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The Effect of Micro Jets on Wall Pressure for Sonic Under Expanded Flow

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ABSTRACT
This paper presents the experimental results on the flow characteristics of a suddenly expanded flow from the convergent nozzle for sonic under expanded case. In the present study micro jets were used to investigate the wall pressure 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 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 length-to-diameter (i.e. L/D) ratio of the sudden expansion duct was varied from 10 to 1. To study the effect of micro jets on the quality of flow in the enlarged duct wall pressure was measured and from the results it is found that the micro jets do not disturb the flow field in the duct. From the results, it is also seen that for L/D in the range L/D = 10 and 8 the flow remains oscillatory mostly for all the area ratios. However, these oscillations are suppressed gradually with the increase in the area ratio, also for all the L/D in the range 3 to 6. The nozzle pressure ratio (NPR) was varied from 1 to 3, however, in the present paper results are presented for under expanded case to ascertain the effectiveness of the micro jets under the influence of favorable pressure gradient (i.e. $P_e/P_a = 1.5$). The present study explicitly reveals that, the wall pressure in a suddenly expanded axi-symmetric duct can be controlled by employing micro jets.

Keywords**-** Area ratio, Length-to-diameter ratio, Micro jets, Sudden expansion, Wall pressure

I. INTRODUCTION

Many scientists in the research area of ballistics have long been concerned with the problem of sudden expansion of external compressible flow over the rear of projectiles and its relationship with the base pressure, since the base drag, which is a significant portion of the total drag is dictated by 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 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. Because of its vide applicability, suddenly expanded flows have been studied extensively. Many researchers attempted to control the base pressure with passive control and some of the successful works are reviewed in the literature survey. Therefore, in the present study an attempt is made to investigate the base pressure control with active control in the form of micro-jets and its effect on wall pressure.

In view of the developments in space flights and missile technology worldwide by all the developed nations as well as few developing countries, the base flows at high Reynolds numbers continue to be an important area of research. It is well known that the base pressure and consequently the base drag at transonic speed could be as high as 50 percent of the total drag during the jet off conditions, however, during the jet on (or power on) mode the effect of base suction will be negligible as the pressure at the base will be very high. Hence, if we are interested to control the base pressure and ultimately the base drag in case of blunt based projectiles and by doing so this would lead to significant increase in the range of the missiles or projectiles, and it will be of great help for defense applications. Presently the world is facing the energy crisis and any decrease in the value of the base drag will be a welcome step. Since, we have reached to a saturation stage as far as the optimization in skin friction drag and wave drag are concerned, there, is not much scope for further investigation is left and controlling the base pressure is the only area left to explore, hence, this study was undertaken to control the base pressure with micro jets. The prime objectives in this study are to control the base pressure, to have smooth development of the flow without oscillations in the duct, to minimize the total pressure loss; the studies are conducted keeping these features in mind. When we scan the literature available it is found that scientists have made attempts to control the base pressure by various passive means, like; ribs, base cavities, ventilated cavities at the blunt base, splitter plate, vortex locked device, stepped base, boattailed bases, and so on. Hence, in the present study the experiments were conducted to control the base pressure as well as the flow development in the enlarged duct was measured to ensure that there is no negative effect of the control on the flow field of the duct. It is well known that whenever either passive or active controls are used in the case of sudden expansion it mandatory on the part of researchers to ensure that the flow field in the enlarged duct is not aggravated and the flow field with and without control are identical.

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 and the features of sudden expansion flow field are shown in Fig. 1.

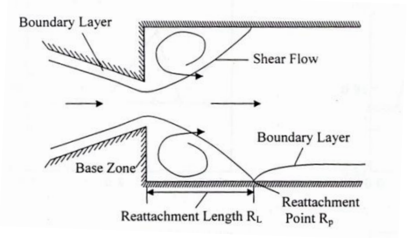


Figure 1: Sudden expansion flow field

II. LITERATURE REVIEW

Wick [1] investigated experimentally the effect of boundary layer on sonic flow through an abrupt cross-sectional. 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. A two-dimensional configuration has been investigated in which air flows through a convergent nozzle and expands abruptly into a rectangular duct of larger cross-section which terminates in a plenum chamber. Kidd et al. [2] conducted Free-flight tests of spin-stabilized projectiles and fin-stabilized missiles with various stepped, flat and boattailed bases at subsonic, transonic and supersonic Mach numbers. They got the results which indicate that sub sonically the addition of a stepped base can significantly reduce the aerodynamic drag over that a flat base. Viswanath P. R. [3] investigated experimentally the zero-lift drag characteristics of multi-step after-bodies that utilize the concept of controlled separated flows at transonic and supersonic speeds. The important geometrical parameters affecting the drag of such after-bodies were identified, and their effects were examined through a parametric study. Their results show that multi-step after-bodies can be design that provide significant total drag reduction (as high as 50 per cent) compared to (unmodified) blunt bases; however, compared to axi-symmetric boattailed after-bodies of a given base area, the multi-step after-bodies have relatively higher drag. Finally, the certain flow features involving separation and reattachment on multi-step after-bodies were discussed based on flow visualization studies. Khan and Rathakrishnan [4-8] 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. An experimental study has been conducted by Lovaraju P. et al. [9] to investigate the effectiveness of passive controls in the form of small tabs and a cross-wire projecting normally into the flow at the nozzle exit, on the characteristics of an axi-symmetric sonic jet operated at three under expansion levels. Their investigation on the effectiveness of cross-wire and tabs on the under expanded sonic jets shows that, both the passive controls are effective in reducing the axial extent of supersonic core significantly. Also, both the controls render the symmetric shock-cell structures unsymmetrical and weaker, all along supersonic core. The cross-wire/tab controlled jets grow wider in the direction normal to the cross-wire/tab at all the operating conditions. However, the tabbed jets grow much wider compared to the cross-wire controlled jets. Shafiqur Rehman and Khan [10] presented the results of an experimental investigation carried out to control the base pressure in a suddenly expanded axi-symmetric passage. They used four micro-jets of 1mm orifice diameter located at 90° interval along a pitch circle diameter of 1.3 times the nozzle exit diameter in the base region was employed as active controls. The test Mach numbers were 1.25, 1.3, 1.48, 1.6, 1.8, 2.0, 2.5 and 3.0. The jets were expanded suddenly into an axi-symmetric tube with cross-sectional area 4.84 times that of nozzle exit area. The length-to-diameter ratio of the sudden expansion tube was varied from 10 to 1. Nozzles generating the above jet Mach numbers were operated with nozzle pressure ratio in the range 3-11. As high as 40 per cent increase in base pressure was achieved. In addition to base pressure, the wall pressure in the duct was also measured. From their experiments, it was found that the wall pressure was not adversely influenced by the micro jets. Baig et al. [11] conducted the experiments to assess the effect of Mach number on base pressure and control effectiveness in a suddenly expanded duct. From the experiments they found that for the given area ratio the base pressure increase with Mach number. The effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts is studied experimentally by Ashfaq et al. [12]. 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. Ashfaq and Khan [13-15] 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.

III. EXPERIMENTAL METHOD

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 Fig. 2, 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/wall 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. 2) 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.

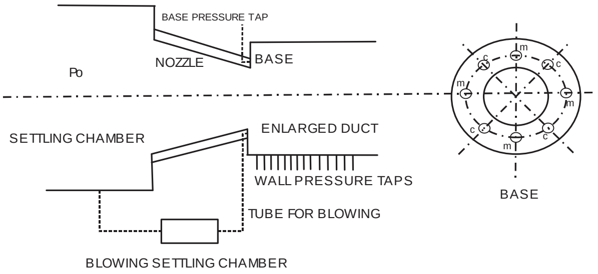


Figure 2: Experimental setup

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 2.56, 3.24, 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 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 and the stagnation pressure in the settling 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° and 95 per cent humidity.

IV. 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. Hence, additional source of energy for micro jets as an active control is eliminated.

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. These oscillations are reflected as variation in the wall pressure distribution of the enlarged duct. Therefore, it becomes mandatory on the part of a researcher working on sudden expansion problems to monitor wall pressure distributions in the enlarged duct. In other words when we employ a control to modify the base pressure level, there is a possibility that the control might augment the oscillatory nature of the flow field in the enlarged duct. To account for this undesirable effect (aggravating the oscillatory nature of the flow field) wall pressure distribution in the enlarged duct was measured for all combination of parameters of the present investigation. 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.

Figures 3(a) to (h) present the wall pressure distribution in the enlarged duct for area ratio 2.56, for L/D 10 to 1 for under expanded case. It is well known from the literature that whenever favorable pressure gradient is present the control in any form either active or passive they become very effective. From the figure it is seen that there is some influence on the wall pressure field in the base region and the wall pressure values with and without control remains the same and this oscillatory nature starts in the vicinity of the base region extending up to x/L = 0.2. Since, the flow is under expanded; therefore, the shear layer which is expanding freely from the nozzle is strongly influenced by the expansion waves standing at the nozzle exit. Therefore, flow coming out of the nozzle will have a tendency to deflect towards the shock, under such circumstances, when the micro jets are activated the entrainment of the micro jets is bound to carry some mass from the base region. It is also, seen that the magnitude of the wall pressure has come down due to the expansion of the flow after exiting into enlarged duct and these results were expected. Once the flow has crossed the reattachment point the flow in the downstream becomes smooth.

Fig. 3(b) presents wall pressure distribution results for L/D = 8. Here, again the wall pressure is highly oscillatory not only within reattachment length but, beyond that point, which starts from the leading edge and continue up to x/L = 0.5. As these figures present results for the lowest area ratio of the present study, hence, the reattachment length will have the minimum value. The reason for this oscillatory nature of the flow may be due the short reattachment length, where as the inertia level is high, and the duct length is getting reduced resulting in reduced suction at the base region. Further, it may be stated that for the L/Ds in the range 10 to 8, the influence of the back pressure will be the minimum.

Figs. 3(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. At x/L = 0.2 there is a smooth increase in the wall pressure and later in the downstream the wall pressure recovery is smooth, it is also seen that the flow field with and without control remains the same. Results for L/D = 4 are shown in Fig. 3(e), from the figure it is seen that wall pressure values for the initial pressure taps has come down, the oscillations and sudden jumps which were seen for the higher L/Ds are absent, however, a smooth increase in the wall pressure is seen at the end of the reattachment point and later in the downstream of the duct the flow is developed smoothly.

Similar results are seen in Fig. 3(f) for L/D = 3, the only difference in the results for L/D = 3 with that of for L/D = 4, is that wall pressure has become slightly oscillatory in nature and when micro jets are activated the control effectiveness is getting reversed at x/L = 0.2 and 0.4. The reason for this nature may due the presence of expansion fan at the nozzle lip as well as the influence of back pressure due the short duct length. Wall pressure results for L/D = 2 are shown in Fig. 3(g), from the result it is seen that there is a jump in the wall pressure for x/L = 0.2 and beyond, this happens to be the edge of the reattachment point, which implies that for short duct the flow is exposed to atmospheric pressure which is affecting the flow development in the duct. For L/D = 1, the results are shown in Fig. 3(h) these results clearly indicate that this length of the duct is not sufficient for the flow to be attached with the duct.

Results for area ratio 3.24 are presented in Figs. 4(a) to (h). For this area ratio the relief available to the flow is slightly more than what it was for area ratio 2.56. Hence, the level of expansion causing the formation of expansion fan at the nozzle lip will have a strong effect on the base pressure as well as on wall pressure and its control effectiveness. Results presented by Figs. 4(a) to (b) are on the similar lines as we have seen for area ratio 2.56 for L/D 10 and 8. This is because when the free shear layer expanding into the suddenly expanded passage finds additional relief, it reattaches downstream of the reattachment point as compared for lower area ratios. This increase in reattachment length helps in modifying the flow field in the base region; in turn the flow is able to suppress the oscillations marginally, which were there for lower area ratio and 16 percent increase in the wall pressure is achieved. Figs. 4(c) to (d) presents results for L/D = 6 and 5. It is seen that the trend is almost identical to that of Fig. 3(c) and (d) with the exception that the magnitude of wall pressure is more compared to that of for area ratio 2.56. For area ratio 2.56 the reattachment length will be small compared to area ratio 3.24 this will lead to the formation of larger reattachment for the same inertia and the same vortex strength at the base causing high wall pressure and this increase in the wall pressure is 16 percent. It is also seen that for L/D = 6 (Fig. 4(c)) there is jump in wall pressure due to the presence of shock wave at the dividing stream line. Similarly, in Fig. 4(d) for L/D = 5, it is seen that the strength of the shock wave has marginally increased and when micro jets are activated, they result in increase of wall pressure within the reattachment length. This may be due to the influence of the shock at nozzle exit which turns the flow away from the base region, thereby weakening the vortex positioned at the base. This result in increase of wall pressure since the weakened vortex at the base encounters the mass flow injected by the micro jets will result in higher value of wall pressure.

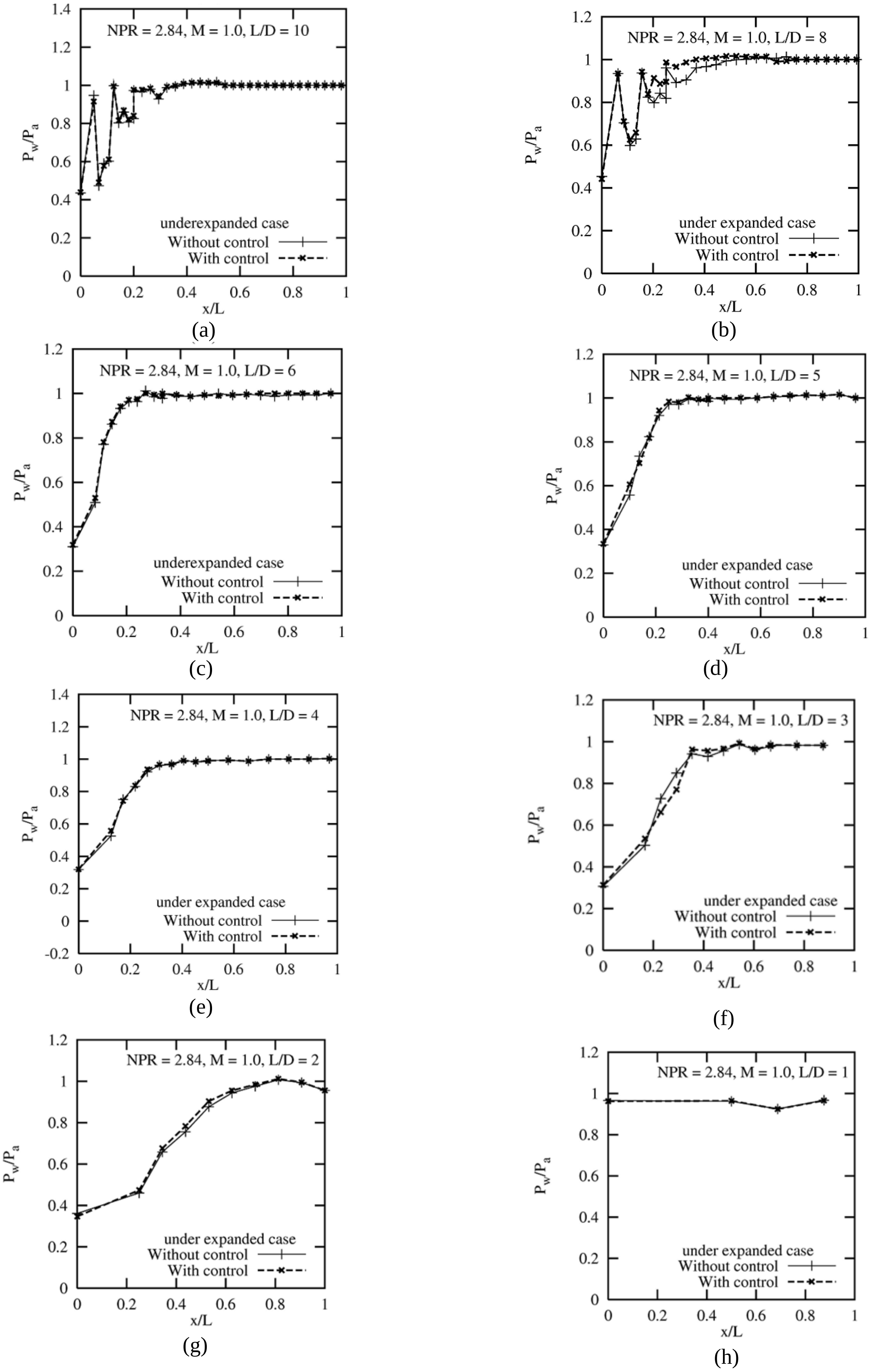
Figs. 4(e) to (f) show the results for L/D = 4 and 3, here again we see the similar results as that of for area ratio 2.56 with initial increase in the value of the wall pressure since for the initial taps which are within the base region, and 33 percent increase in the wall pressure is achieved for L/D = 4 & 3. For this particular L/D the major contributor is the influence of atmospheric pressure as well as the entrainment of the flow from the surrounding area and due to the turbulent mixing. For L/D = 2 and 1, the results are shown in (Fig. 4(g) to (h)). From the figure it is seen that for L/D = 2 (Fig. 4(g)) the wall pressure assumes very high value, which; shows that the flow is no more attached with the wall. Results for L/D = 1 are shown in Fig. 4(h) since flow is not attached at L/D = 2, then for L/D = 1 it is automatically detached.

The wall pressure distribution for area ratio 4.84 are presented in Figs. 5(a) to (h) for L/D = 10, 8, 6, 5, 4, 3, 2 and 1, respectively. Figs. 5(a) to (b) present the results for L/D = 10 & 8. If we compare these results with those for area ratio 3.24, it is found that due to the increase in the area ratio there is increase in the wall pressure of around 30 percent, also, it is seen that the oscillations in the base region are there but there is definite reduction in the magnitude as well as the wave length. The reasons for this behavior may that for this area ratio the relief enjoyed by the suddenly expanded flow is much more than what it was for area ratio 3.24. Hence, for the same level of expansion causing the formation of shock or expansion fan at the nozzle lip will have a strong effect on the wall pressure as well as its control effectiveness. These results imply that the flow field becomes sensitive to the relief effect at the expanded plane. However, it should be realized that increase of area ratio beyond certain limiting value will not ensure the effects mentioned above for suddenly expanded flows both in subsonic and supersonic flows. The flow will tend towards free jet nature and under such circumstances the base suction enjoyed in sudden expansion will not be present.

Fig. 5(c) to (d) presents the wall pressure results for L/D ratios = 6 and 5. Here, again there is about 35 percent increase in initial value of the wall pressure as compared to the area ratio 3.24. Another peculiar behavior is observed here is the presence of a powerful shock at x/L = 0.3 due to which the wall pressure shoots up by 33 percent and then for the next wall pressure tap it is almost comes down to the same value as it was for the previous value. This may be due to the interaction of the shock wave, reflection of the shock from the wall, interaction of the free shear layer, and interaction with the vortex in the base region. Fig 5(e) presents the results for L/D = 4, from the figure it is seen that there is increase in the oscillations in the flow as compared to the results for same L/D for lower area ratios. The wall pressure has increase by 35 percent for the same condition for area ratio 3.24.

Fig. 5(f) presents the results for L/D = 3, the trend is same as that of for lower area ratios and there is a increase in the value of wall pressure as compared to the previous cases for the same L/D ratio. The wall pressure has gone up by 75 percent as compared to for area ratio 3.24 for the same parameters. The flow is no more attached with the duct wall for the cases when L/D is = 2 and 1.

The results for the highest area ratio of the present investigation namely, 6.25 are presented here. Figs. 6(a) to (f) present the wall pressure variation as function of non-dimensional duct length, and NPR for different L/D ratios of the present study. For this area ratio the relief enjoyed by the suddenly expanded flow is much more than what it was for area ratio 4.84. Hence, the level of expansion causing the formation of shock or expansion fan at the nozzle lip will have a strong effect on the wall pressure as well as its control effectiveness. This is because when the free shear layer expanding into the suddenly expanded passage finds sufficient relief, it re-attaches immediately downstream of the reattachment point for lower area ratios which; is not the case for this area ratio. This increase in reattachment length helps the formation of a powerful vortex at the base causing high values of wall pressure. But for lower area ratio as well as the for L/D = 10 & 8 they are unable to dictate such a high value of the wall pressure as well as the reattachment length as the strength of the shock wave at the nozzle lip remains



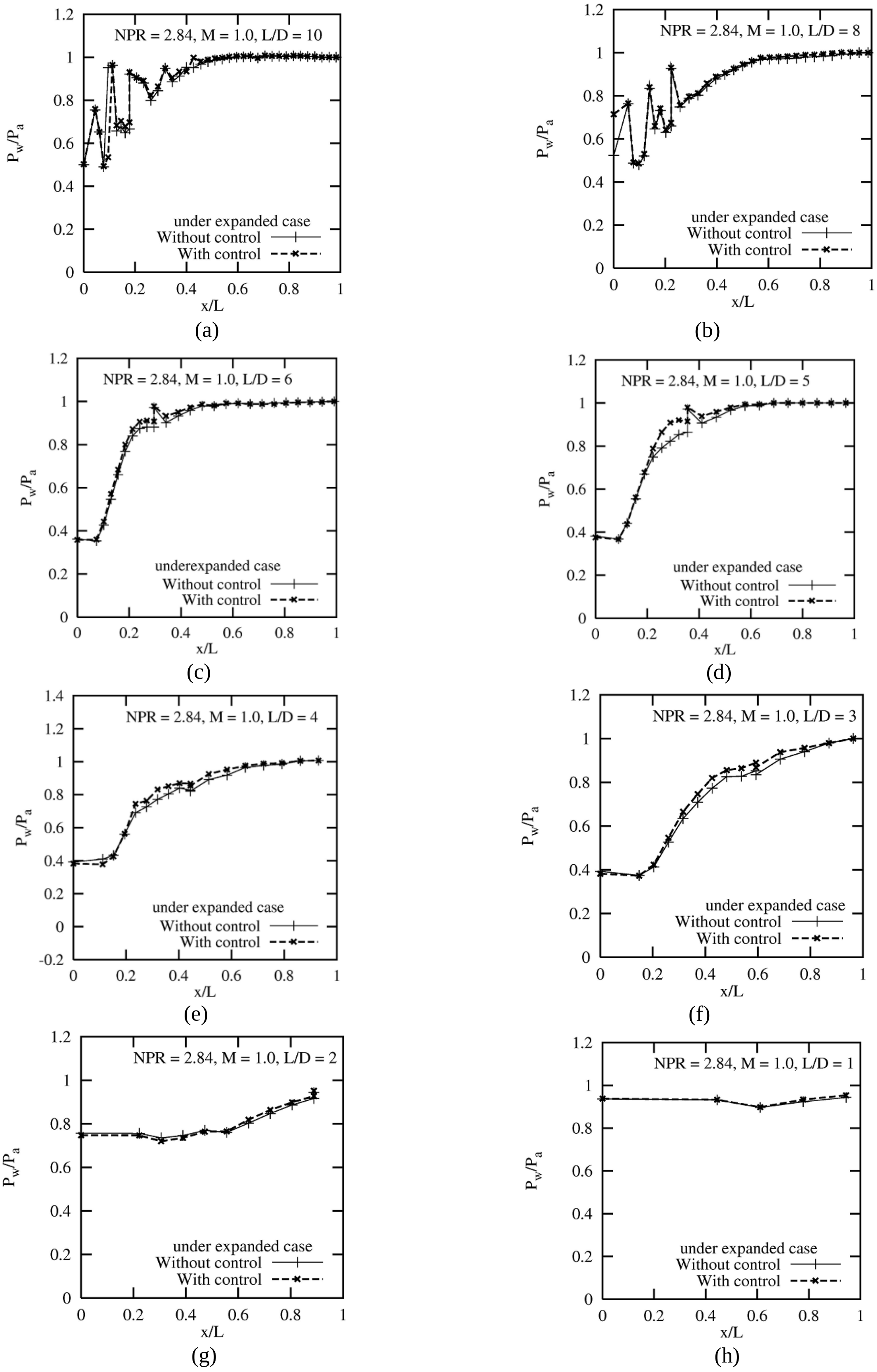
(a) (b)

(c) (d)

(e) (f)

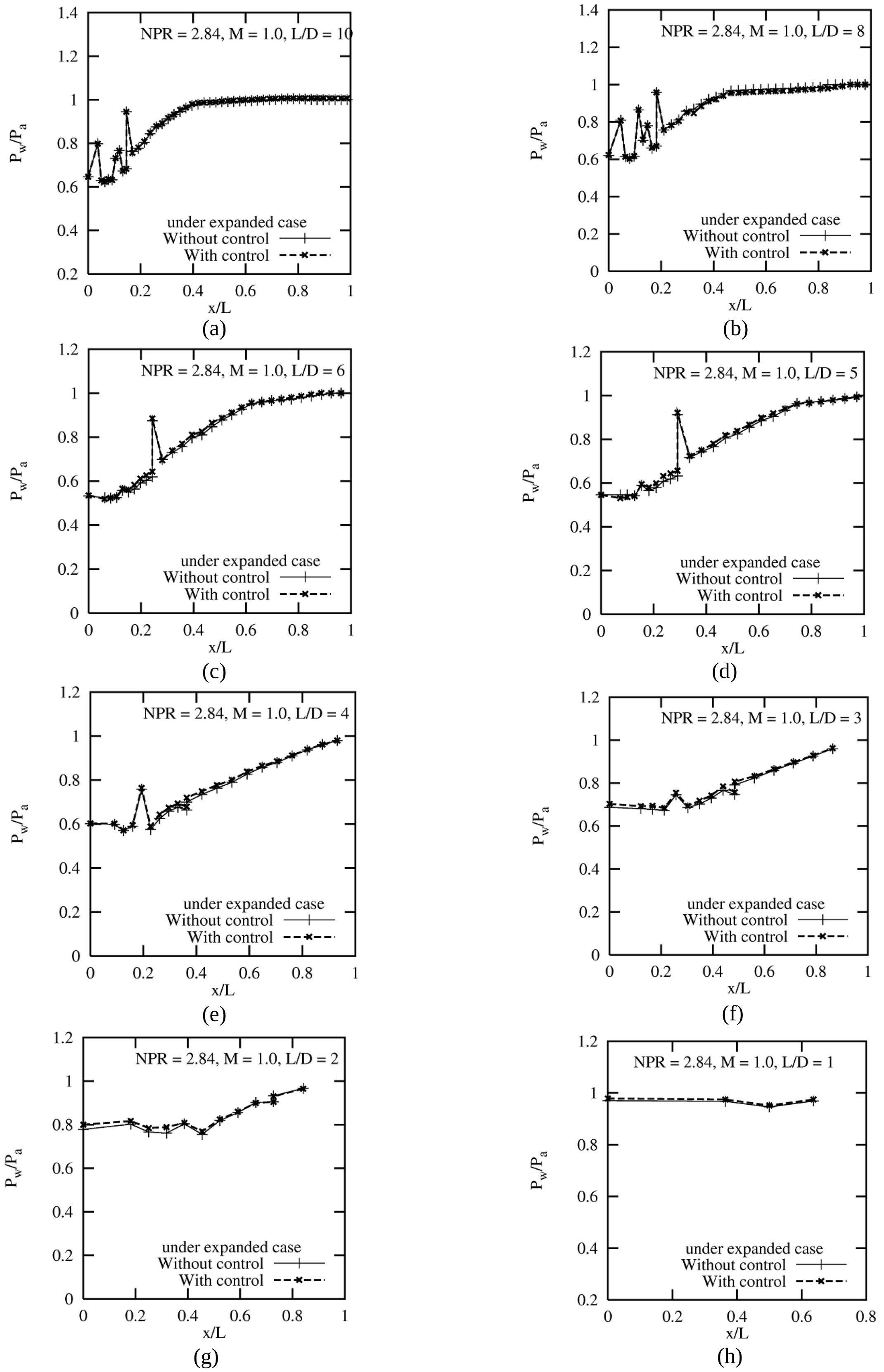
(g) (h)

Figure 3: Wall pressure distribution for area ratio 2.56



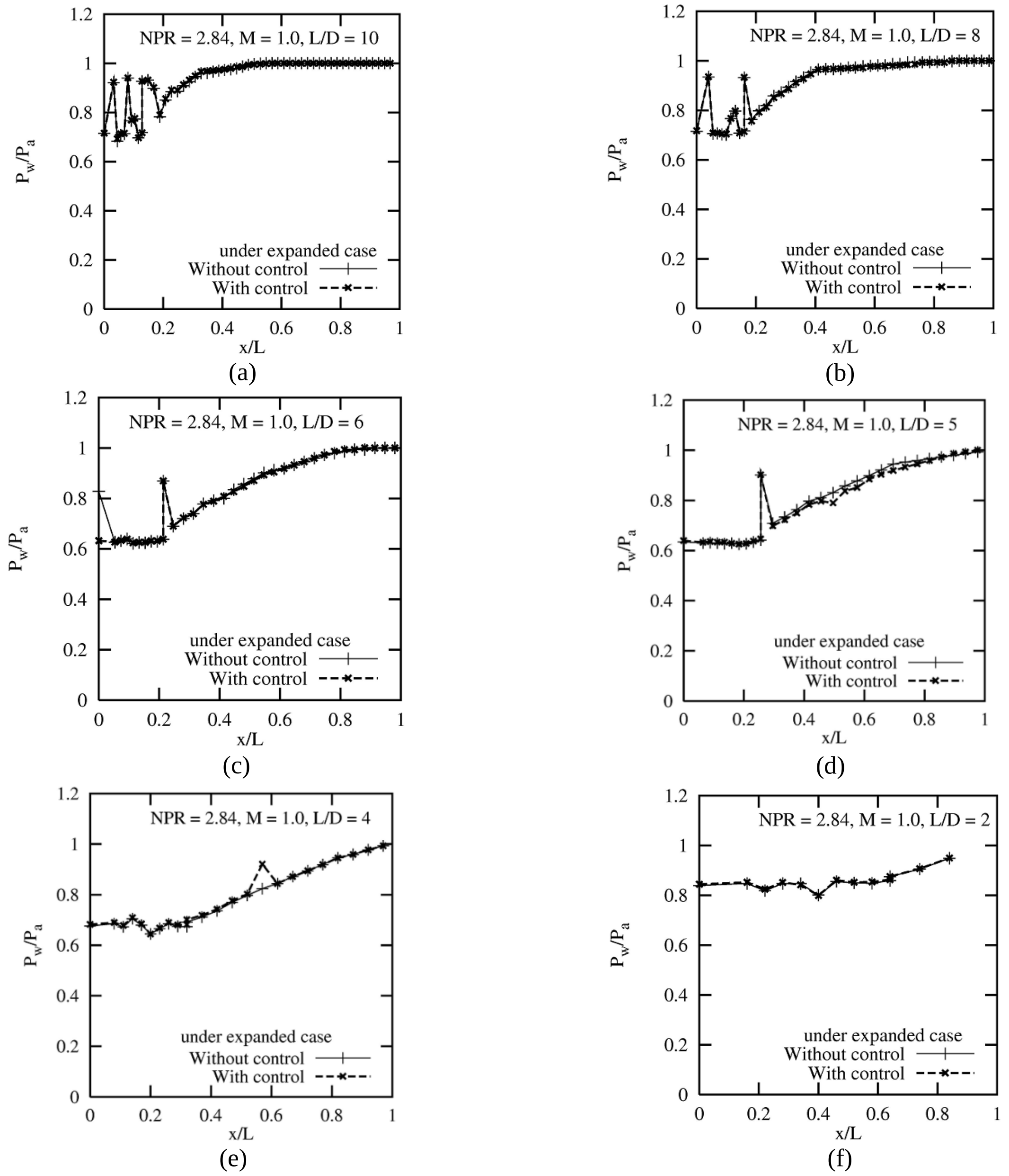
(a) (b)
(c) (d)
(e) (f)
(g) (h)

Figure 4: Wall pressure distribution for area ratio 3.24



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 5: Wall pressure distribution for area ratio 4.84



(a) (b)

(c) (d)

(e) (f)

Figure 6: Wall pressure distribution for area ratio 6.25

the same, further, with the increase of area ratio causing the flow to deflect towards the shock. This causes hindrance to the formation of a strong vortex at the base. Because of this the base pressure shoots up with increase of area ratio & for higher L/Ds namely L/D = 10 & 8. Also, the control becomes ineffective since the shock strength dominates the flow process.

Results for L/D = 10 & 8 are shown in Figs. 6(a) to (b). In Fig. 6(a) for L/D = 10 it seen that the initial value of the wall pressure is quite high as compared to the lower area ratios, and as high as nearly 71 percent increase in the wall pressure is achieved and this increase is simply because of the increase in the area ratio from 2.56 to 6.25 as the level of expansion and inertia level is the same. It is also observed for both the L/Ds namely L/D = 10 & 8 that within the 30 percent of the duct length, and the flow field is oscillatory in nature, this may be due to the suction which was created by the vortex at the base as well as due to the range of L/D ratio and reattachment length.

Results for L/D = 6 and 5 are shown in Figs. 6(c) to (d), respectively, they, also exhibit similar trend as it was seen for area ratio 4.84, however, the starting value is increased by 13 percent with that of for the lowest area ratio, but this increase in initial value is only 50 percent, when compared with the area ratio 4.84. Here, it is also seen that a shock wave is formed at x/L = 0.3 and then wall pressure value comes down to the original value.

Similar results are seen in Figs. 6(e) & (f) with slight increase in the initial value of the wall pressure as well increased level of oscillation, this may be due the combined effect of all the parameters of the present study. Results for some lower L/Ds are not presented here, as expected they do not show any definite trend, they indicate that the duct length is just insufficient for the flow to be attached with the duct wall and the jet behaves almost like a free jets and the base vortex present is unable to reflect in any change in the flow field. However, it should be realized that increase of area ratio beyond some limiting value will not ensure the effects mentioned above for suddenly expanded flows both in subsonic and supersonic flows. This limit may for area ratio more than 6 and above. The flow will tend towards free jet nature and under such circumstances the base suction enjoyed in sudden expansion will not be present.

V. CONCLUSIONS

From the above discussion the following conclusions can be drawn:

- The relief and L/D combination results in control effectiveness at various NPRs taking the wall pressure above or below the value of the wall pressure for with and without control case. This simply implies that level of wall pressure is sensitive to the combination of parameters under study. If the base suction enhancement is desired then area ratio in the range 2.0 to 6.25 and L/D 10 to 4 seem to be the choice and if high value of base/wall pressure is required to achieve then the area ratio in the range 6.5 to 10 and the L/D ratio in the range 5 to 4 is the choice.
- When relief effect due to increase of area ratio is beyond some limit, the flow from the nozzle discharged into the enlarged duct tend to attach with reattachment length other than the optimum for the formation of strong vortex at the base. This process makes the NPR effect on wall pressure to become insignificant. However, NPR in the range 3 to 7 still will have some influence on the wall pressure, we have conducted the experiments for NPRs in the range 1.5 to 3 only and also the control will be considerably more effective.
- Furthermore, the Mach number and NPR at which the wall pressure starts increasing or decreasing will depend on increase or decrease of area ratio. This is so because as the area ratio goes up the flow which is expanding from the nozzle finds sufficient space to relax and propagate downstream without encountering the flow at the base region and the enlarged duct wall. When L/D is beyond some limiting value the relaxing flow re-attaches with the duct and when boundary layer grows downstream of the reattachment point. For area ratio 6.25 this limiting value appears to be around L/D = 4.
- These results once again emphasize that the control effectiveness is case sensitive and one has to identify the proper combination of NPR, area ratio, and L/D ratio for a given Mach number to achieve the desired control effectiveness.
- From the results it is found that the control in the form of micro jets do not disturb the flow field in the enlarged duct. It is also seen that for the lower L/D ratio namely 2.56 and 3.24 the L/D = 1 and 2 are sufficient for the flow to be attached with duct wall and 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 increase in the wall pressure value for
- the initial length of the duct and the flow is oscillatory.

All the non-dimensional wall pressure presented in this paper is within an uncertainty band of ± 2.6 per cent. Further, all the results are repeatable within ± 3 per cent.

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