jet strikes the duct wall. He concluded that, the mechanism of internal and external flow was principally the same and base pressure phenomenon in external flow could be studied relatively easily by experiments with internal flow. The problem of base pressure in transonic and supersonic flow for cases in which the flow approaching the base is sonic or supersonic after the wake was investigated by Korst [3]. He devised a physical flow model based on the concepts of interaction between the dissipative shear flow and the adjacent free stream and the conservation of mass in the wake. The base flows at supersonic speeds were investigated by Badrinarayanan [4]. Detailed measurements in the wake flow behind blunt based two-dimensional and three-dimensional bodies were made at M = 2.The results throw some light on the behaviour of separated flows and indicate the importance of flow reversal. The effect of air injection at the base shows that the base pressure increases significantly with air injection. Anderson and Williams [5] 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 [6] 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. Srikanth and Rathakrishnan [7] 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 [6].Rathakrishnan et. al [8] 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 [9]. 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 [10] reviewed the flow management techniques for base and after-body drag reduction the problem of turbulent base flows and drag associated with it. His review paper presents the development that have taken place on the use of passive techniques or devices for axi-symmetric base and net after-body drag reduction in the absence of jet flow at the base. In particular, 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. The broad features of the flow and the likely fluid-dynamical mechanism associated with the devices leading to base drag reduction were highlighted. Flight-test results assessing the effectiveness of some of the devices were compared with data from wind tunnels. This 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.

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 [12] 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 [13] 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 effect of level of expansion in a suddenly expanded flow and the control effectiveness has been reported by Khan and Rathakrishnan [14]. 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. [15] 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 [16] 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, majority of them are studies without control. Even among the available literature on investigation of base flows with control, most of them, used only passive control by means of grooves, cavities and ribs. Only very few studies report base flow investigation with active control. 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.

III. EXPERIMENTAL SETUP

Fig. 1 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 1.87, 2.2 and 2.58. 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. 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 was used for measurement of duct wall pressure distribution.

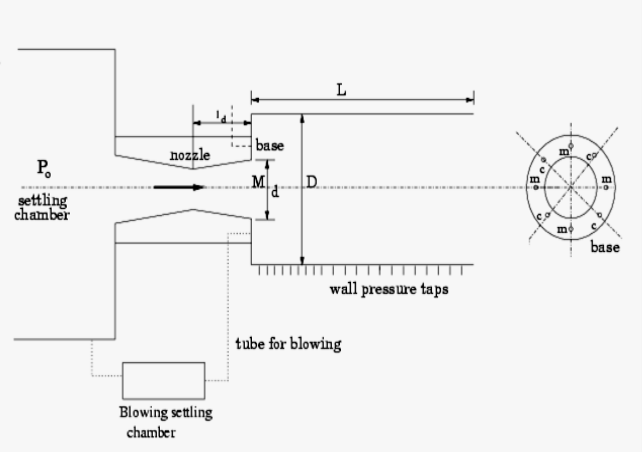

Fig 1 Experimental Set

IV. 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 stagnation pressure in the main settling chamber.

Base pressure results as function of Mach number for various NPRs for L/D = 10 are presented in Figure 2. It is seen that for NPRs in the range 3 to 5 the control in the forms of the Micro jets is insignificant and the base pressure increases with the increase of Mach number and decreases with increase of NPR. The physical reasons for this behavior are that the flow remains over expanded for this range of level of expansion. For Correct expansion the NPRs required for Mach 1.87, 2.2, and 2.58 are 6.4, 11, and 19. At NPR 7 the trend is similar to that at previous NPRs, but control results in decrease of base pressure. Only at Mach 1.87 the jet is slightly under expanded at NPR 7. When NPR is further increased namely up to 9 and 11 for Mach 1.87 and 2.2 the control results in increase of base pressure. However, at Mach 2.58 the control results in decrease of base pressure. Figure 3 presents the results for L/D = 8. It is seen from the figure that the trend is on the similar lines as discussed above for L/D = 10. Results for L/D = 6 are shown in figure 4. From the figure it is seen that the results for NPRs in the range 3 to 7 show the similar trends as discussed for L/D = 10 & 8 with minor changes in the trends of the control effectiveness. This trend may be due to the decrease in the L/D and influence of the atmospheric pressure influencing the flow development in the enlarged duct. Results for L/D = 5 are shown in figure 5. Results for NPRs 3 and 5 show the similar behavior as discussed above. However, the trend for NPR 7 and Mach 2.2 is different. It is found that the base pressure has increased substantially and control results in decrease of base pressure. This trend may be due to the combined effect of the Mach number, level of expansion and the effect of the L/D ratio.

Results for L/D = 4 are shown in figure 6. For NPRs 3 and 7 the base pressure values have increased compared to the previous values and the control effectiveness is only marginal. At NPR 7 for Mach 2.2 base pressure assumes a high value compared to the higher L/Ds and control results in decrease of base pressure. Whereas for NPRs 9 and 11 the control results in increase of base pressure at Mach 1.87 and 2.2 but at Mach 2.58 the base pressure value is high compared to the previous two Mach numbers. The physical reasons for this behavior may be due to the level expansion and jets remain over expanded for the entire range of the NPRs.

Results for L/D = 3, 2, and 1 are shown in figures 7 to 9. At NPRs 3, 5 and 7 the flow is not attached with the enlarged duct. However, at NPRs 9 and 11 at L/ D = 3 for Mach numbers 1.87 and 2.2 the flow is attached with the duct wall. L/D = 2 and 1 are not sufficient for the flow to be attached with the duct. Hence, no specific comment could be given for the variation in the base pressure.

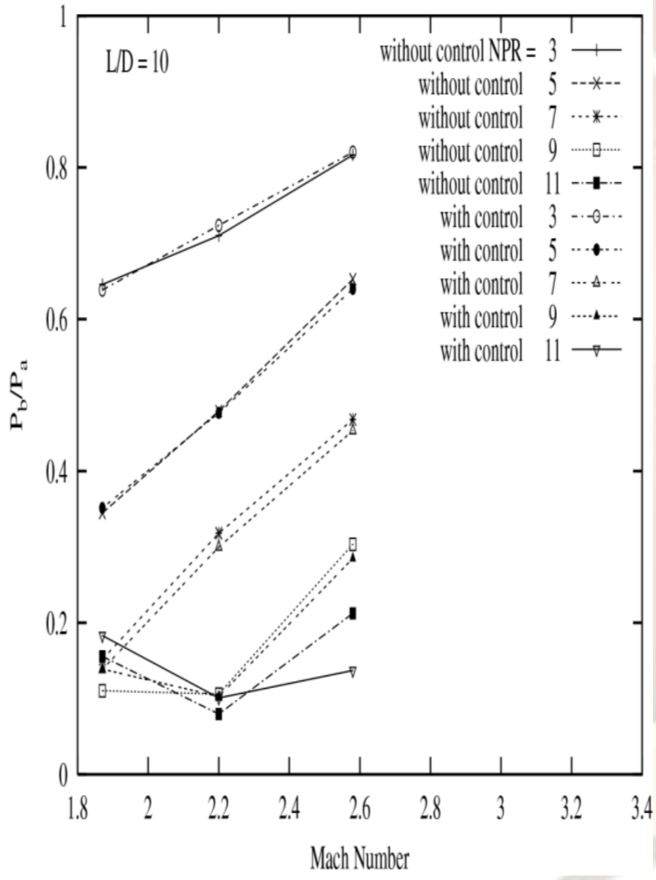

Fig 2 Base pressure variation with Mach number for L/D=10

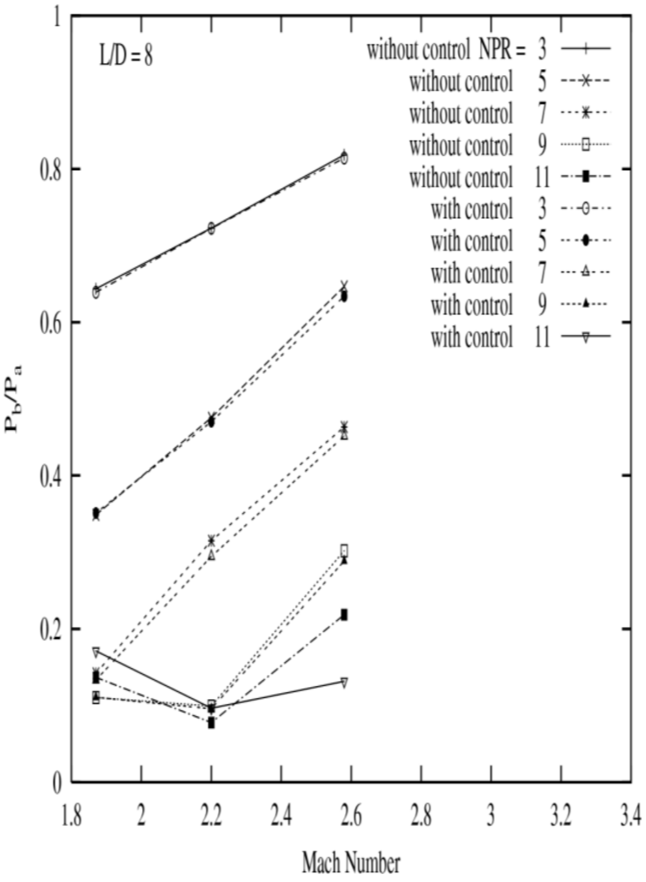

Fig 3 Base pressure variation with Mach number for L/D=8

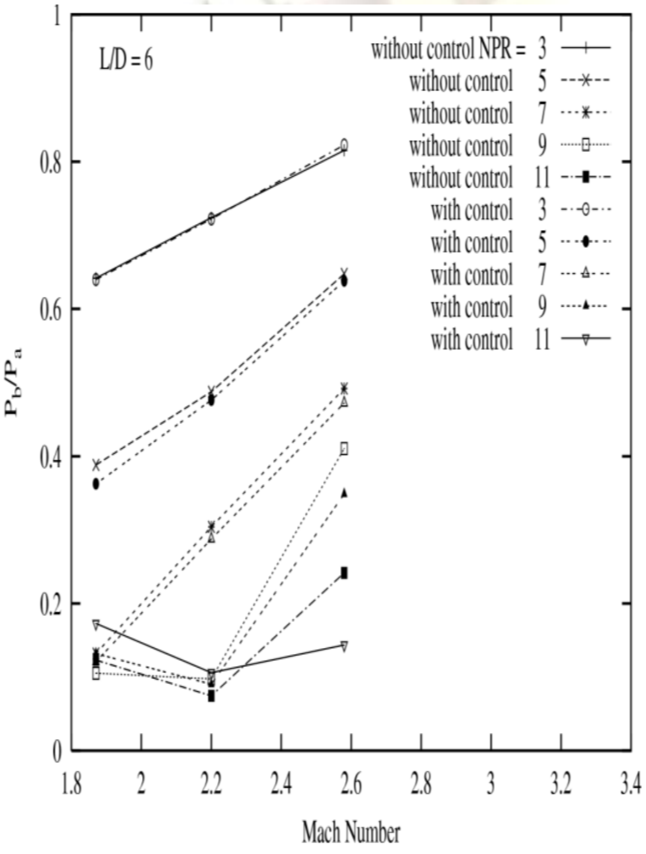

Fig 4 Base pressure variation with Mach number for L/D=6

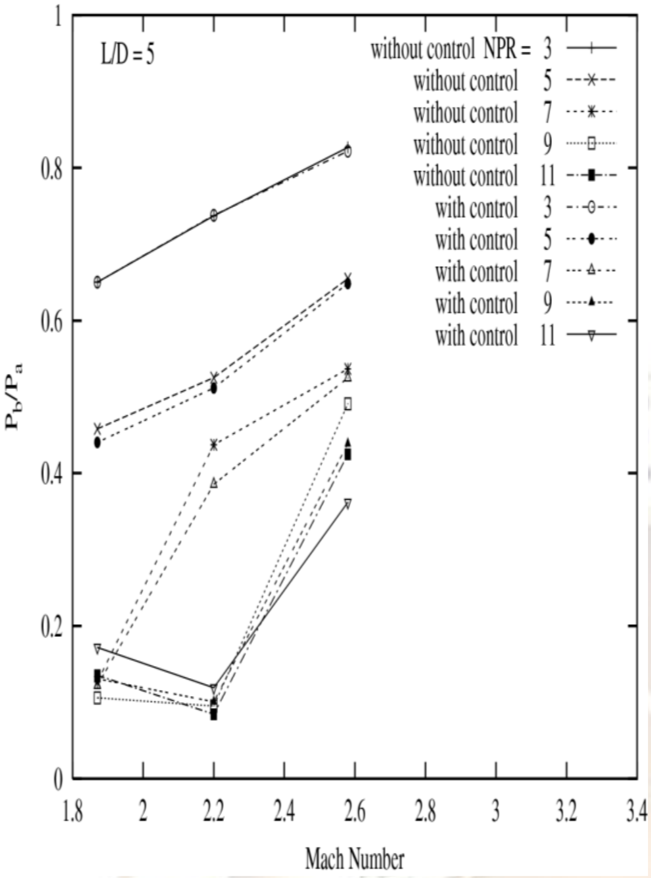

Fig 5 Base pressure variation with Mach number for L/D=5

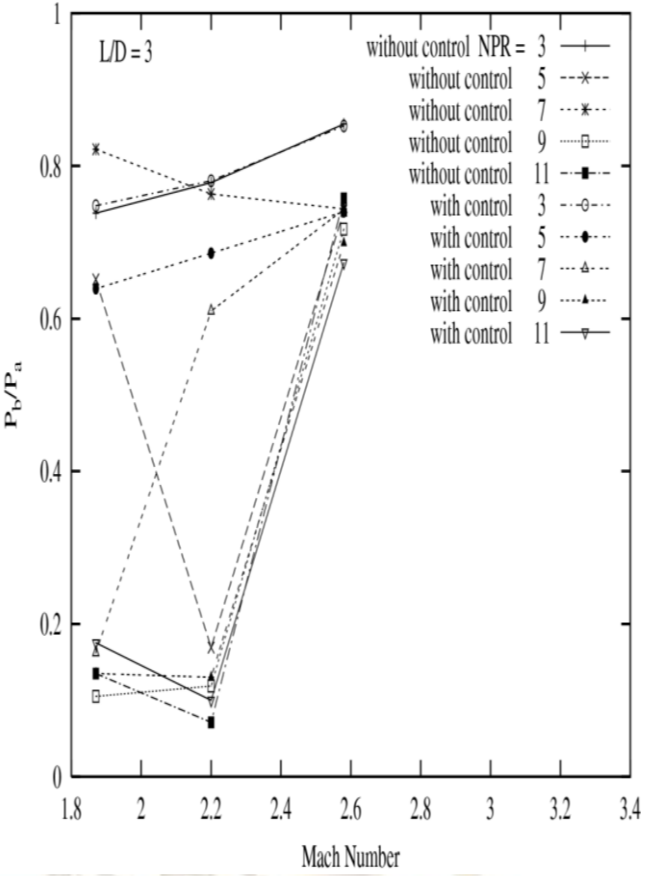

Fig 7 Base pressure variation with Mach number for L/D=3

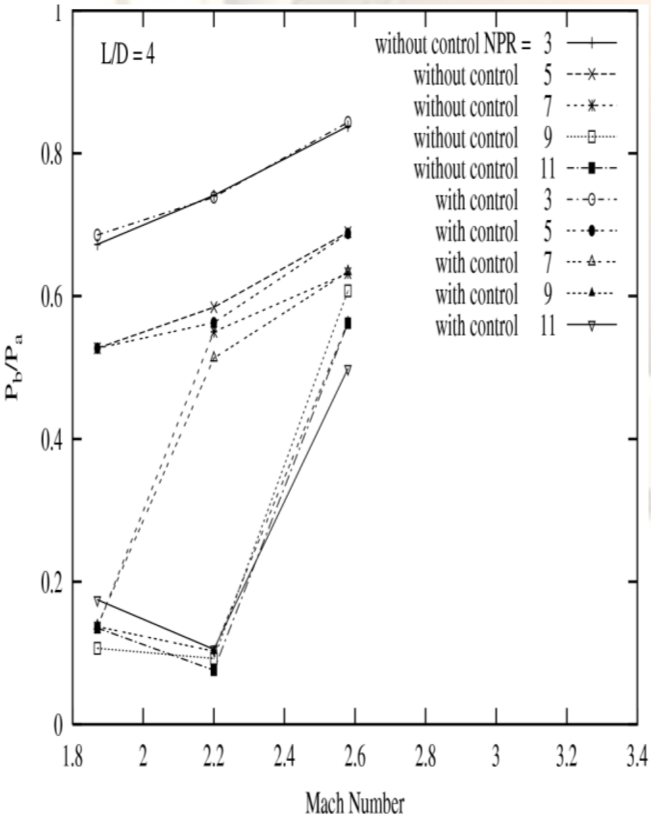

Fig 6 Base pressure variation with Mach number for L/D=4

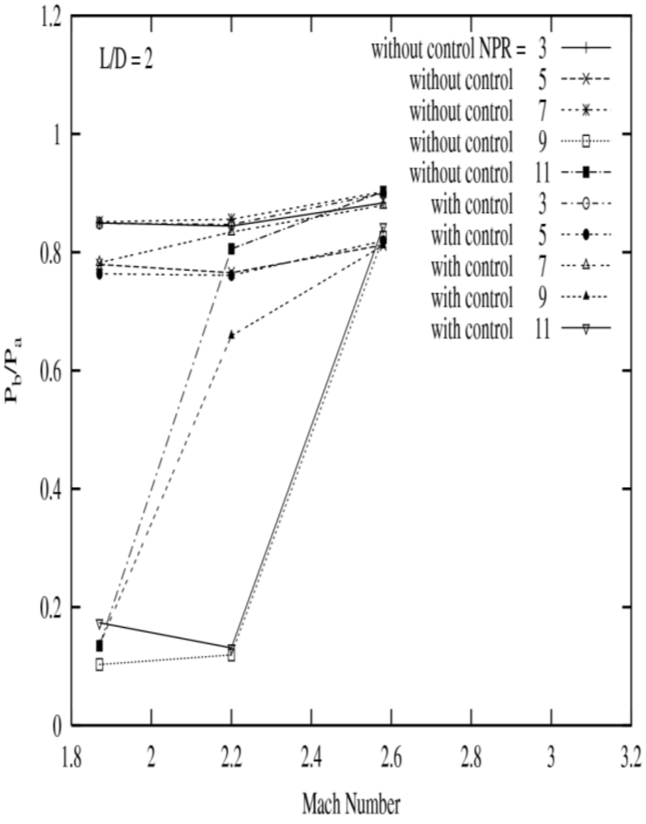

Fig 8 Base pressure variation with Mach number for L/D=2

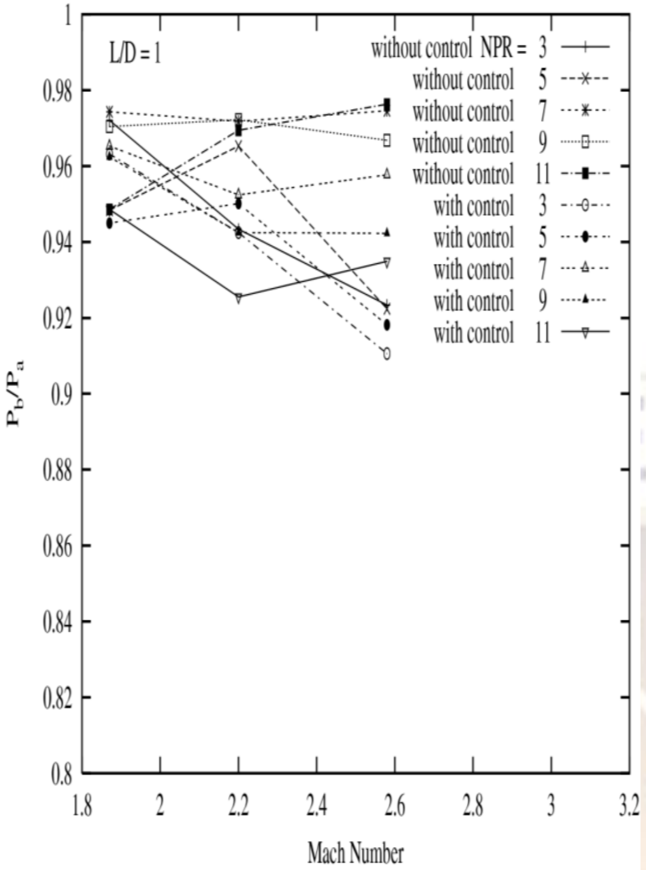

Fig 9 Base pressure variation with Mach number for L/D=1

V. WALL PRESSURE DISTRIBUTION

It can be seen from figures 10 to 12 that the location of Microjets at three different locations does not augment the wall pressure. The wall pressure studies are verily required to understand the oscillatory nature of flow which is one of the major problems in active methods of controlling base flows.

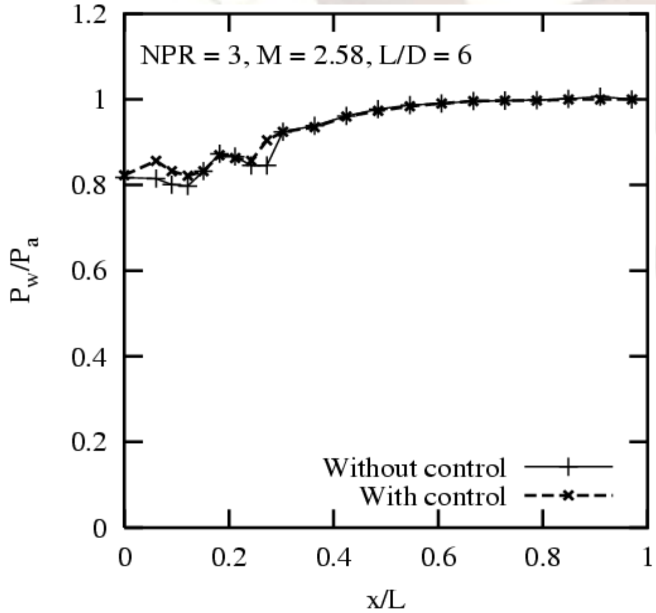

Fig 10 Wall Pressure distribution at NPR=3

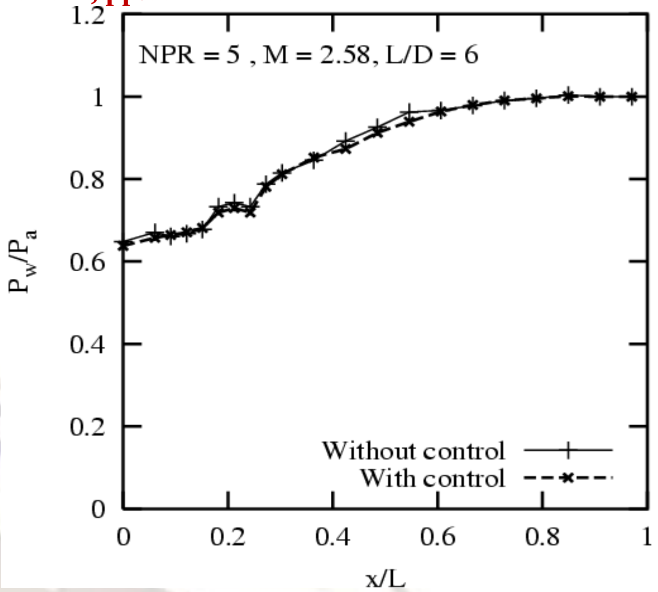

Fig 11 Wall Pressure distribution at NPR=5

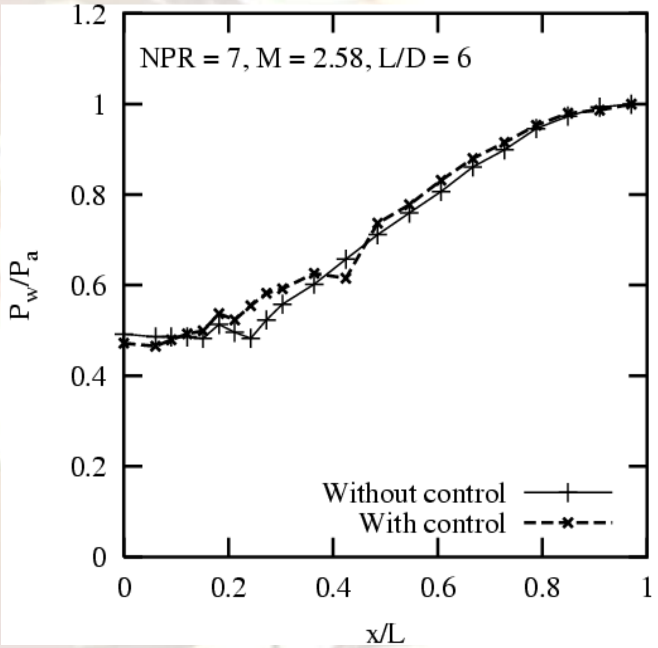

Fig 12 Wall Pressure distribution at NPR=7

VI. CONCLUSION

With increase in NPR the base pressure will decrease and when the jets are correctly expanded then again the base pressure will increase. For lower values of NPRs the control effectiveness is marginal, however, the same becomes effective with the increase in NPRs. In other words when jets are under expanded the control becomes effective. This is in agreement with Rathakrishnan & Sreekanth where they observed that whenever favorable pressure gradient exist the active/Passive controls become effective. L/D = 4 seems to be the minimum length required for the flow to be attached at Mach 2.58, whereas this value is L/D = 3 for Mach 1.87 and 2.2. The base pressure is function of Mach number, Nozzle pressure ratio, L/D ratio. The base pressure value progressively increases with the increase of Mach number.

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