Active Control of Flow through the Nozzles at Sonic Mach Number

Syed Ashfaq[1], Sher Afghan Khan[2] and E. Rathakrishnan[3]

[1]Research Scholar, JJTU, Rajasthan, India, 09370901947.
[2]Beary's Institute of Technology, Mangalore, Karnataka, India, 09845531478,
[3]Aerospace Engineering Department, IIT Kanpur, UP, India

ABSTRACT

The effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts are studied experimentally. As 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. The Mach number of the present study is unity. 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 experimental results, it is found that the micro jets can serve as active controllers for base pressure. Further, the control effectiveness of the micro jets is getting enhanced under the influence of favourable pressure gradient. 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.

Key words: Micro jets, Base pressure, Wall pressure, Mach number, Sudden expansion.

Corresponding Author: Syed Ashfaq

INTRODUCTION

A sudden expansion of flow both in 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 the 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 the flight where the expansion of the flow is inward rather the outward as in the previous example.

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 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.

Mathur and Dutton [2] 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. With increasing bleed flow rate, the average base pressure was found to increase initially, attain a peak near an injection parameter of I = 0.0148, and then decrease with further increase of I. The optimum bleed condition near I = 0.0148 is also characterized by a weak corner expansion, a minimum value of free-shear layer angle, and the near-disappearance of the re-circulation region (reverse velocity) along the centerline of the near wake.

Khan and Rathakrishnan [3-7] 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. [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. 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.

The effect of offset position of the annular rib on suddenly expanded supersonic flow studied by Rajaguru Nathan et al. [9]. The flow from Convergent- Divergent (CD) nozzle expanding into circular pipe has been investigated experimentally. They found that the position of rib was of considerable influence over the base pressure and wall pressure distribution in the enlarged duct. For each NPR, the increase in rib position increases the base pressure. With the increase in NPR, the increase in base pressure with rib position also increases. Wall pressure distribution changes tremendously with the change in rib position. The wall pressure increases upstream of rib with an increase in NPR and rib position.

Layek et al. [10] carried numerical simulation to study the laminar flow in a symmetric sudden expanded channel subjected to a uniform blowing/suction speed placed at the lower and upper porous step walls. The governing equations for viscous flow have been solved using finite-difference techniques in pressure-velocity formulation. The results obtained compared with the available experimental and numerical results of similar problems. They noted that the recirculating region formed near the step walls diminishes in its length for increasing values of blowing speed applied at the porous step walls. For a suitable blowing speed, the re-circulation zone disappears completely. The critical Reynolds number for the flow bifurcation (i.e. flow asymmetry) was obtained and it increases with the increase of the blowing speed. The critical Reynolds number for symmetry breaking of the flow decreases with the increasing value of suction speeds. The primary and the secondary recirculating regions formed near the channel walls are controlled using blowing.

Pandey and Kumar [11] studied the flow through a nozzle in a 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 was sufficient for the smooth development of flow keeping in view all the three parameters like base pressure, wall static pressure and total pressure loss.

Vikram Roy et al. [12] 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.

The experimental investigations carried out to study the variations in base pressure at different levels of over expansion of jet in a suddenly expanded axi-symmetric duct were presented by Baig & Khan [13]. The two different fixed levels of Over Expansion selected in the study were 0.277 and 0.56. The area ratio of the study was 3.24. The jet Mach numbers at the entry to the suddenly expanded duct, studied were 2.2 and 2.58. They found that at a high level of over expansion micro jets are marginally effective.

An experimental investigation to study the effectiveness of micro jets to control the base pressure in a suddenly expanded axi-symmetric ducts when the micro jets are placed at different location (i.e. at the base, at the duct, and at base as well as in the duct) presented by Baig et al. [14]. The area ratio of the study was 3.24. They found, as high as 60 per cent increase in base pressure was achieved for Mach number 2.58 at NPR 11.

Baig et al. [15] 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.

Pandey et al. [16] have done the analysis of wall static pressure variation with a fuzzy logic approach to have smooth flow in the duct. Three area ratio chosen for the enlarged duct were 2.89, 6.00 and 10.00. The primary pressure ratio was taken as 2.65 and the cavity aspect ratio was taken as 1 and 2. The study was analyzed for length to diameter ratio of 1, 2, 4 and 6. The nozzles used were De Laval type and with a Mach number of 1.74 and 2.23. The analysis based on fuzzy logic theory indicates that the length to diameter ratio of 1 was sufficient for smooth flow development if only the basis of wall static pressure variations was considered.

Khan et al. [17] carried out an experimental investigation to study the effectiveness of micro jets to control base pressure in suddenly axi-symmetric ducts. The Mach numbers of the suddenly expanded flows were 0.2, 0.4, 0.6, 0.8, and 0. 9. The jets were expanded suddenly into an axi- symmetric tube with cross-sectional area 2.56, 3.24, 4.84 and 6.25 times that of the nozzle exit area. It was found that the micro jets can serve as active controllers for base pressure if the control pressure was higher than the settling chamber pressure. Also, the micro jets do not adversely influence the wall pressure distribution.

EXPERIMENTAL METHOD

Figure 1 shows the experimental setup used for the present study. At the exit periphery of the nozzle there are eight holes as shown in figure, 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 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. 1) 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, 4.0, 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 of L/D 10. The lower L/Ds was achieved by cutting the length after testing a particular L/D value.

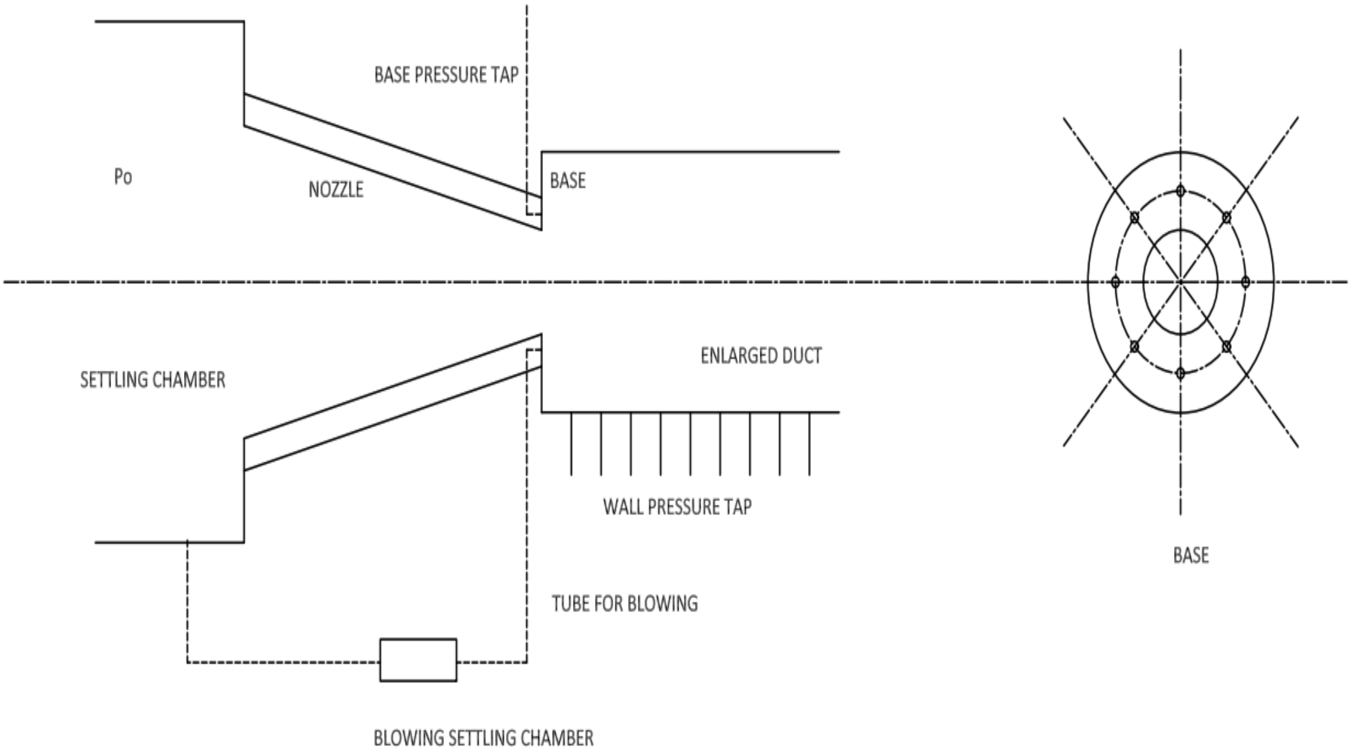

Fig. 1: Experimental Setup

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 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. The base pressure variation with L/D ratio and the area ratio for sonic flow for Mach number one with and without control is shown in figs. 2 & 3. Fig. 2 shows the base pressure results as a function of L/D for area ratios namely, 2.56, 3.24, 4.84 and 6.25. It is seen from the figure that the control effectiveness in the form of micro jets is only marginal for all the area ratios and L/Ds. The reasons for this behavior may be due to the presence of Mach waves and jets exiting from the nozzle are correctly expanded. Here the results presented are for ideally or correctly expanded case. As stated in the literature that whenever the jets are under expanded the control becomes very effective. From the figure it is seen that for lower L/D the base pressure assumes very high value. The physical for this behavior is the insufficient length of the duct which results in the detached flow. Also, the flow is exposed to the ambient pressure due to the insufficient length of the duct. Further, it is seen that the lowest area ratio assumes the lowest value of base pressure and with the increase in the area ratio the value of base pressure progressively increases.

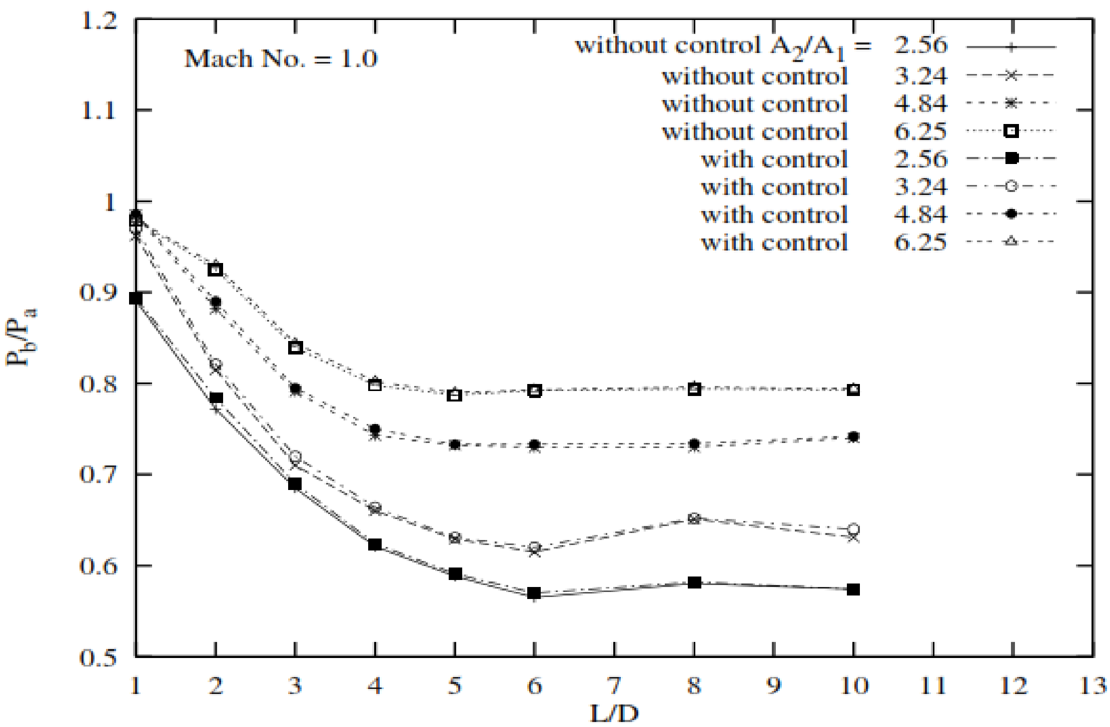

Fig. 2: Base Pressure Variation wit L/D Ratio

It is to be noted that in addition to the influence of the wave at the nozzle lip, 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. 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. Also, the location of the micro jets will also influence the flow field in the base region.

The base pressure results as a function of area ratio for different L/D is shown in figure 3. 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 as compared for the higher area ratio. Since the Mach number is constant hence the strength of the vortex will remain the same. From the results it is evident that value of 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 minimum duct length required for the area ratio 2.56 is L/D = 2 whereas, for the highest area ratio this requirement is L/D = 3.

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.

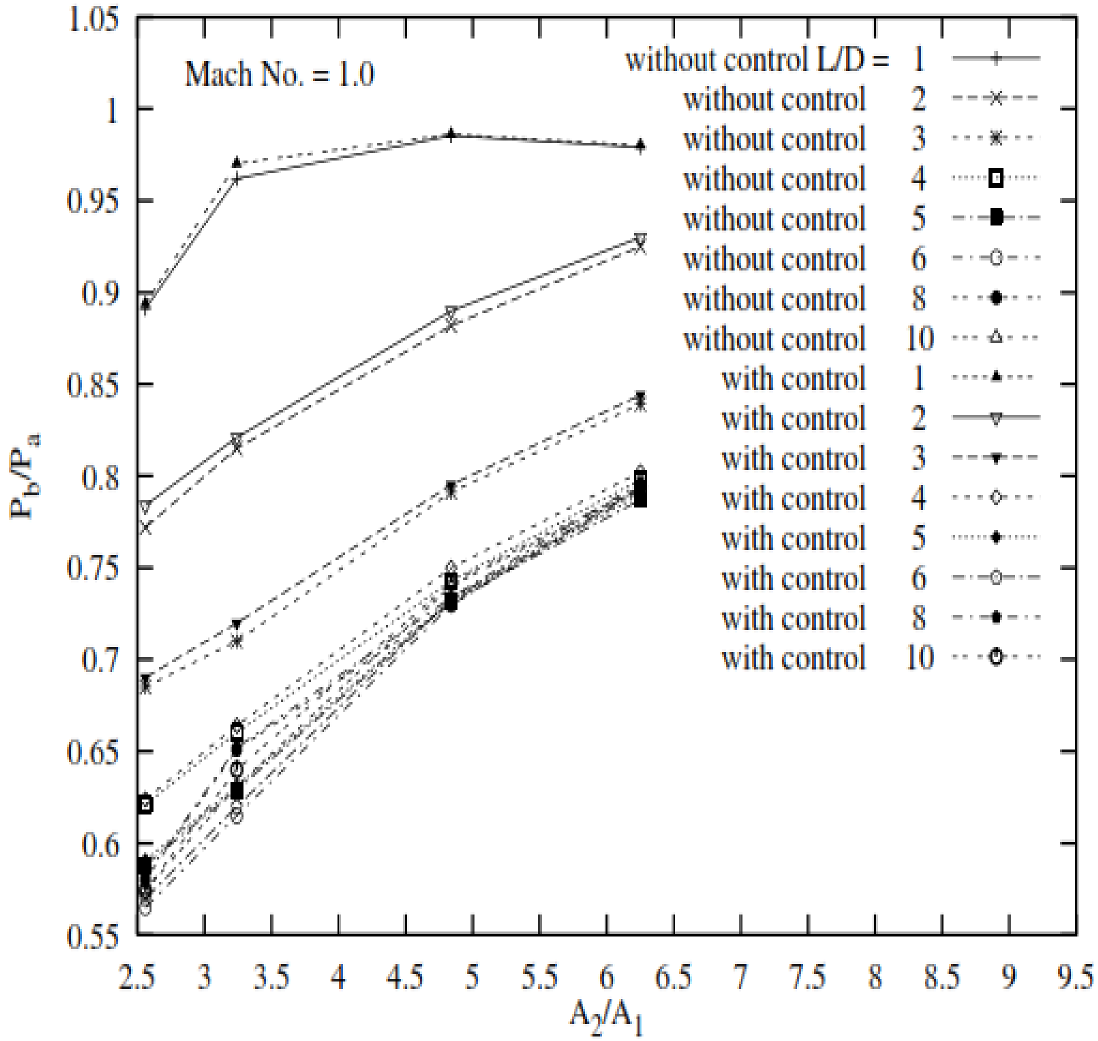

Fig. 3: Base Pressure Variation with Area Ratio A_2/A_1

Percent change in base pressure with L/D and area ratio are shown in figs. 4 & 5. The percentage change in base pressure as a function of L/D for all the four area ratios are shown in figure 4. The trend is wavy in nature and no definite conclusion can be drawn in view of the presence of Mach waves at the nozzle lip which in turn will influence the base vortex and hence the base pressure. Similar results are shown in figure 5 when the percentage change in base pressure as a function of area ratio is plotted for various L/Ds. It is seen that the maximum gain is for the lowest area ratio namely 2.56. It is expected that the control effectiveness will improve when micro jets are activated in the presence of favorable pressure gradient.

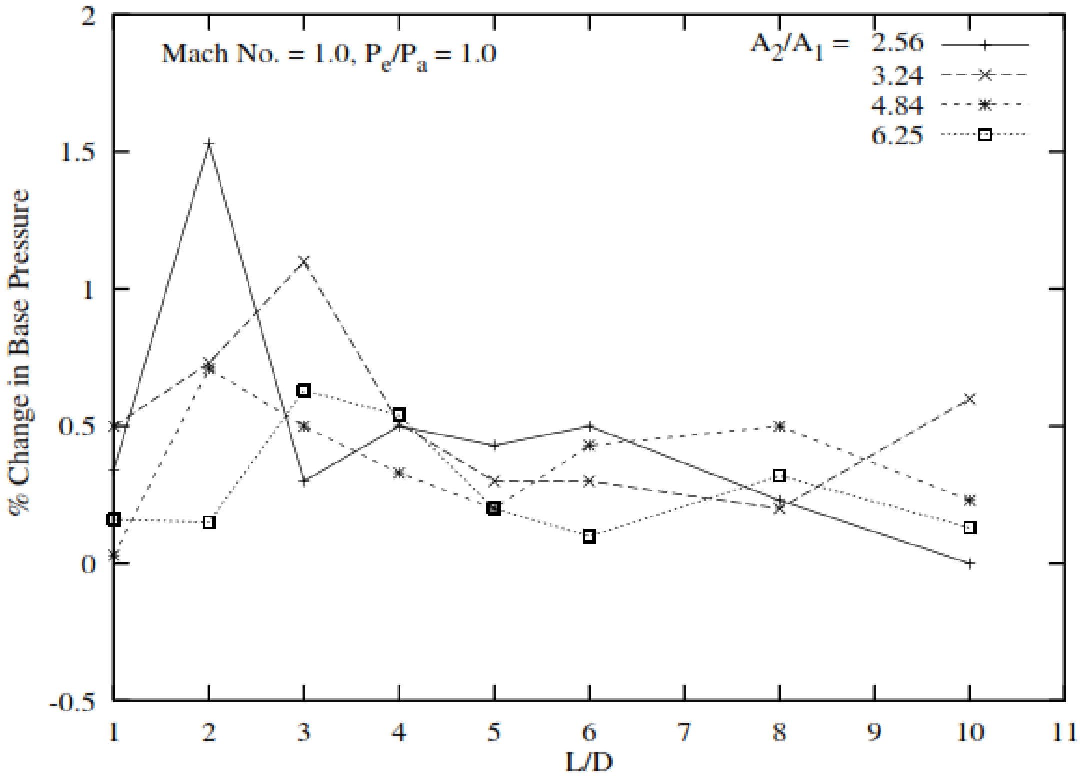

Fig. 4: Percentage Change in Base Pressure Variation with L/D

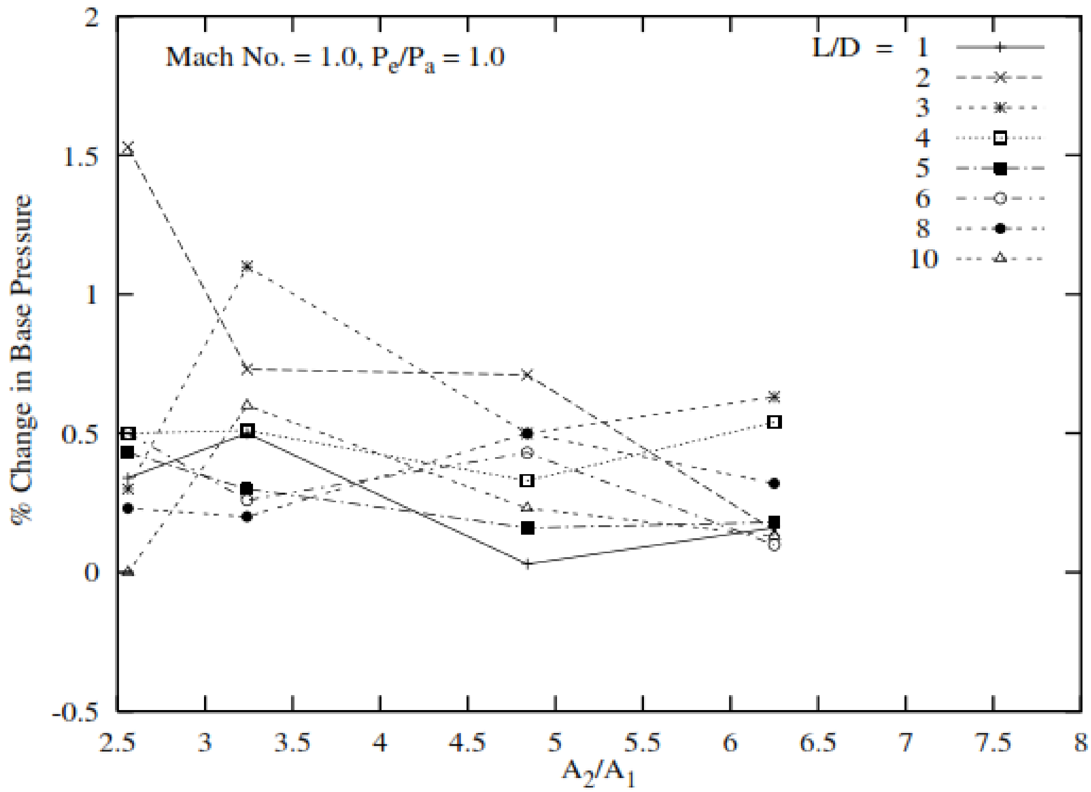

Fig. 5: Percentage Change in Base Pressure Variation with Area Ratio A_2/A_1

Issue 3, Vol.2 (March 2013)
ISSN 2249-6149

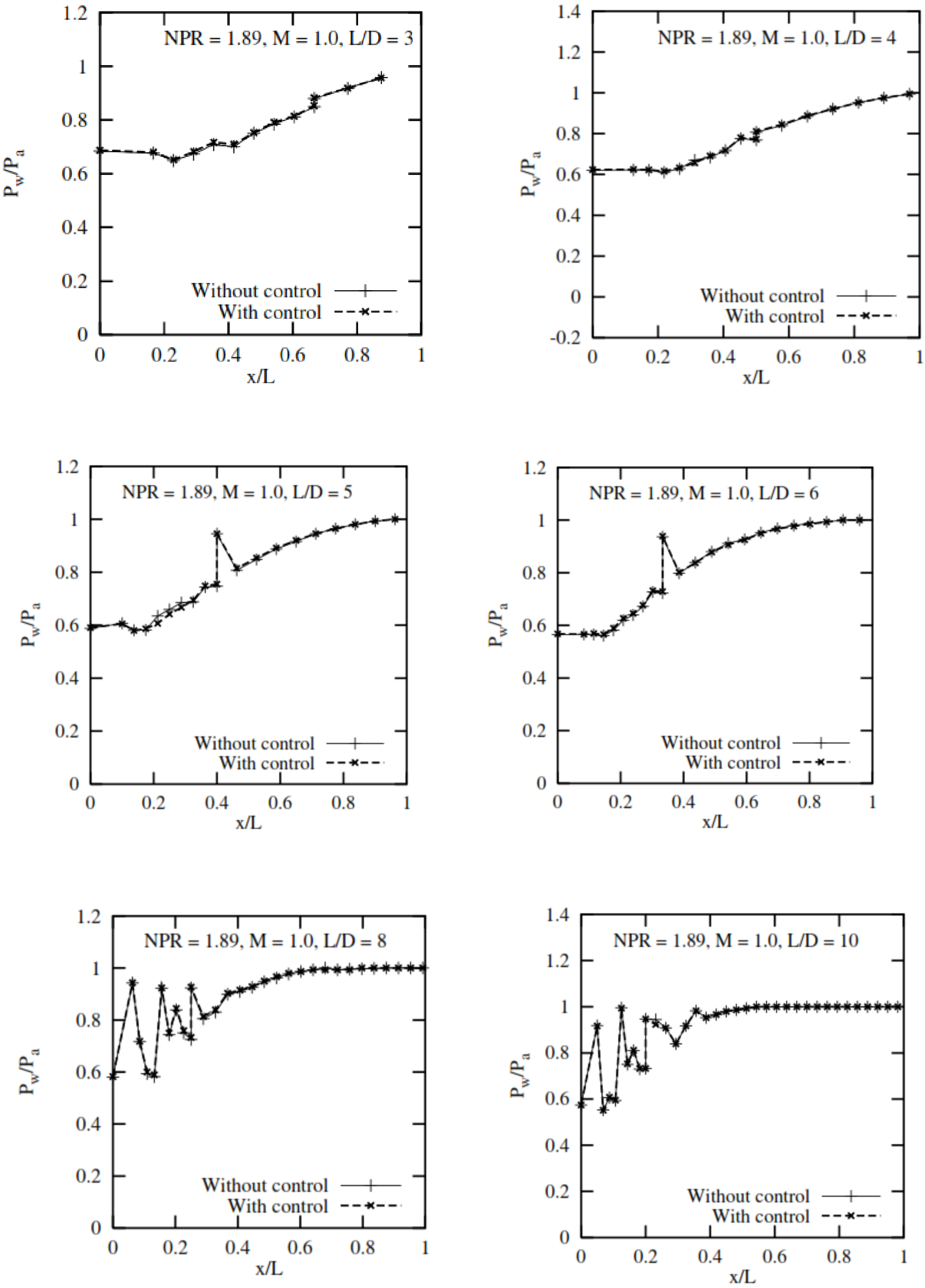

Fig. 6: Wall Pressure Distribution

Figure 6 presents the wall pressure distribution in the enlarged duct. 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 ratio namely L/D = 3 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 30 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 within the reattachemnt length.

CONCLUSION

From the above results it is found that the effectiveness of the Micro jets is marginal in controlling the base pressure. However, the effectiveness will improve when the micro jets are employed in the presence of a favorable pressure gradient. They can be used as an effective controller of the base pressure to control the flow field in the base region of the duct and hence control the base drag. Further, it is found that the minimum duct length required for the flow to be attached to the enlarged duct wall is seems to be L/D = 2 for lower area ratio and L/D = 3 for higher area ratios of the present study. 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. All the non-dimensional base pressure presented in this paper are within an uncertainty band of ± 2.6 per cent. Further, all the results are repeatable within ± 3 per cent.

REFERENCES

[1] Wick R. S., “The Effect of Boundary Layer on Sonic Flow through an Abrupt Cross-sectional Area Change”, Journal of the Aeronautical Sciences, Vol. 20, pp. 675-682, 1953.

[2] Tarun Mathur and J. Craig Dutton, “Base-Bleed Experiments with a Cylindrical Afterbody in Supersonic Flow”, Journal of Spacecraft and Rockets, Vol. 33 No. 1, pp. 30-37, 1996.

[3] S. A. Khan and E. Rathakrishnan, “Active Control of Suddenly Expanded Flows from Over expanded Nozzles”, International Journal of Turbo and Jet Engines (IJT), Vol. 19, No. 1-2, pp. 119-126 2002.

[4] S. A. Khan and E. Rathakrishnan, “Control of Suddenly Expanded Flows with Micro Jets”, International Journal of Turbo and Jet Engines (IJT), Vol. 20, No.2, pp. 63-81, 2003.

[5] S. A. Khan and E. Rathakrishnan, “Active Control of Suddenly Expanded Flow from Under Expanded Nozzles”, International Journal of Turbo and Jet Engines, (IJT), Vol. 21, No. 4, pp. 233-253, 2004.

[6] S. A. Khan and E. Rathakrishnan, “Control of Suddenly Expanded Flow from Correctly Expanded Nozzles”, International Journal of Turbo and Jet Engines (IJT), Vol. 21, No. 4, pp. 255-278 2004.

[7] S. A. Khan and E. Rathakrishnan, “Control of Suddenly Expanded Flow”, Aircraft Engineering and Aerospace Technology: An International Journal, Vol. 78, No. 4, pp. 293-309, 2006.

[8] R. Jagannath, N. G. Naresh and K. M. Pandey, “Studies on Pressure Loss in Sudden Expansion in Flow Through Nozzles: A Fuzzy Logic Approach”, ARPN Journal of Engineering and Applied Sciences, Vol. 2, No. 2, pp. 50-61, 2007.

[9] K. Rajaguru Nathan, K. Vijayaraja, S. Elangovan, E. Rathakrishnan, “Effect of Annular Rib Position in Suddenly Expanded Supersonic Flow”, Proceedings of the International Conference on Aerospace Science and Technology, Bangalore, India, 2008.

[10] G. C. Layek, C. Midya, S. Mukhopadhyay, "Effects of Suction and Blowing on Flow Separation in a Symmetric Sudden Expanded Channel", Nonlinear Analysis: Modelling and Control, Vol. 13, No. 4, pp. 45-465, 2008

[11] K. M. Pandey, Member, IACSIT and Sushil Kumar, "Flow through Nozzle in Sudden Expansion in Cylindrical Ducts with Area Ratio 2.89 at Mach 2.4: A Fuzzy Logic Approach", International Journal of Innovation, Management and Technology, Vol. 1, No. 3, pp. 305-311, 2010.

[12] Vikram Roy, Snehamoy Majumder, Dipankar Sanyal, "Analysis of the Turbulent Fluid Flow in an Axi-symmetric Sudden Expansion", International Journal of Engineering Science and Technology, Vol. 2(6), pp. 1569-1574, 2010.

[13] M. Ahmed Ali Baig, Sher Afghan Khan, "A Study on Suddenly Expanded Flow at Different Levels of Over Expansion for Area Ratio 3.24", International Journal of Scientific & Engineering Research, Vol. 3, Issue 8, pp. 1-6, 2012.

[14] M. Ahmed Ali Baig, S. A. Khan and E. Rathakrishnan, "Experimental Investigations on Wall Pressure in Suddenly Enlarged Ducts at Supersonic Mach number Regimes", International Journal of Emerging trends in Engineering and Development, Vol. 6, Issue- 2, pp. 496-504, 2012.

[15] M. Ahmed Ali Baig, Sher Afghan Khan, and E. Rathakrishnan, "Control of Nozzle Flow in Suddenly Expanded Duct with Micro Jets", International Journal of Engineering Science & Advanced Technology [IJESAT], Vol. 2, Issue-4, pp. 789 – 795, 2012.

[16] K. M. Pandey, Jagannath Rajshekharan and Sukanta Roga, "Wall Static Pressure Variation in Sudden Expansion in Flow through De Laval Nozzles at Mach 1.74 And 2.23 In Circular Ducts without Cavities: A Fuzzy Logic Approach", International Journal of Soft Computing and Engineering (IJSCE), Vol. 2, Issue-1, pp. 303-310, 2012.

[17] Sher Afghan Khan, M. Ahmed Ali Baig and E. Rathakrishnan, "Subsonic Jet Control With Micro Jets", International Journal of Emerging trends in Engineering and Development, Vol. 5, Issue- 2, pp. 269-275, 2012.