Studies on Wall Pressure Flow Control by Micro Jets for High Area Ratio

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ABSTRACT

This paper discuss the experimental results on the flow characteristics of a suddenly expanded flow from the convergent nozzle for subsonic Mach numbers. An Active control in the form of micro jets were used to investigate the effectiveness of micro jets on wall pressure flow field in the enlarged duct. Accordingly 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 numbers of the present studies were M = 0.9, 0.8, and 0.6 and the area ratio (ratio of area of suddenly expanded duct to nozzle exit area) studied was 6.25. The length-to-diameter (i.e. L/D) ratio of the sudden expansion duct was varied from 10 to 1. From the results, it is seen that the flow in the base region is dominated by the waves, however, the magnitude of the waves has reduced considerably due to the very high area ratio, also, it is found that for L/D in the range L/D = 10 and 8 the flow remains oscillatory for all the Mach numbers. However, these oscillations are suppressed gradually either with the decrease in the L/D ratio in the range 3 to 6 or with decrease in the level of inertia level. The minimum suddenly expanded duct length required for the flow to be attached is the present study has shown that the wall pressure in a suddenly expanded axi-symmetric duct can be controlled by employing micro jets at the base. It is found that the flow field in the enlarged duct with and without control remained the same hence, we summarized that active control in the form of micro jets are not disturbing the field.

Key words: Wall pressure, Sudden expansion, Mach number, Active Control, Area ratio
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INTRODUCTION

Flow through Suddenly expanded axi-symmetric ducts fields found several applications in many engineering problems of practical importance, such as pipe networks, heat exchangers, nuclear reactors, combustors and combustion chambers and so on. The need for controlling such flow fields has motivated studies of these flows. Researchers carried experiments using passive control mechanisms because they give the desired results without the need for separate mechanisms. But in case of active control, separate mechanisms are used.

In real life engineering applications, base pressure at the base of high-speed jet has long been one of the important issues. The base pressure characteristics of incompressible flows have been well known to date as this value is very small normally it is 10 percent of the skin friction drag. However, the base pressure at subsonic, transonic, and supersonic speeds would be different due to the compressibility effects and shock waves present in the flow field. It is also well known that the base pressure at the transonic speed could be as high as 50 percent of the total drag. Hence, a small increase in base pressure will result in considerable decrease in the base drag which; in turn will result in increase in the range of missiles, shells, projectiles, and air-crafts. A number of scientists have made an attempt to deal with the problem of drag reduction techniques, various methods like ventilated cavities at the blunt base, ribs, base cavities, ribs, step bodies, splitter plate at the base and boattailing, etc. are the few of the passive means are attempted by the scientists working in the field of drag reduction techniques. No attempt has been made to use the active control. Hence, in the present paper, an attempt has been made and experiments were performed to understand the base pressure characteristics at sub sonic speeds. An active control in the form of Micro jets has been used at the base as a control mechanism to control the base pressure emphasis is placed on the control of the base pressure using a simple orifice. A variety of supersonic jet plumes have been explored to investigate the flow variables influencing the base pressure. The results obtained were validated with existing experimental data and discussed in terms of the base pressure and discharge coefficient of the orifice. However, since the air is being drawn from the main settling chamber, hence, the maximum value of the control pressure will be the stagnation pressure in the main settling chamber. To have a variable control pressure which more than the stagnation pressure of the main settling chamber then in that case we need to have a separate source of the energy so that we can ascertain the effectiveness of the micro jets under the variable control pressure, however, in the present study no such attempts were made. The present study is focusing attention on the flow development in the enlarged duct, effect of the control on the wall pressure distribution and as well as the control effectiveness in the form of micro jets.

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. Steltz and Benedict [2] with various other investigators analyzed the sudden enlargement problem in an elaborate manner both theoretically and experimentally. Chow et al. [3] studied the problem of transonic flow past boattails with the numerical relaxative schemes. They restricted preliminary calculations to a particular model configuration for boaatailed afterbody. They learned that the small disturbance treatment of the inviscid part of the transonic flow is not adequate even though the model appears to be relatively slender, thus, the full potential equation must be employed for its study. They presented that the "strong interaction" character of these problems within the transonic flow regime will be fully illustrated from the results obtained from their study even though the flow has not been separated away from the boattailed afterbody. Gharib [4] studied influence of externally forced initial flow conditions on axisymmetric cavity shear layer. A sinusoidally heated strip upstream of the cavity excited Tollmein-Schlichting waves that, after amplification by the boundary layer, were introduced to the cavity shear layer. It was shown that by selecting a forcing frequency, which satisfies a phase difference criterion between two corners of the cavity and has an amplitude that is above the threshold amplitude, it is possible to excite a naturally non-oscillating shear layer. It was also shown that the frequency and amplitude of the oscillation in the self sustained mode can be controlled through external forcing. By using a feed-back control scheme, upto 40 per cent reduction of the velocity fluctuation level could be obtained. Kruiswyk and Dutton [5] studied effects of base cavity on subsonic near-wake flow. They experimentally investigated the effects of base cavity on the near-wake flow-field of a slender two-dimensional body in the subsonic speed range. Three basic configurations were investigated and compared, they are a blunt base, a shallow rectangular cavity base of depth equal to one half of the base height and a deep rectangular cavity base of depth equal to the base height. Schlieren photographs revealed that the base qualitative structure of the vortex street was unmodified by the presence of the base cavity. The weaker vortex street yielded higher pressures in the near-wake for the cavity bases, and increases the base pressure coefficients in the order of 10 to 14 per cent, and increases in the shedding frequencies of the order of 4 to 6 per cent relative to the blunt-based configuration. The effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts is studied experimentally by Ashfaq et al. [6-9] for flow through the nozzle at sonic, sonic under and sub sonic Mach number. 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 was found that the micro jets do not disturb the flow field in the duct.

EXPERIMENTAL METHOD

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 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

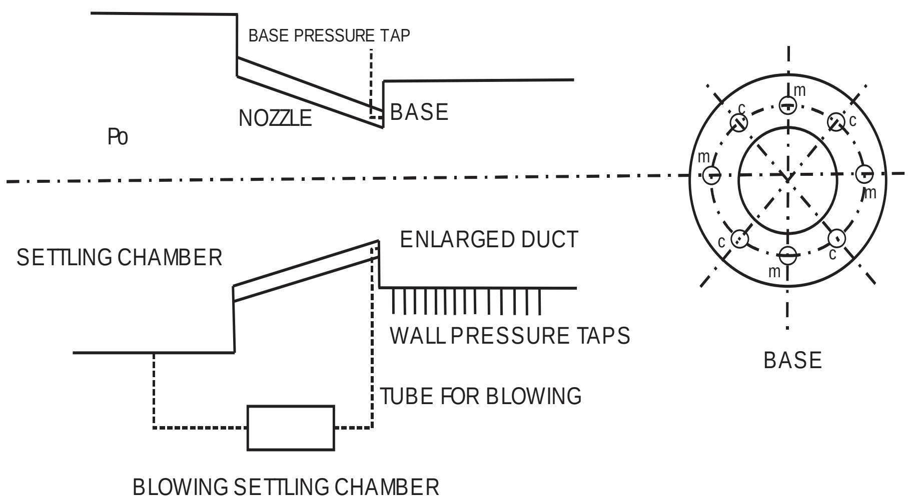


Fig. 1: Experimental Setup

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 10 mm and the area ratio of the model was 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 were achieved by cutting the length after testing a particular L/D value.

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 pressure in the control chamber will be the same as the NPR of the respective runs since we have drawn the air from the main settling chamber. One of the common problems encountered in suddenly expanded flow field is that the pressure field in the enlarged duct becomes oscillatory whenever; passive or active controls are employed. To quantify the effect of control on wall pressure distribution P_w/P_a for the two cases, namely with and without control have been compared.

Figs. 2(a) to (h) present the wall pressure distribution in the enlarged duct for L/D = 10 to 1 tested of the present case for Mach number M = 0.9. Figs. 2(a) to (b) present the results for L/D = 10 and 8 from the figures it is seen that the wall pressure is influenced by the micro jets in the base region for initial twenty percent length of the duct, and the wall pressure values for with and without control cases remains the same. It is also, seen that the oscillatory nature in the flow starts in the vicinity of the base region extending up to the duct length location at x/L = 0.2. The reasons for this behavior may be due to the flow being correctly expanded, therefore, the shear layer coming out from the nozzle is influenced by the relaxation available to the flow due to high area ratio, which; in turn forms expansion waves in the base region. Therefore, when the flow is coming out of the nozzle will have a tendency to deflect away from the base, under such conditions, when the micro jets are activated the micro jets are bound to entrain some mass from the base region. It is also, seen that the magnitude of the wall pressure is fluctuating in the base flow region mainly due to the presence of the waves as it is visible in Figs. 2(a) and (b) for L/D ratio = 10 and 8. It is also seen that once the flow has crossed twenty percent length from the exit of the nozzle the flow in the downstream becomes very smooth and also free from the waves.

Figs. 2(c) to (d) present the wall pressure results for L/D = 6 and 5. The wall pressure behavior in these figures is different from the previous figures. From x/L = 0.0 to 0.2 the wall pressure maintains constant value of around 0.88; then there is a jump in the duct wall pressure value at the non-dimensional location of x/L = 0.28, further, downstream waves are not seen in the flow and the flow development in the enlarged duct is smooth, it is also seen that the flow field with and without control remains the same for both the cases, the reason for this trend could be due the value of the Mach number M = 0.9, which; is in the proximity of sonic Mach number, when this flow is coming out from the nozzle experiences sudden increase in the area ratio which will result in further expansion of the flow, under such conditions flow will undergo expansion, reflection from the enlarged duct wall, and the recombination; these may be the reasons for this behavior.

Fig. 2(e) presents wall pressure results for L/D = 4. It is seen that the wall pressure values show waviness till the duct location x/L = 0.2, and in the downstream the flow develops smoothly and recovery in the wall pressure is fast. The reasons for this oscillatory nature in the wall pressure flow field may be due to the reduction in the duct length, which; in turn will influence the base flow, and the back pressure too will try to modify the flow field, under these conditions when the micro jets are activated the flow field is strongly influenced. The wall pressure results for L/D = 3 are shown in Fig. 2(f), from the figure it is seen that wall pressure value has marginally increased from the previous L/D ratio and remains constant till x/L = 0.4, and later the flow proceeds downstream with smooth recovery in the wall pressure. Similar results are seen in Fig. 2(g) to (h) for L/D = 2 and 1, these results clearly indicate that this length of the duct is not sufficient for the flow to be attached with the suddenly expanded wall hence; the flow from the nozzle will behave as a free jet.

Results for Mach number M = 0.8 are presented in Figs. 3(a) to (h) for all the L/Ds of the present case. Figs. 3(a) to (b) presents the results for Mach number M = 0.8; for L/D = 10 and 8, these results are on the similar lines as we have discussed earlier for Mach number M = 0.9. The only difference in the present case and the previous case, that there is decrease in the inertia value due to the reduction in the Mach number from 0.9 to 0.8, which means that the inertia value has decreased. It is also seen from the figures that the oscillations are completely suppressed, at x/L = 0.2, there is small jump the wall pressure this may be due the presence of a shock wave at the reattachment point, and the influence of the back pressure, resulting in increase in the initial value of wall pressure. In the downstream the development of the flow field is smooth. Figs. 3(c) to (d) presents the results for Mach number M = 0.8; for L/D = 6 and 5, these results are on the similar lines as we have discussed earlier for Mach number M = 0.9 except a small difference. Figs. 3(e) to (f) presents results for L/D = 4 and 3. It is seen that the trend is almost identical to that of Fig. 2(e) and (f) with the exception that the magnitude of wall pressure is marginally increased as compared to that of for Mach number M = 0.9. Here, also it is seen that the value of the wall pressure for initial three taps is constant then there flow shows waviness; later the flow development is very smooth, and the values of wall pressure for with and without control are same which indicates that the flow field is undisturbed. Figs. 3(g) to (h) show the results for L/D = 2 and 1, it is seen that for both the L/D = 2 and 1, the wall pressure assumes very high value for the initial first tap itself, which; shows that the flow is no more attached with the duct wall and it behaves as free jets without getting influenced by the base region as well as the micro jets.

The wall pressure distribution for Mach number M = 0.6 are presented in Figs. 4(a) to (h) for L/D = 10, 8, 6, 5, 4, 3, 2 and 1, respectively. Figs. 4(a) to (b) present the results for L/D = 10 & 8. If we compare these results with those for earlier two Mach number M = 0.9 and 0.8, it is found that due to the decrease in the Mach number, the wall pressure has achieved very high value almost that of the atmospheric pressure from very first tap itself, it is a quite different phenomena is taking place, it further shows that the strength of the vortex is very weak which; is unable to create any suction at the base. The micro jets are unable to influence the duct wall flow field at all. As far as results for L/D = 8 are concerned they exhibit the similar trends as it was found for higher Mach number. It is seen that the oscillation are limited to x/L = 0.1 and the amplitudes are very low, but it does contain few peak value of wall pressure. The reasons for this behavior may due to the decrease in the Mach number of the flow, which; has reduced the inertia of the flow significantly. Hence, for the same area ratio the level of expansion causing the formation of shock wave or expansion fan at the nozzle lip will have a strong effect on the wall pressure. These results imply that the flow field is sensitive to the level of expansion, inertia available at the nozzle exit and the relief available at the expanded plane.

Figs. 4(c) to (d) presents the wall pressure results for L/D ratios = 6 and 5. Here, again there is about 20 percent increase in initial value of the wall pressure as compared to Mach number M = 0.8. From the figure it is observed that a shock is positioned at x/L = 0.35 due to which the wall pressure has increased by 10 percent and then for the next wall pressure tap it has come down to the initial value. Figs. 4(e) to (h) presents the results for L/D = 4, 3, 2, and 1, from these figures it is seen that the wall pressure has almost equal to the atmospheric pressure which; means that for such low level of inertia base vortex is unable to influence the base region and more so, the flow is not attached with the duct for L/D = 4 onwards, the wall pressure flow field is no more attached with the duct wall for these cases, and the jet behaves as free jet.

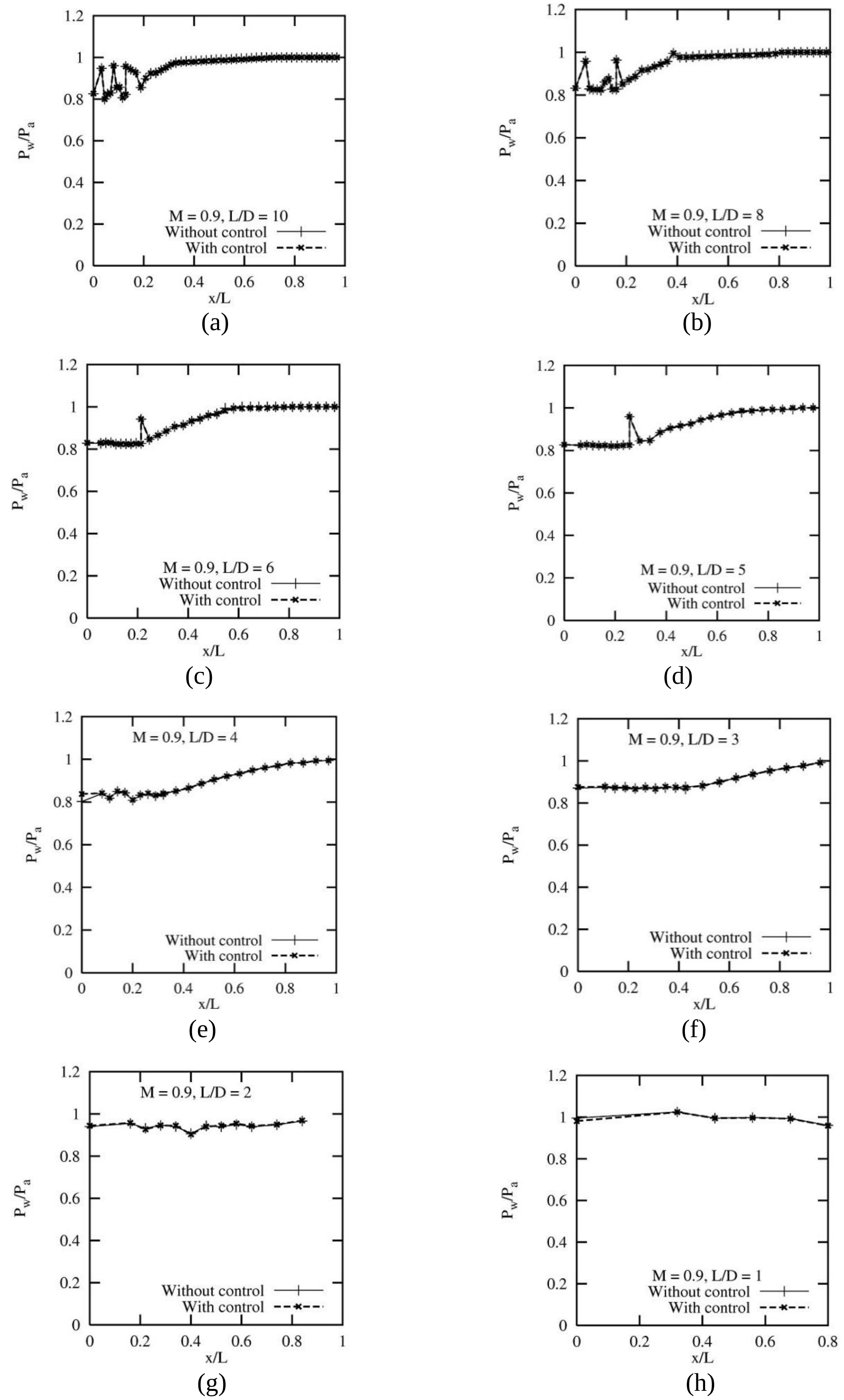
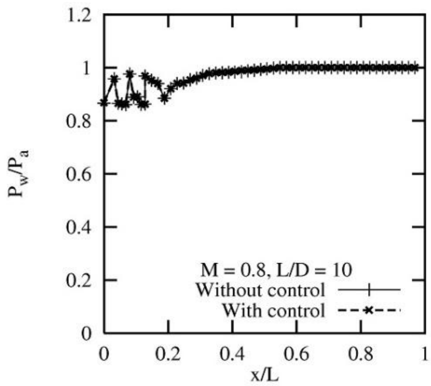
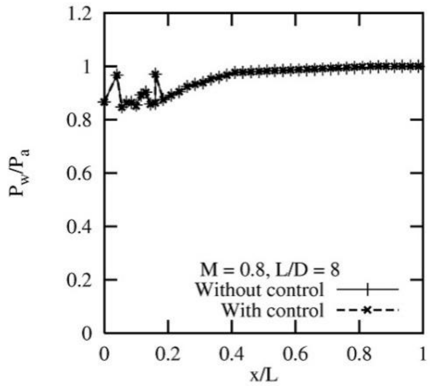


Fig. 2: Wall Pressure Distribution



(a)



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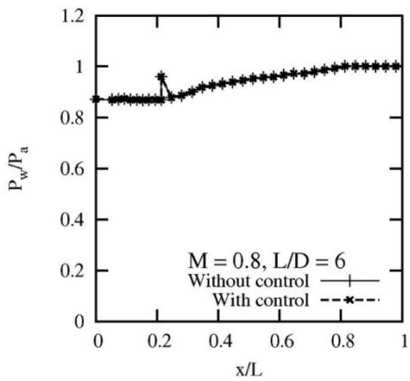
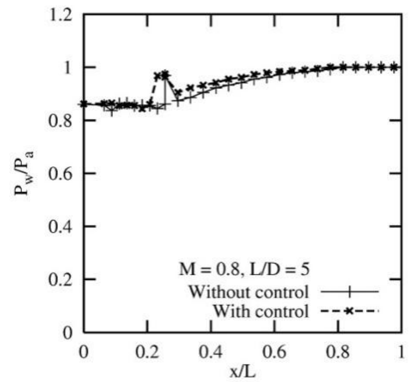


(c)



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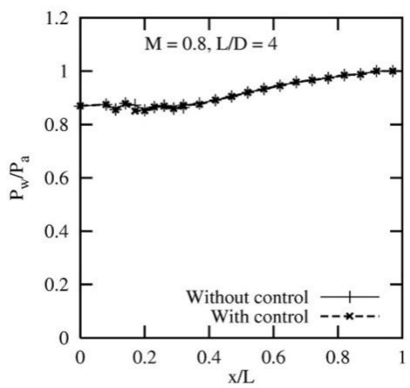
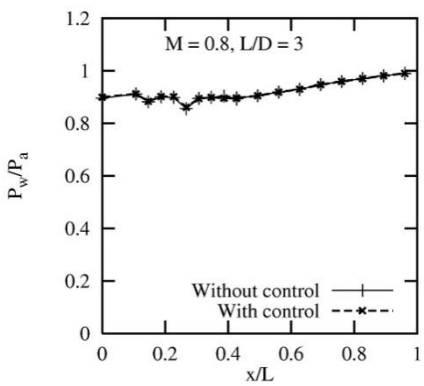


(e)



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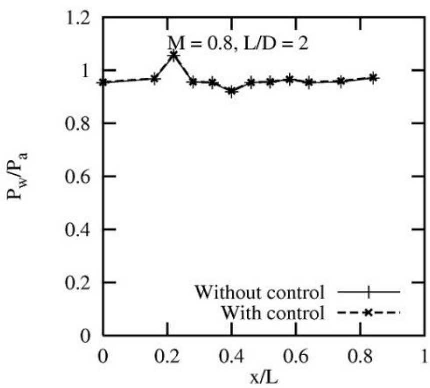
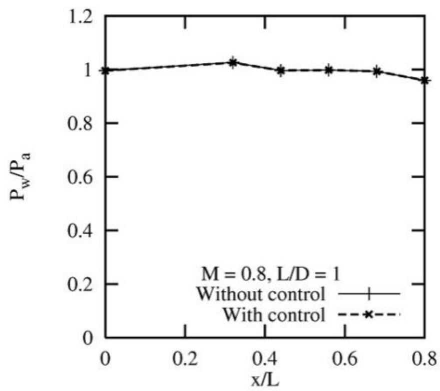
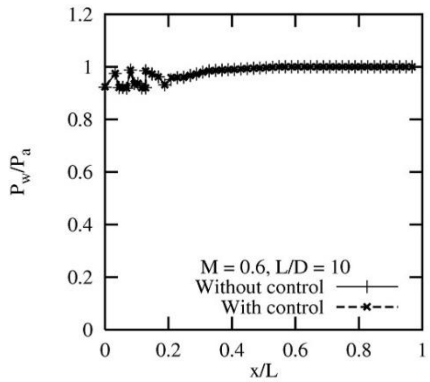


(g)

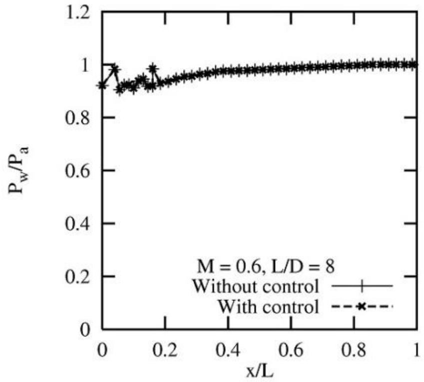


(h)

Fig. 3: Wall Pressure Distribution



(a)



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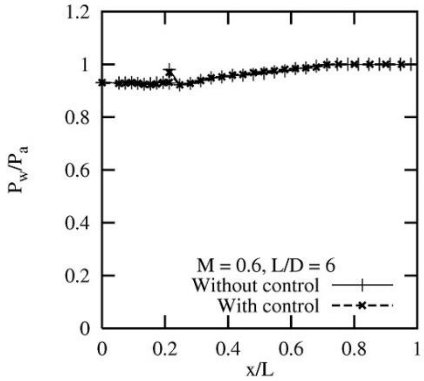

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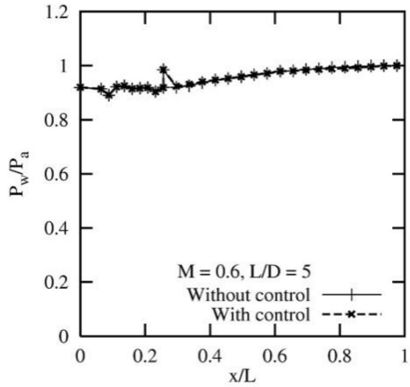

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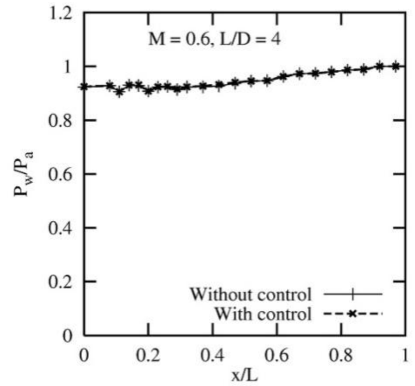

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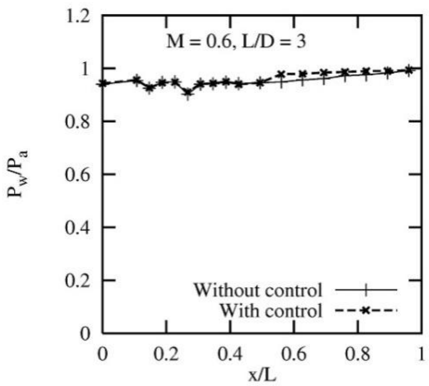
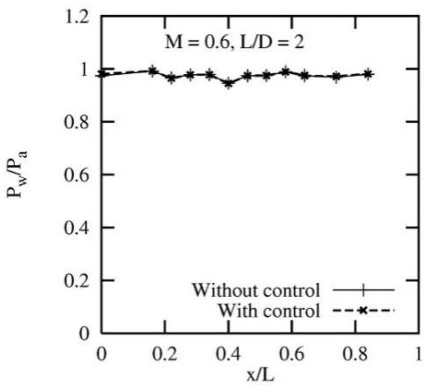
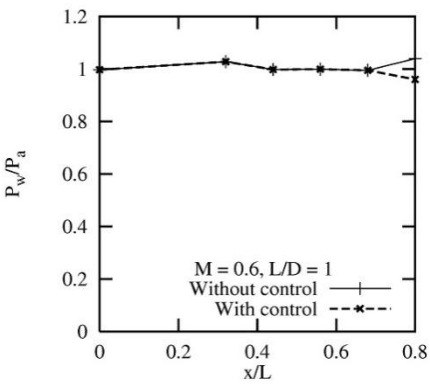


(f)



(g)



(h)

Fig. 4: Wall Pressure Distribution

CONCLUSION

From the above results the following conclusions can be drawn:

- The flow field in the wall duct is dominated by the waves, however, their amplitude has reduced significantly due the additional relief available to the flow.
- It is seen that the reflection of the waves from the wall, recompression and recombination's are taking place in the base region of the duct wall within the twenty percent length of the duct wall.
- From the results it has been demonstrated that the flow from the nozzles with correct expansion is not free from the waves as it can be seen from the suddenly expanded duct flow field.
- The flow field is oscillatory within the reattachment length; later the development of the flow and the wall pressure recovery is very smooth. This happens mostly for L/D = 10, 8, 6, and 5 only.
- With the gradual decrease in the Mach number, results in decrease in the inertia value; which in turn results in increase in the magnitude of the wall pressure for all the L/Ds of the present study.
- The minimum duct length requirement seems to be L/D = 4 for the parameters of the present study.

From the above discussion it is observed that the control has got no adverse effect on the suddenly duct wall flow field. With this it can be taken that the micro jets can serve as base pressure controller without imposing any adverse effect in the suddenly expanded duct flow field. All the non-dimensional wall 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.

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