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Experimental Investigation of Flow through Convergent Nozzle and Influence of Micro Jets on the Enlarged Duct Flow Field

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Abstract

Airflow from convergent axi-symmetric nozzle expanded suddenly into circular duct of larger cross-sectional area than that of nozzle exit area were studied experimentally, focusing attention on the wall pressure and the flow development in the enlarged duct. The flow parameters considered in this investigation are the Mach number at the nozzle exit and the nozzle pressure ratio. The geometrical parameters considered are the area ratio between the sudden expansion duct cross-section and the nozzle exit area and the length-to-diameter ratio of the duct. In the present study micro jets were used to investigate the effect of micro jets on the flow field in the suddenly expanded duct. An active control in the form of four micro jets of 1 mm orifice diameter located at 90^0 intervals 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 4.84. 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, it is proved that the correctly expanded flow is dominated by waves; also, it is found that for L/D in the range L/D = 10 and 8 the flow remains oscillatory mostly 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.

Keywords: Area ratio, Wall pressure, Micro jets, Mach number

1. 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. It is well known that the pressure at the base of high-speed projectiles is lower than the ambient pressure, and the manner in which most ballistics test data have been presented would lead one to the conclusion that the base pressure ratio is only a function of the flight Mach number. The experimental study of sudden expansion with internal flows has the following advantages over the external flows. Firstly the volume of air supply needed is greatly reduced by eliminating the need for tunnel with large enough cross-section so that the wall interference will not disturb flow over the model. Secondly, also, the 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.

Comparison of External and Internal flows. The first factor is that there are wall shear stresses acting on the wake and the re-attached boundary layer in the internal flow apparatus, and there are no equivalent shear stresses in the external flow. The second and possibly more important factor is that internal flow upstream of the sudden expansion is invariably accompanied by severe pressure gradients, if the approach section has parallel walls, while the pressure gradients along the cylindrical portion of the projectile is usually very small. The third factor is that the jet boundary will be intersected by Mach lines (expansion lines) originating at the opposite corner, which is not the case in external flow.

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.

2. 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. Kruiswyk and Dutton [2] 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 un-modified 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 co-efficient 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. [3]-[5]. 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. They presented the results of experimental studies to control the base pressure from a convergent nozzle under the influence of favourable pressures gradient at sonic Mach number. 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. They concluded that, unlike passive controls the favourable pressure gradient does not ensure augmentation of the control effectiveness for active control in the form of micro jets. 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.

3. EXPERIMENTAL SETUP

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 1, 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 main settling chamber with the control 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 figure 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.

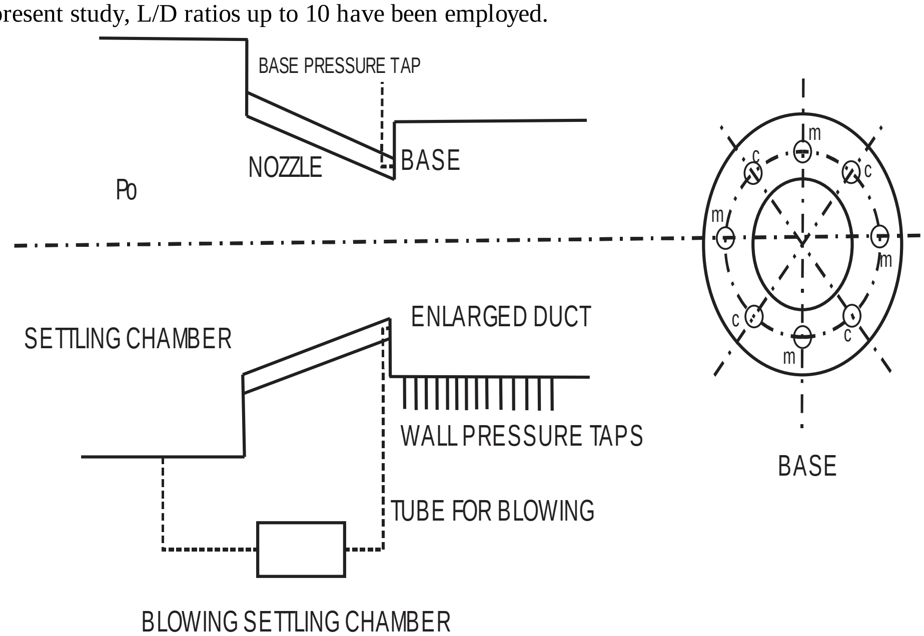

Figure 1 Experimental setup

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 (i.e. 10 mm) and the area ratio of the model was 4.84 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, the stagnation pressure in the main settling chamber and the pressure in the control 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° Celsius and 95 per cent humidity.

4. 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 for L/D 10 to 1 for correctly expanded case at Mach number M = 0.9. Figs. 2(a) to (b) present the results for L/D = 10 and 8 and from the figure it is seen that there is a marginal influence on the wall pressure field 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 and this oscillatory nature starts in the vicinity of the base region extending up to the duct length x/L = 0.2. Since, the flow is correctly expanded; therefore, the shear layer which is coming out from the nozzle is influenced by the additional relaxation available to the flow due to the sudden increase in the area ratio, which in turn forms expansion waves, and further downstream in the flow, the base vortex is unable to create the suction in this case, since the level of expansion is unchanged. Therefore, flow coming out of the nozzle will have a tendency to deflect away from the base, and under such conditions, when the micro jets are activated the micro jets are bound to influence the base region. It is also, seen that the magnitude of the wall pressure is fluctuating due the presence of the waves in the flow region, however, the magnitude is small due to additional relief available to the flow. Hence, we can say that the correctly expanded flows will be wave dominated as it is reflected in Figs. 2(a) and (b) for L/D ratio = 10 and 8. It is also seen that once the flow has crossed the reattachment point the flow in the downstream expands smoothly and the waves from the wall duct have disappeared. 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 0.8; then there is a jump in the duct wall pressure value at the non-dimensional location at x/L = 0.25, and thereafter at the later stage waves are not seen in the flow and the flow expands smoothly resulting in the increased wall pressure, it is also seen that the flow field with and without control remains the same for both the cases. Results for L/D = 6 and 5 have once again proved that the correctly expanded flows are wave dominated, the reason for this trend could be that we are considering the flow Mach number M = 0.9, which; is very close to sonic Mach number, when this flow is coming out from the nozzle experiencing sudden increase in the relaxation which will result in further expansion of the flow, the flow will undergo, expansion, reflection from the duct wall, and recombination; these may be the reasons for this trend. Fig. 2(e) presents wall pressure results for L/D = 4. It is seen that the wall pressure values are constant till x/L = 0.2, later there is small kink and small jump in the wall pressure; further, downstream of the flow becomes smooth and recovery of wall pressure is progressive. The reasons for this non-oscillatory behavior of the wall pressure flow field may be due to the reduction in the duct length, the effect of the back pressure to the base flow field and ineffectiveness of the base vortex positioned at the base. The wall pressure results for L/D = 3 are shown in Fig. 2(f), from the figure it is seen that wall pressure values have marginally increased and remained constant till x/L = 0.3, later in the flow there are small fluctuations in the wall pressure flow field and later wall pressure recovery is smooth. Similar results are seen in Fig. 2(g) to (h) for L/D = 1 and 2, these results clearly indicate that this length of the duct is not sufficient for the flow to be attached with the duct wall, hence; the flow from the nozzle behaves as a free jet.

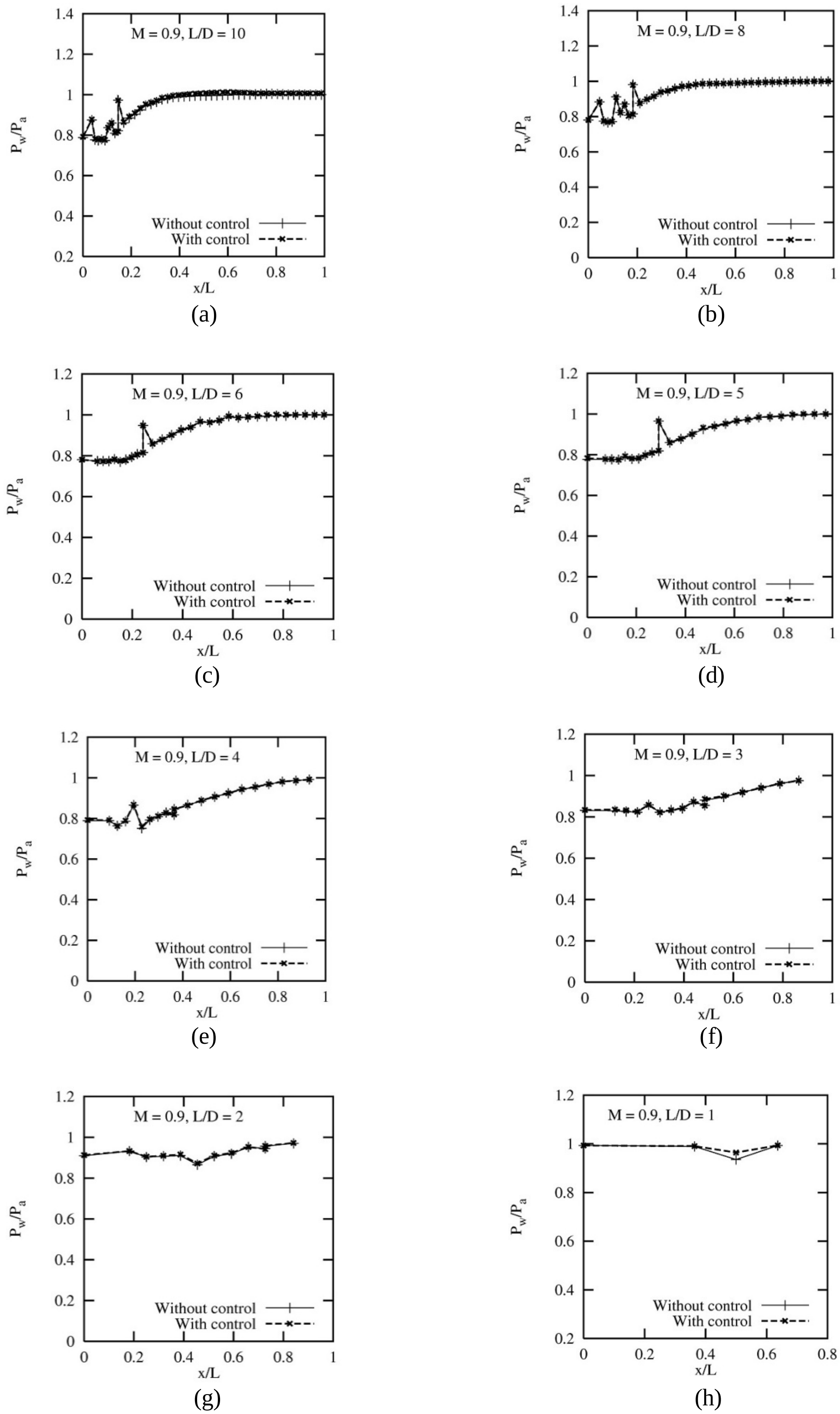

Figure 2 Wall pressure distribution

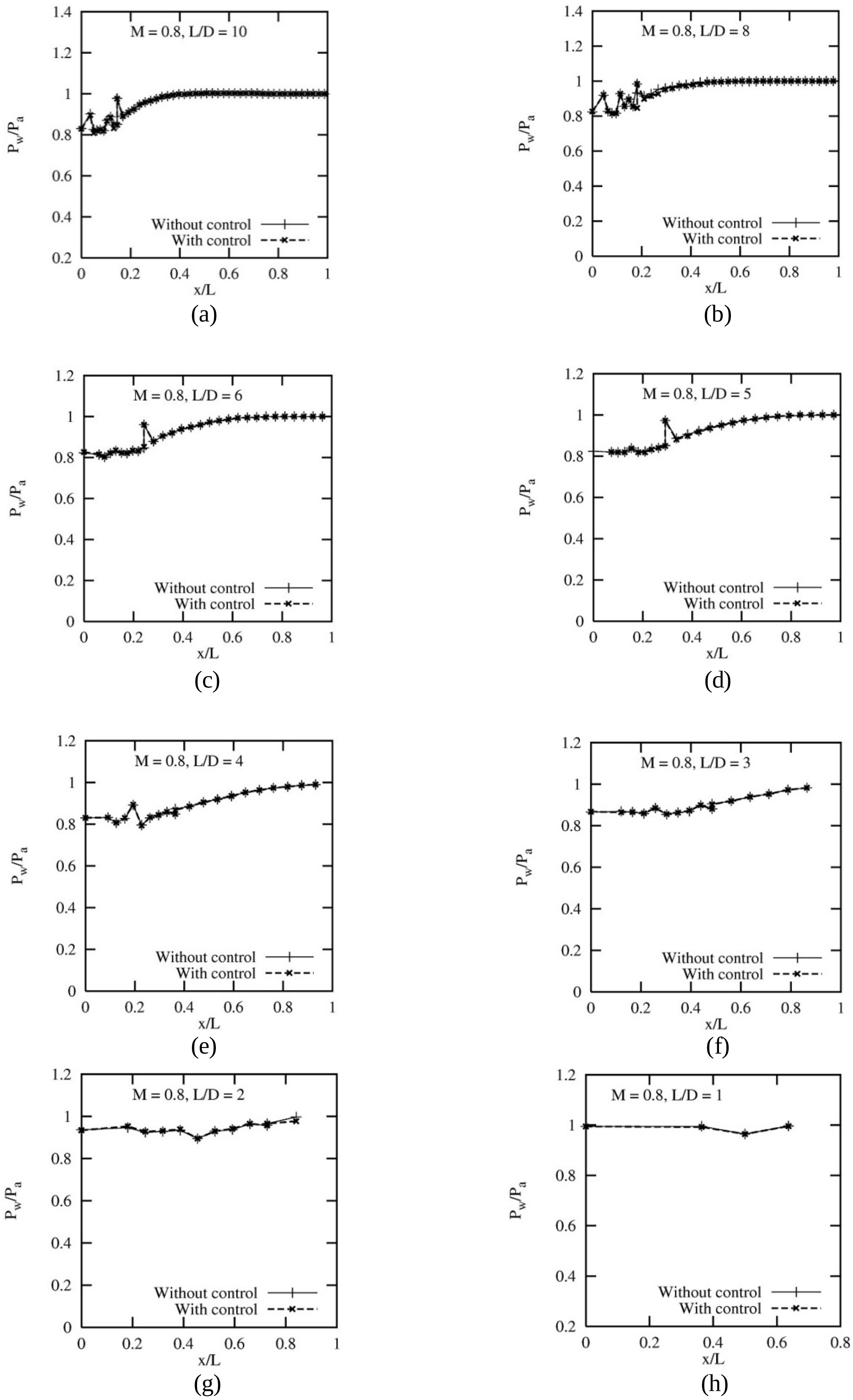

Figure 3 Wall pressure distribution

Results for Mach number M = 0.8 are presented in Figs. 3(a) to (h) for all the L/Ds. Figs. 3(a) to (d) and the results presented for Mach number M = 0.9; for L/D 10 and 8 are on the similar lines. The only difference in the present case and the previous case, that there is decrease in the Mach number from 0.9 to 0.8, which means that there is a slight decrease in the inertia value resulting in vortex at the base. It is also seen from the figures that the oscillations are suppressed significantly, and the domain length of flow oscillation in the duct is limited to x/L = 0.2, this may be due the decrease in the inertia, resulting in increase in the initial value of wall pressure, and with increased relief when micro jets are activated they flow downstream without much affecting the flow in the base region. Once, the flow has crossed forty percent duct length from the nozzle exit the flow development is smooth. 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 due to the reduced inertia level. It is seen that the value of the wall pressure for initial three taps is constant, and then there is a smooth increase; later the flow develops smoothly, the values of wall pressure for with and without control are same which indicates that the flow field is undisturbed due to the presence of the control in the form of micro jets. 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 wall pressure tap itself, which; shows that the flow is no more attached with the duct wall and once again; it behaves as free jets without getting influenced by the vortex at 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 substantial decrease in the Mach number, the wall pressure has achieved a high value almost as the atmospheric pressure after first tap itself, these results show totally different behavior, which; means that the strength of the vortex has reduced considerably thereby vortex is unable to create substantial suction which otherwise it was able to create high base suction for higher Mach number as the area ratio is kept constant. This may be the reason that the micro jets are not able to influence the duct wall flow field at all with the decrease in the Mach number. 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 = 0.2 and the amplitudes of the oscillation are very low. The reasons for this behavior may be the same as discussed earlier. 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. Fig. 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 wave 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) and (f) presents the results for L/D = 4 and 3, from the figure it is seen that there is an increase in the initial value of the wall pressure and the flow has become non-oscillatory as compared to the results for same L/D for higher Mach numbers. The wall pressure is almost equal to the atmospheric pressure which; means that for such low level of inertia base vortex is unable to influence the base region at all and the flow is not attached for the L/D = 3 and beyond. From the Figs. 4(f) to (h) it is clearly visible that the flow is no more attached with the duct wall for these cases, the jet behaves as free jet.

5. CONCLUSIONS

From the above results we can draw the following conclusions:

- The flow field in the wall duct is dominated by the presence of the waves.
- 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, thereby making the flow oscillatory.
- From the results it has been demonstrated that the flow from the nozzles with correct expansion is not free from the waves as this has been witness from the wall pressure flow field of the suddenly expanded duct.
- It is found that the flow field is oscillatory within the reattachment length region; 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 for all the Mach numbers of the present test.
- It is found that with the decrease in the Mach number, which; results in decrease in inertia value, results in increase in the magnitude of the wall pressure for all the L/Ds of the present study.
- The minimum duct length requirement for the flow to be attached with the duct wall seems to be L/D = 3 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 values presented in this paper are within an uncertainty band of ± 2.6 per cent. Further, all the results are repeatable within ± 3 per cent.

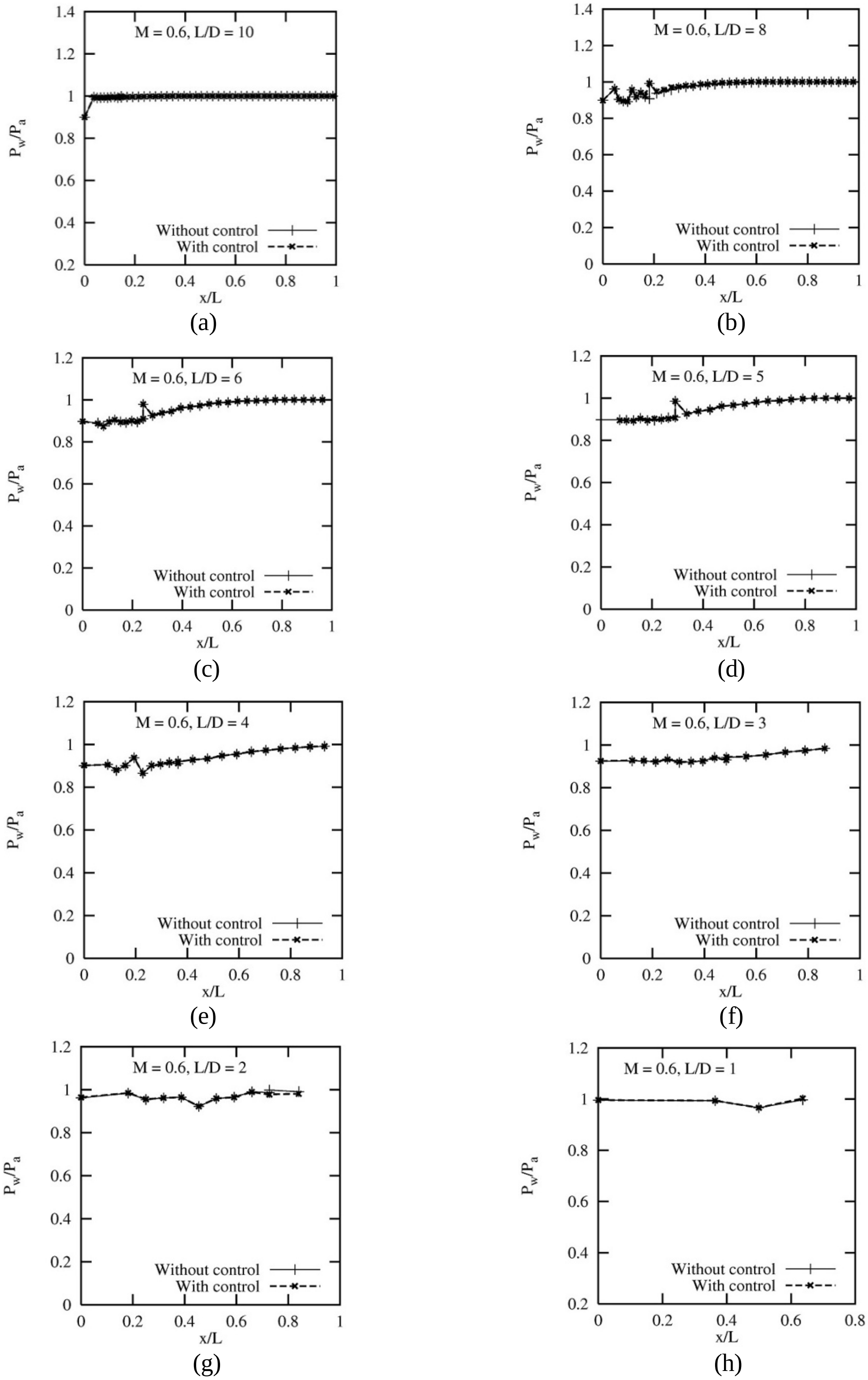

Figure 4 Wall pressure distribution

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