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Wall Pressure Studies in a Suddenly Expanded Flow for Area Ratio 2.56

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ABSTRACT

This paper presents the results of an experimental work carried out to find the wall pressure distribution in a suddenly expanded duct. The enlarged duct is attached to the exit of a convergent- divergent axisymmetric nozzle. The area ratio (i.e. ratio between cross sectional area of the sudden expansion duct and the nozzle exit area) considered in the present study is 2.56. The jet entering the suddenly expanded duct is at supersonic Mach numbers regime of 1.87, 2.2 and 2.58. The length to diameter ratio considered is 10. The nozzle pressure ratio (NPR) used is 3, 5, 7, 9, and 11 for all the Mach numbers. An active control method in the form of Microjets is used to control the base pressure. The prime investigations are towards finding the effect of Microjets on wall pressure for above said parametric conditions. It is found that the duct wall pressure distribution, which usually becomes oscillatory when controls are employed, does not get adversely affected with Microjets.

Keywords: ***Wall pressure, Nozzle pressure Ratio, Supersonic Flow, Convergent-Divergent Nozzle***

I. INTRODUCTION

Researchers in the field 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 considerable 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 flow field of abrupt axi-symmetric expansion is a complex phenomenon characterized by flow separation, flow recirculation and reattachment. Such a flow field may be divided by a dividing streamline (dividing surface) into two main regions, one being the flow recirculation region, the other being the main flow region as illustrated in Fig. 1.1

Sudden expansion of flow both in subsonic and supersonic regimes of flow is an important problem with 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 previous example.

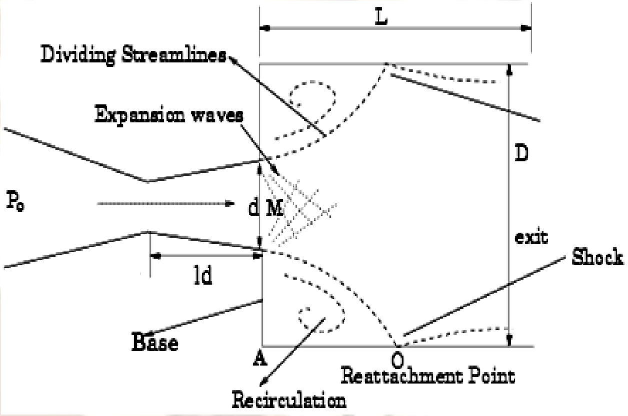


Fig.1.1. Sudden Expansion Flow Field

II. LITERATURE REVIEW

Hall and Orme [1] studied compressible flow through sudden enlargement in a pipe, both theoretically and experimentally, and showed a good agreement between theoretical and experimental results. They developed a theory to predict the Mach number in a downstream location of sudden enlargement for known values and Mach number at the exit of the inlet tube, with incompressible flow assumption. They also assumed that the pressure across the face of the enlargement was equal to the static pressure in the small tube just before the enlargement. But this assumption is far away from reality, it is a well established fact that the pressure across the face in the recirculation region, namely the base pressure is very much different from the pressure in the smaller tube just before the enlargement. They used a nozzle and tube arrangement for the experiments and studied the problem with a range of throat Mach numbers from 0.0 to 1.0. Heskestad [2-3] in his experiments applied a suction scheme to flow through sudden enlargement. He concluded that for fixed geometry and Reynolds number, gradual increase in suction rate from zero caused progressively more rapid expansion into the larger pipe diameter, a process which accelerated toward a critical suction rate and then continued slowly. Nicoll and Ramaprian [4] investigated performance of conical diffusers with annular injection at inlet. The effects of injection rate and diffuser geometry on the pressure recovery and stall were discussed. Results indicate that the improvement in diffuser performance is significant even at moderate rates of injection. An analytical method based on the solution of the boundary layer equations by the Patankar-Spalding finite difference method was used to obtain predictions of pressure recovery with inlet injections. The predictions compare well with the experimental results. Bar-Haim and Weihs [5] studied boundary-layer control as a means of reducing dragon fully submerged bodies of revolution. He concluded that the drag of axisymmetric bodies can be reduced by boundary-layer suction, which delays transition and can control separation. The boundary-layer transition was delayed by applying a distributed suction technique. Optimization calculations were performed to define the minimal drag bodies at Reynolds numbers of 107and 108. The reduction in drag relative to optimal bodies with non controlled boundary layer was 18 and 78 per cent, at Reynolds numbers of 107and108. Ackeret [6] studied special features of internal flow. He concluded that there is a predominant role played by the equation of continuity, especially if compressibility is involved and in aeronautics big deflection of the air streams are avoided as far as possible but inducted flow, they may be quite common. If the width of the duct is not growing too fast along its length, separation is followed by re-attachment. He observed that, in case of internal flow also, three-dimensional boundary layers can appear as in external flow. Anderson and Williams [7] worked on base pressure and noise produced by the abrupt expansion of air in a cylindrical duct. They used stagnation pressure ratios of the forcing jet from atmospheric to six times atmosphere for various length to diameter ratios. With an attached flow the base pressure was having minimum value which depends mainly on the duct to nozzle area ratio and on the geometry of the nozzle. The plot of overall noise showed a minimum at a jet pressure approximately equal to that required to produce minimum base pressure. Mueller [8] studied analytically the determination of turbulent base pressure in supersonic axisymmetric flow. As per their analysis the axisymmetric base pressure may be classified as assuming either rising or constant pressure along the jet mixing region. A modification in the re-compression component of the basic pressure rise flow model plus an accurate computer solution of the nonlinear equation for axisymmetric mixing produces base pressure results that agree well with data were suggested. Mueller [9] studied analytically the influence of initial flow direction on the turbulent base pressure in supersonic axisymmetric flow. His results show excellent agreement between analytical results for γ= 1.4, Tb/T0a= 1, Mj= 2.0, and rb/rc= 0.58, and the experimental data of Reid and Hastings [10]. Durst et al. [11] studied low-Reynolds number flow over a plane symmetric sudden expansion. The flow was depending totally on Reynolds number and the nature was strongly three- dimensional. At higher Reynolds number the flow became less stable and periodicity became increasingly important in the main stream, accompanied by a highly disturbed fluid motion in the separation zones as the flow tended towards turbulent. They reported flow visualization and laser anemometry measurements.

Pandey and Kumar [17] studied the flow through nozzle in sudden expansion for area ratio 2.89 at Mach 2.4 using fuzzy set theory. From their analysis it was observed that L/D = 4 is sufficient for smooth development of flow keeping in view all the three parameters like base pressure, wall static pressure and total pressure loss. The above review reveals that even though there is a large quantum of literature available on the problem of sudden expansion, majority of them are studies without control. Even among the available literature on investigation of base flows with control, most of them used only passive control by means of grooves, cavities and ribs. Only very few studies report base flow investigation with active control.

III. EXPERIMENTAL SETUP

The experiments are conducted in the jet facility at High Speed Aerodynamics Laboratory, Aerospace Engineering Department, Indian Institute of Technology Kanpur, India. The layout of the laboratory is shown in Fig. 2.

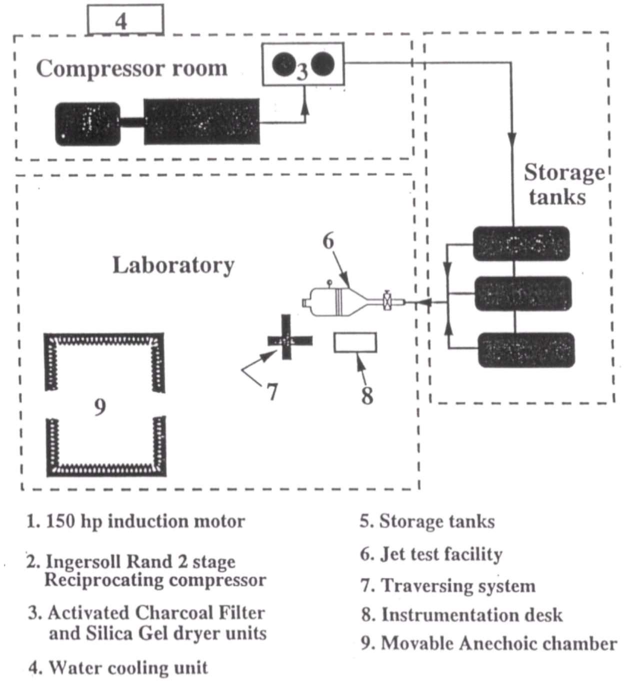


Fig. 2 Layout of the Laboratory

Figure 3 shows the schematic diagram of experimental setup used for the present study. At the exit periphery of the nozzle there are eight holes four of which (marked c) were used for blowing and the remaining four (marked m) were used for base pressure (Pb) measurement. Control of base pressure was done, by blowing through the control holes (c), using the pressure from the settling chamber by employing a tube connecting the settling chamber and the control holes (c). The pressure taps are provided on the wall of the enlarged pipe to measure wall pressure distribution in the duct.

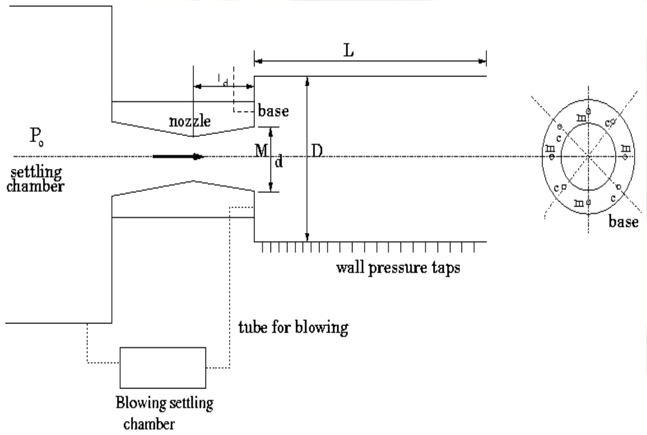


Fig. 3 Experimental Set-up

Fig. 4 Test jet facility

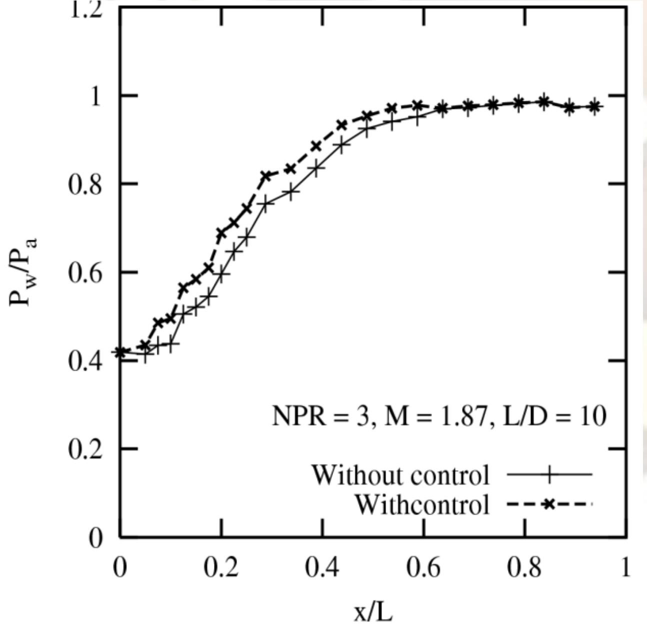
IV. RESULTS AND DISCUSSION

One of the major problems associated with base flows is the oscillatory nature of pressure field in the duct just downstream of the base region. This can be understood by scanning the wall static pressure along the duct. In the present investigation, attention is focused to study the effect of the active control on the duct wall pressure field. To study this wall pressure distribution for all the Mach numbers, tests were conducted with and without controls for all the area ratios. The wall static pressure distribution along the duct length for area ratio 2.56 is presented in figures 5(a)-(f) to 7(a)-(f). The L/D ratio selected for present study is 10.

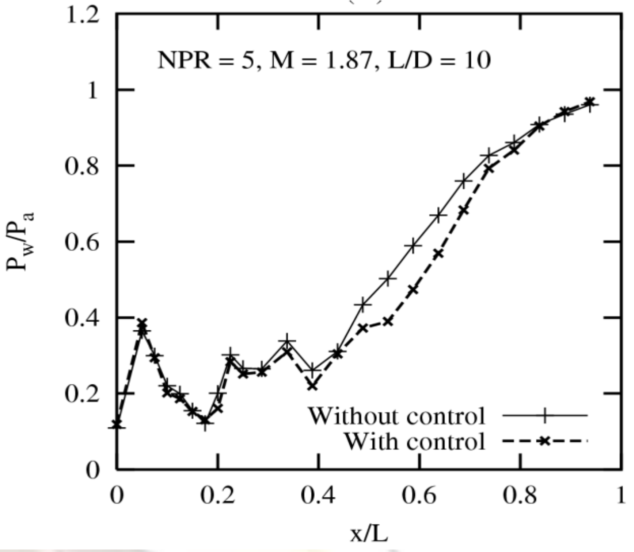
Figure 5(a) to 5(e) shows the results of Wall pressure at Mach 1.87 for NPR 3, 5, 7, 9, 11 respectively. Figure 5(f) indicates the wall pressure distribution at correct expansion for Mach 1.87. It can be seen that the flow field is oscillatory in nature for NPR =7, 9 and 11 as these NPRs are under expanded. For Mach number 1.87 correct expansion occurs at NPR = 6.4. For low NPRs (3 and 5) it can be seen that the graphs are not showing any oscillatory nature. For all these NPR's the jets are over expanded. In all graphs, wall static pressure is reaching close to atmospheric pressure at the exit of the enlarged duct. For L/D = 10, at NPR = 7 and 9 micro jets are effecting the flow field but are not aggravating the flow field, which is a major advantage of Microjets. For NPR = 5, wall static pressure reaches atmospheric pressure very rapidly and remain close to ambient pressure for remaining (about 80%) length of the duct.

Figure 6(a) to 6(e) shows the results of Wall pressure at Mach 2.2 for NPR 3, 5, 7, 9, 11 respectively. Figure 6(f) indicates the wall pressure distribution at under expansion for Mach 1.87. For mach 2.2, the correct expansion occurs at NPR= 10.7. For NPR= 9 and 11 wall pressure field is exhibiting oscillatory nature. For NPR = 3, 5 and 7 it is observed that wall pressure distribution is showing smooth variation. For this Mach number also, in most cases micro jets are not affecting the wall pressure flow field. For Mach number 2.2 it is found that at L/D=10 and at higher NPRs (9 and 11) oscillatory flow field is obtained, but these oscillations decrease as the L/D ratio decreases. For this Mach number no significant increase in reattachment length is obtained for any NPR and L/D combination. For this case it is found that about 10% increase in reattachment length is obtained when controls are employed.

Figure 7(a) to 7(e) shows the results of Wall pressure at Mach 2.58 for NPR 3, 5, 7, 9, 11 respectively. Figure 7(f) indicates the wall pressure distribution at over expansion for Mach 1.87. All graphs presented for this Mach number are for overexpansion NPR, as maximum NPR that is employed is less than that required for correct expansion. For this Mach number NPR for correct expansion is 19.3. Oscillatory flow field is not observed for this Mach number. This may be due to the fact that all NPRs employed are over expanded. In some cases, for this Mach number micro jets are affecting the flow field substantially, specially at NPR = 9. For L/D = 10 at NPR= 9 it can be seen that reattachment length is increasing significantly. This is considered to be a major advantage as for all other Mach numbers there is no significant increase in reattachment length for higher L/D ratios. Further, it is observed that in all cases, at the duct exit zone the wall static pressure with control and without control is almost the same and is close to atmospheric pressure.



5(a)



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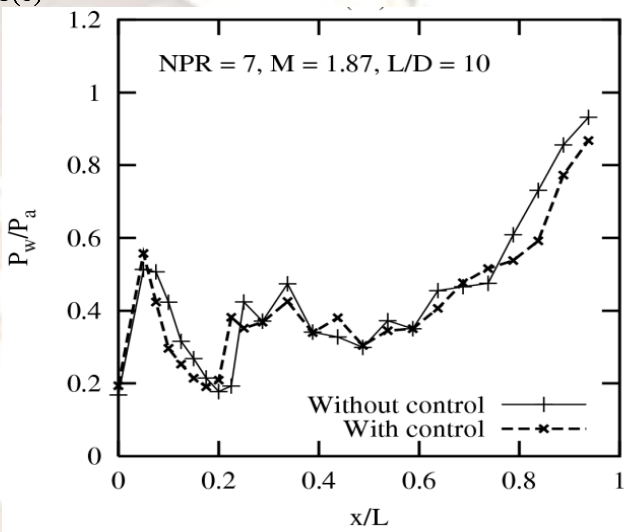
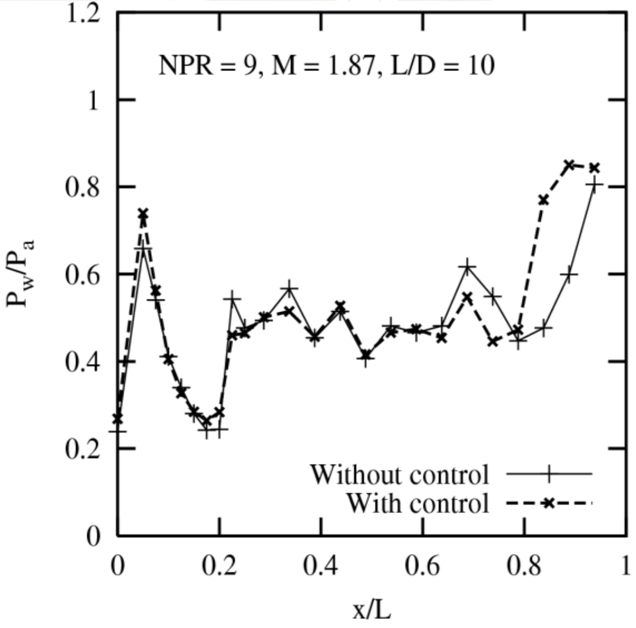
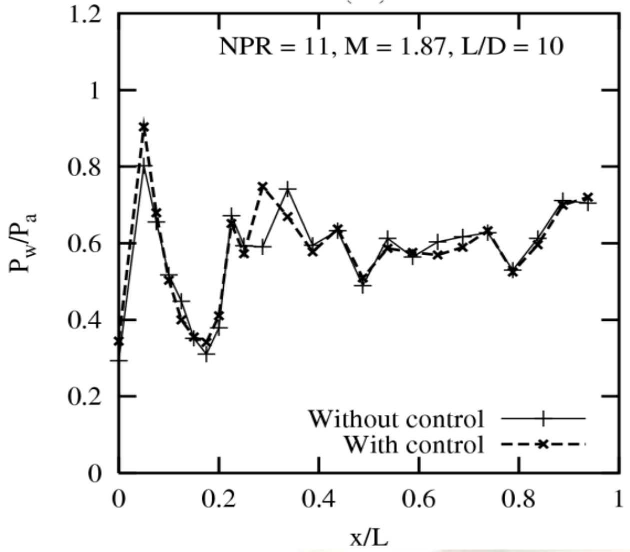


5(c)



5(d)



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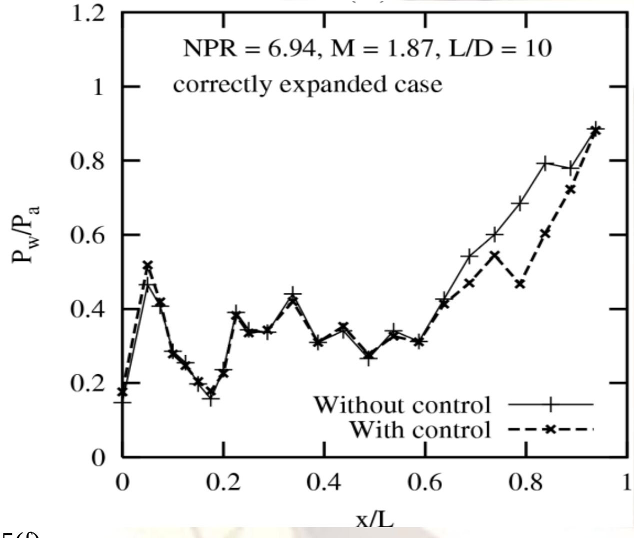
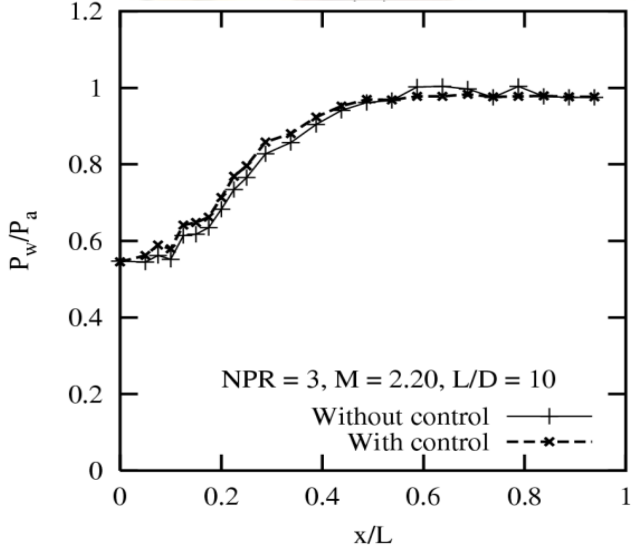
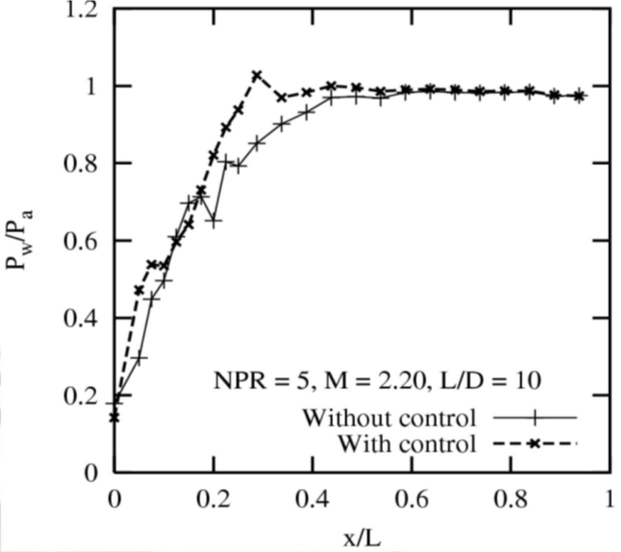


5(f)



6(a)



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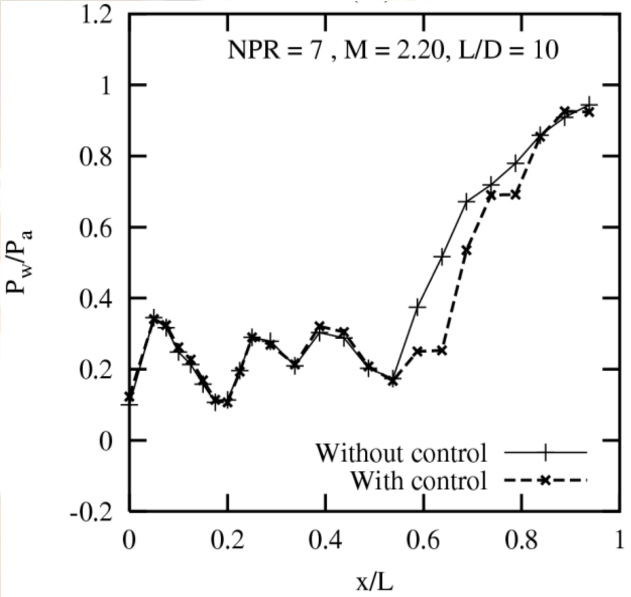

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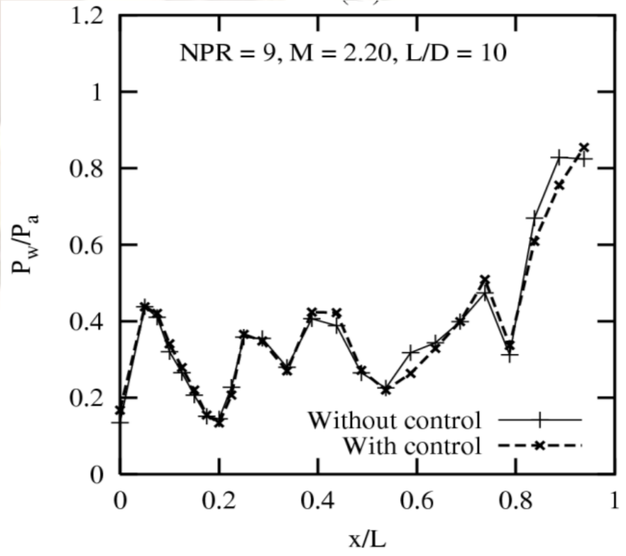

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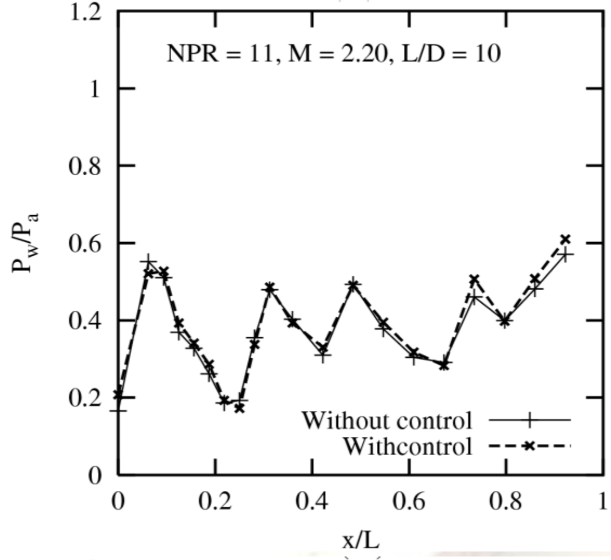

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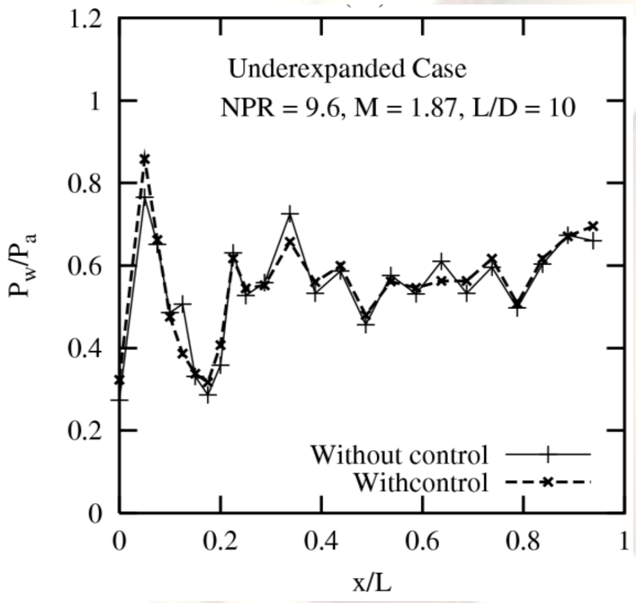
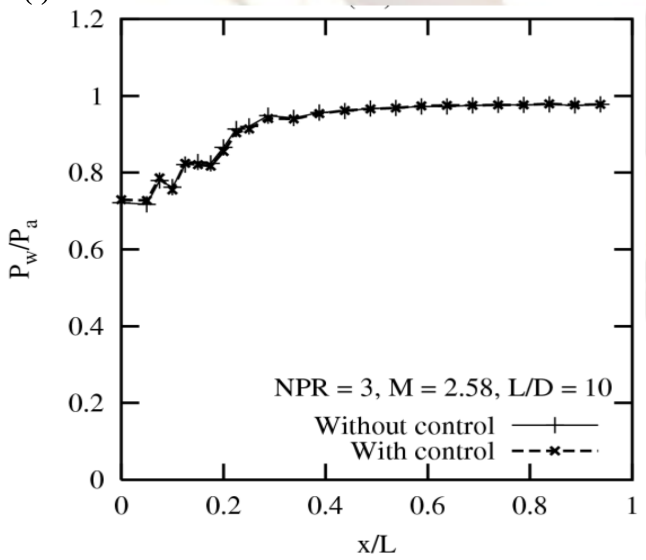
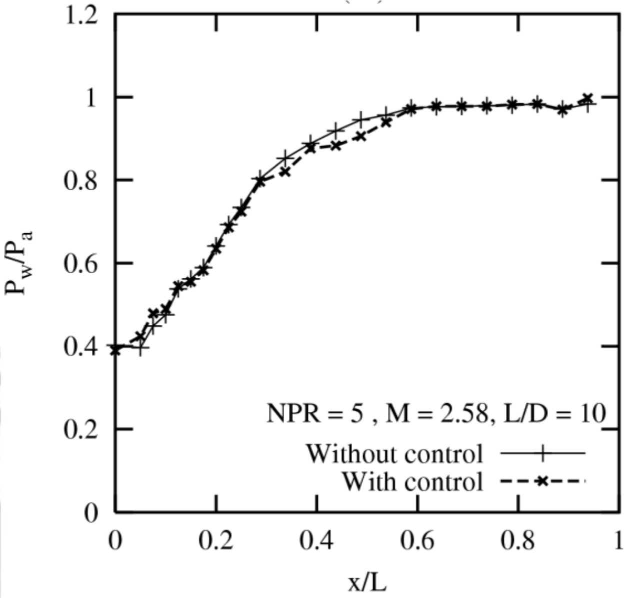


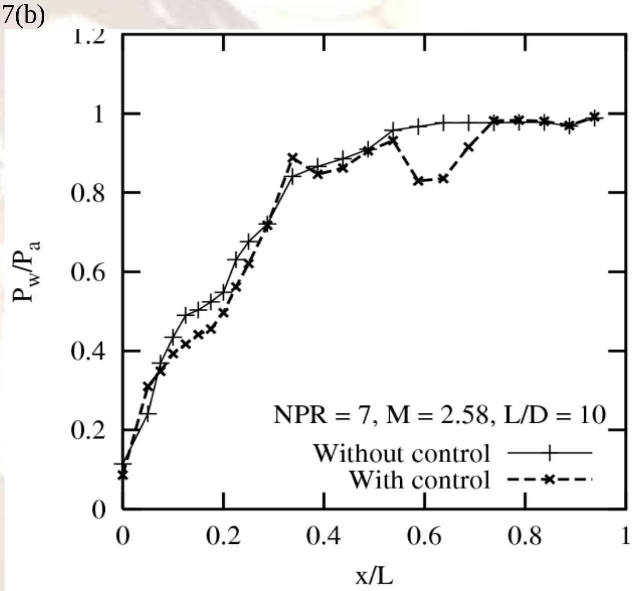
6(f)



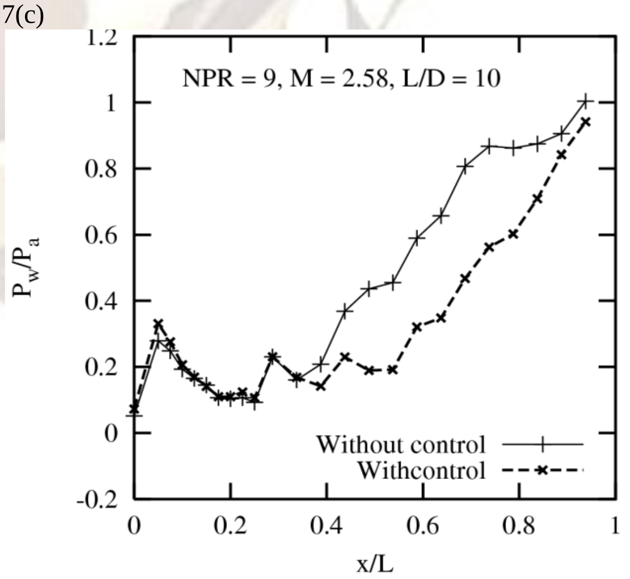
7(a)



7(b)



7(c)



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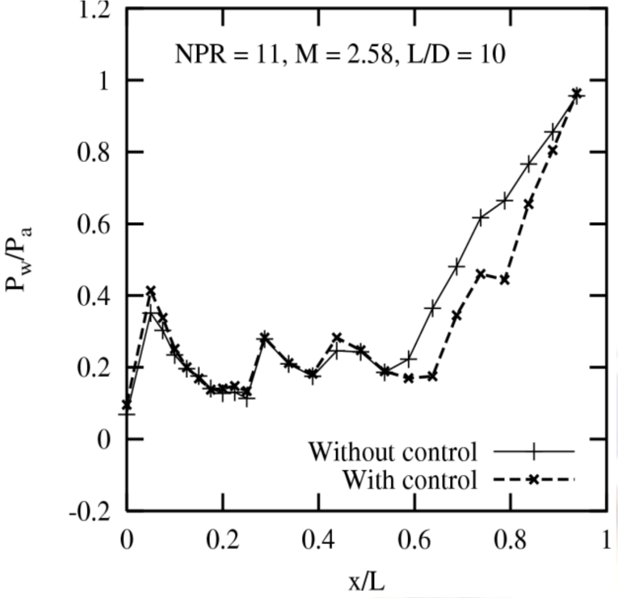

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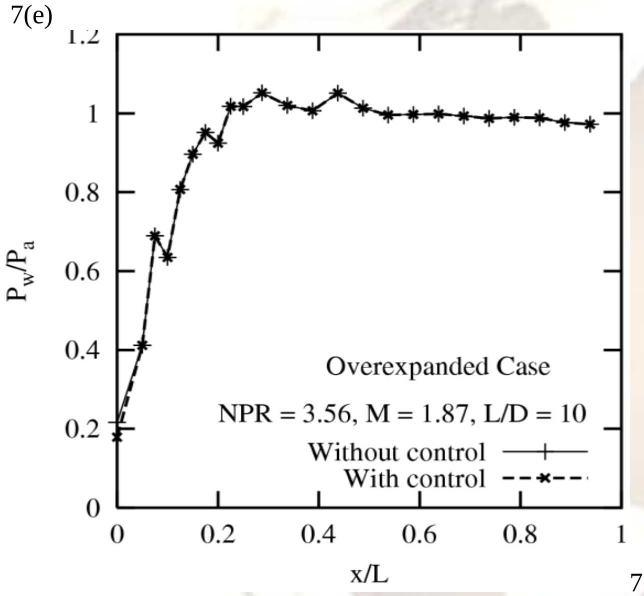

7(f)

V. CONCLUSION

`It is seen from these results that in most of the cases the pressure field with control and without control behave almost identical. This ensures that the active control doesn't influence the wall pressure field adversely rendering the flow to become oscillatory and this can be considered as one of the major advantage. A large portion of the plots for NPR = 3 are flat and are close to atmospheric pressure.

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