

Studies on Flow from Convergent Nozzle with Sudden Expansion and Control Effectiveness under the Influence of Micro Jets

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Abstract

Sudden expansion fluid flow is of great importance. In the present study experiments are conducted to control the base pressure from a convergent nozzle. Active control in the form of micro jets are used as an active control of 1 mm orifice diameter located at 900 intervals along a pitch circle diameter of 1.3 times the nozzle exit diameter in the base region. Area ratio of the present study i.e. ratio of area of suddenly expanded duct to nozzle exit area studied is 4.84. Nozzle pressure ratio (NPR) and length-to-diameter (L/D) ratio are main geometric and inertia parameters considered in the present study. Accordingly, Tests are conducted for NPR in the range of 1.5 to 3.0, in the steps of 0.5. L/D ratio of the enlarged duct was considered are from 10 to 1, and tests were carried out for L/D 10, 8, 6, 5, 4, 3, 2 and 1. From the experimental studies, it is found that, unlike in the case of passive controls, the favourable pressure gradient does not ensure augmentation of the control effectiveness for active control in the form of micro jets. It is found that it is case sensitive as with increase in the NPR the wave pattern at the base region will be changing continuously. Further, it is found that the micro jets are activated they do not disturb the flow field in the enlarged duct.

Keywords

Base Pressure, Wall Pressure, Nozzle Pressure Ratio, Active Control, Micro Jets

1. Introduction

In many engineering flow problems, the Reynolds number is usually very high, and the boundary-layer concept can be applied. This approach can even be applied to "strong interaction" problems where both viscous and inviscid flow mechanisms must be considered simultaneously before the solution can be established. The present investigation involves the separation of flow at the corner of the lip of the convergent nozzle and belongs to the category of strong interaction. The analyses on the inviscid flow field associated with the convergent nozzle-free jet and the viscous flow of turbulent jet mixing and reattachment are separately presented. Because the base pressure is very low in comparison with the upstream stagnation pressure, a curved sonic line prevails within the jet flow. The configuration of the sonic line changes as the back pressure (base pressure) varies. If the growth of the boundary layer along the nozzle wall can be ignored.

Fig. 1 is a schematic diagram of a flow past a sudden enlargement in cross-sectional area from a convergent nozzle. For an assumed base pressure, a mixing process occurs along the wake boundary. Since the Reynolds number is usually very large, the mixing process is turbulent. The mixing process provides the mechanism of momentum transport and prepares the viscous layer for the subsequent process of the recompression. In various analyses, it is assumed that the mixing region is divided into two layers along the dividing streamline that separates the flow from the upstream nozzle and the fluid trapped within the wake.

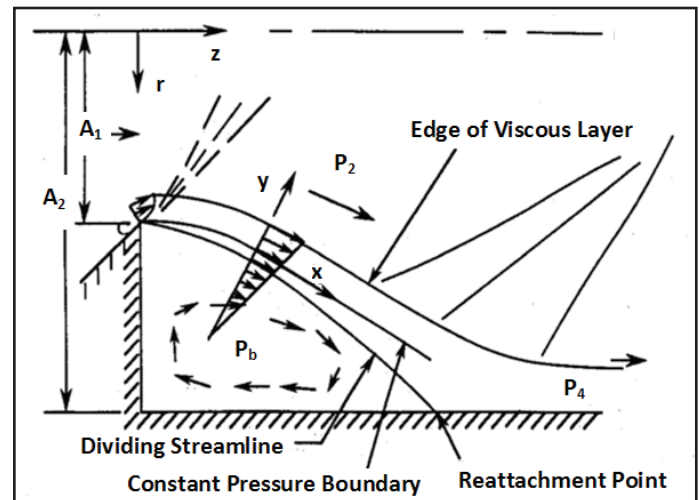


Fig. 1: View of the Suddenly Expanded Flow Field through Convergent Nozzle

As a result of conservation of mass within the wake, the flow above the dividing streamline proceeds downward and subsequently undergoes a recompression process until the dividing streamline stagnates on the wall. The flow below the dividing streamline is eventually turned back to form the re-circulatory wake flow. For simplicity, it is assumed that the similar-energetic flow field prevails throughout the flow so that consideration of the energy equation is conveniently eliminated. It is interesting to observe that the dividing streamline is rapidly energized immediately after separating from the lip of the nozzle through the jet mixing process, until a maximum value is reached. Subsequently, the velocity of the dividing streamline is reduced as a result of recompression, and the vanishing value is reached at the point of reattachment, even though a continuous transfer of mechanical energy through shearing action takes place throughout this region. This mechanism is also responsible for an additional rise of pressure along the wall after reattachment. Expressions for the transport of the fully developed turbulent jet mixing process relied on a similarity parameter so that the fully developed velocity profile can be related to a homogeneous coordinate with the corresponding eddy diffusivity. Since none of the actual situations will correspond to an environment for the fully developed flow, the proper value for any practical situation is not known. It was found that the variation of the base pressure ratios is very minor.

Low base pressure at blunt in the many engineering problem connected with fluid dynamic drag, a vast number of investigations, both theoretical and experimental, considering base pressure and base drag have been performed. The rapid growth of interest in supersonic drag problems associated with the development of supersonic aircraft, projectiles, missiles, and spacecraft was one reason for the fact that the theory made greater advances at high Mach numbers than at low speeds and that more experiments were performed in this velocity range to verify the theoretical

results. Due to its vast applicability; suddenly expanded flows have studied extensively. Many researchers attempted to control the base pressure with passive means and some of the works relevant to the present study are reviewed in the section to follow. Therefore, in the present study an attempt has been made to investigate the base pressure control with active control in the form of micro jets from a convergent nozzle to ascertain the control effectiveness of the micro jets at various level of expansion.

II. Literature Survey

According to Hoerner [1] the boundary layer was an insulating layer that reduces the effectiveness of the jet as a pump. The base corner was thought of as a sump with two supplies of mass. It was found from their studies that the boundary layer flow around the corner is first source and the second source was the back flow in the boundary layer along the wall of expanded section. This back flow occurred because of the pressure difference across the shock wave originating where the jet strikes the wall. He concluded that the mechanism of internal and external flow was principally the same and base pressure phenomenon in external flow could be studied relatively easily by experiments with internal flow. Wick [2] studied experimentally the effect of boundary layer on sonic flow over a sudden cross-sectional area change. He observed that the pressure in the expansion corner was associated to the boundary layer type and thickness upstream of the enlargement. He deliberated that the boundary layer as a source of fluid for the corner flows. They studied two-dimensional air flows through a convergent nozzle which is expanded abruptly into a rectangular channel of higher cross-section. Wood [3] studied the effect of base bleed on a periodic wake. He concluded that Base bleed reduces the drag of an aerofoil, by delaying the onset of instability in the separated shear layers. The proportion of vorticity which actually enters the vortex sheet after being shed from the model falls from an initial value of about 0.5 as the shear layers increase in length. In his experiment, the optimum bleed was given by a bleed coefficient of 0.125. This gives a drag reduction equal to that produced by a long splitter plate and it was thought that little further improvement is possible by any method of wake interference. No attempt was made by Wood to explain either how base bleed stabilizes the shear layer or why very small bleed quantities appear to have the reverse effect. The method used by the Wood to determine the properties of the vortex street was an indirect one, based on the assumed validity of the VON KARMAN vortex street. Heskestad [4] 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. It is found that for one particular geometry, Reynolds number, and suction rate beyond critical value the initial border to the remaining pocket of separated flow behind the step appeared common to expansion ratios greater than a certain minimum. On the other hand, turbulence was found to propagate increasingly faster into the potential core of the flow as expansion ratio increased. Durst et al. [5] 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. At Reynolds number of 56 the separation region behind each step were of equal length for each step but at Reynolds number of 114, the two separation regions were having different lengths leading to asymmetrical velocity profiles. At Reynolds number of 252, a third separation zone was found on one wall. There were substantial three-dimensional effects in the vicinity of the separation regions. Liu [6] studied axi-symmetric transonic turbulent base pressure. It was stipulated that the inviscid flow field can be produced from an equivalent body and the inviscid flow so established guide; the viscous flow processes of mixing and re-compression along the wake. The viscous-inviscid interaction is manifested by the fact that the characteristic parameters required to establish the corresponding inviscid flow were determined through viscous flow considerations. Extension of this approach to study the base pressure of transonic flow past a backward facing step in axi-symmetric configuration was reported. Gharib and Roshko [7] studied the effect of flow oscillations on cavity drag. Their results showed that self-sustained, periodic oscillations of the cavity shear layer are associated with low cavity drag. In this low-drag mode the flow regulates itself to fix the mean-shear-layer stagnation point at the downstream corner. Above a critical value of the cavity width-to-depth ratio there is an abrupt and large increase of drag due to the onset of the "wake mode" of instability. It was also shown by the measurement of the momentum balance how the drag of the cavity is related to the state of the shear layer, as defined by the momentum transport and Reynolds stress, and how these are related to the amplifying oscillations in the shear layer. The cavity shear layer was found to be different, in several respects, from a free shear layer. A simple momentum integral model for estimating the minimum or "critical" swirl intensity required to produce central recirculation in a swirling sudden expansion flow is presented by Hallet [8]. An explicit equation is given for the critical swirl as a function of expansion ratio and inlet velocity profile shape, the latter expressed by the radius of the solid body vortex core and a parameter describing an axial velocity maximum or minimum on the axis. The model is tested against experimental data for expansion diameter ratios from 1.25 to 3.0 and a variety of inlet conditions, and found to give good predictions. Durrett et al. [9], studied radial velocity component measurements in cylindrical tubes have been difficult to make because of optical aberrations introduced by the curved tube wall. They got it is particularly troublesome in gas flows where refractive index matching techniques cannot be employed. Their investigation utilized a specially designed correction lens system to overcome this problem. As a result it was possible to map the axial and radial velocity behavior in detail for the air flow downstream of a sudden expansion in a cylindrical duct. Quantities measured and derived included mean velocities, turbulence intensities, turbulent kinetic energy and Reynolds stress. The weak secondary recirculation zone existing just below the sudden expansion was clearly identified and mapped. Where possible the measurements were compared with numerical predictions based on a $k-\epsilon$ model. Rathakrishnan, Ramanaraju and Padmanaban [10] studied the influence of cavities on suddenly expanded subsonic flow-field. They studied air flow through a convergent axisymmetric nozzle expanding suddenly into an annular parallel shroud with annular cavities experimentally. They concluded that the smoothening effect by the cavities on the main flow-field in the enlarged duct was well pronounced for large ducts and the cavity aspect ratio had significant effect on the flow-field as well as on the base pressure. From their results it is seen that increase in aspect ratio

from 2 to 3 results in decrease of base pressure but for increase in aspect ratio from 3 to 4 the base pressure goes up. Hwang et al. [11] investigated the base pressure of a sudden enlargement from a tapering nozzle and from their investigation which concerns the determination of the back-pressure-independent base pressure associated with the convergent flow accelerating device which followed with a sudden enlargement in cross-sectional area. The point of reattachment acts as a saddle point singularity for the system of equations explaining the viscous flow recompression. Combination with whole momentum balance, the base pressure and the position within the wake area where recompression initiates can be determined. Experiments were conducted for sudden expansion for convergent nozzles for different area ratios and for various convergent angles. Rathakrishnan [12] conducted the experiments to find optimum geometry of ribs for the minimum possible base pressure, over a range of Mach numbers from low subsonic levels to sonic. Airflow from convergent axisymmetric nozzle expanded suddenly into circular duct of larger cross-sectional area than that of nozzle exit area were studied. Khan and Rathakrishnan [13-17] 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. Syed Ashfaq et al. [19-20] studied sudden expansion problem experimentally focusing attention on the base pressure and the flow development in the duct. The experimental investigation on suddenly expanded flow field covering the above flow and geometrical parameters revealed that the base pressure is strongly influenced by the geometrical parameters viz length to diameter ratio, Mach number and the nozzle pressure ratio (NPR).

III. Experimental Procedure

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 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 4 mm each and remaining was made at an interval 8 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.

The experimental setup of the present study consisted of an axisymmetric nozzle followed by a concentric axisymmetric 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. The suddenly expanded ducts were fabricated out of brass pipe.

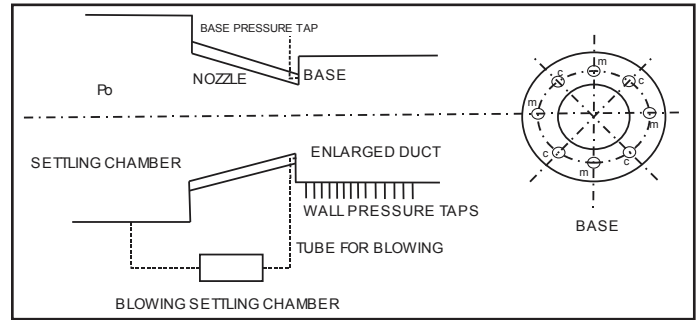


Fig. 2: Experimental Setup

Model length was ten times the inlet diameter so that the duct has a maximum $L/D = 10$. The lower L/D s 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 $+60^\circ$ C and 95 per cent humidity.

IV. Results and Discussions

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 are non-dimensionalized by dividing them with the ambient pressure (i.e. the back pressure). In the present study the control pressure in the control chamber will be the same as the NPR of the respective runs as the air is drawn from the main settling chamber.

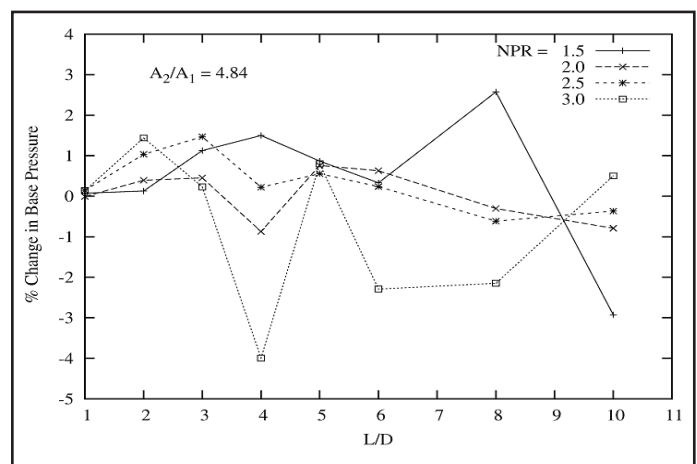


Fig. 3: Percentage Change in Base Pressure Variation with L/D

The base pressure results for area ratio 4.84 are presented in this paper. It is to be noted that in addition to influence of shock or expansion wave at the nozzle lip, the relief effect due to increase of area ratio also will influence the base pressure. Furthermore, it should be kept in mind that for lower area ratio, the micro jets

at the base were located at mid pitch circle diameter (pcd) of the base, whereas for area ratio 4.84 the micro jets are closer to the nozzle exit (not at the middle of the base). This is because pcd for micro jets was kept constant for all the area ratios.

The percentage change in the base pressure as a function of L/D is shown in fig. 3 for various NPRs in the range from 1.5 to 3. From fig. 3 it is seen that at NPR = 1.5 the control is not effective at lower L/D's since the flow in the duct is not attached at these duct lengths, however, at higher L/D's the control results in increase as well as decrease of the base pressure. For NPRs 2.0 and 2.5 the control effectiveness is marginal. However, at NPR = 3, the control becomes effective and control results in decrease of base pressure. NPR 3 falls under the category of favourable pressure gradient, and it is well known from the literature that active as well as passive control becomes effective whenever, there is a favourable pressure gradient. Further, it is seen that L/D's up to 3 the control is not effective. One of the reasons for this behaviour may be due to the insufficient length of duct and flow is no more attached with duct wall rather it is exposed to the atmosphere and the base vortex is unable to create any suction at the base which otherwise it is able to do at higher L/Ds. Other reasons for this trend may be due to the presence of waves and their strength at different NPRs, inviscid-viscous interaction, interaction of the flow with the base vortex, due to the increased area ratio and hence effect of the relief available to the flow, and the interaction of the free shear layer.

Non-dimensional base pressure results for NPR = 1.5 is shown in Fig. 4. From the figure it is seen that the control becomes effective from L/D = 3 onwards which is the minimum duct length required for the flow to be attached with the enlarged duct wall. Further, it is observed that the control results in increase of the base for all the L/Ds > 3, except at L/D = 10 where, control results in decrease of base pressure this strange behavior may be due to the effect of back pressure at L/D = 10.

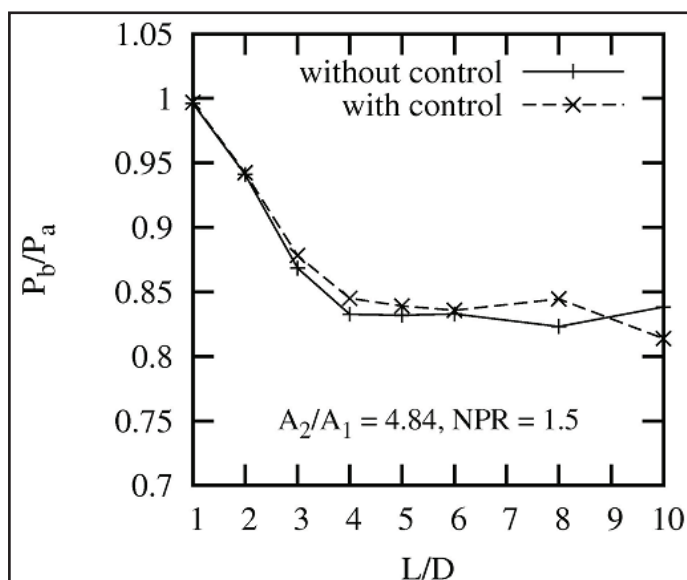


Fig. 4: Base Pressure Variation with L/D

Base pressure results for NPR = 2 are shown in fig. 5. From the figure it is seen that the control effectiveness is only marginal, also, it is seen that for L/D in the form range 3 to 6 the control results in increase of base pressure even though marginal and for L/D > 6 the control results in decrease of base pressure. Further, it observed that as the NPR increases from NPR 1.5 to 2.0 and

once the flow is attached with the duct wall the magnitude of the base pressure is also progressively decreasing with NPR as it can be seen that at L/D = 4 for NPR = 1.5 the magnitude of the non-dimensional base pressure is around 0.82, where as for NPR = 2.0, this value comes down to 0.7, which results in 15 percent reduction in the non-dimensional base pressure value. This reduction in the value is on the expected lines. Whenever, the inertia of the flow is increasing the strength of the base vortex will increase which in turn will result in decrease of the base pressure.

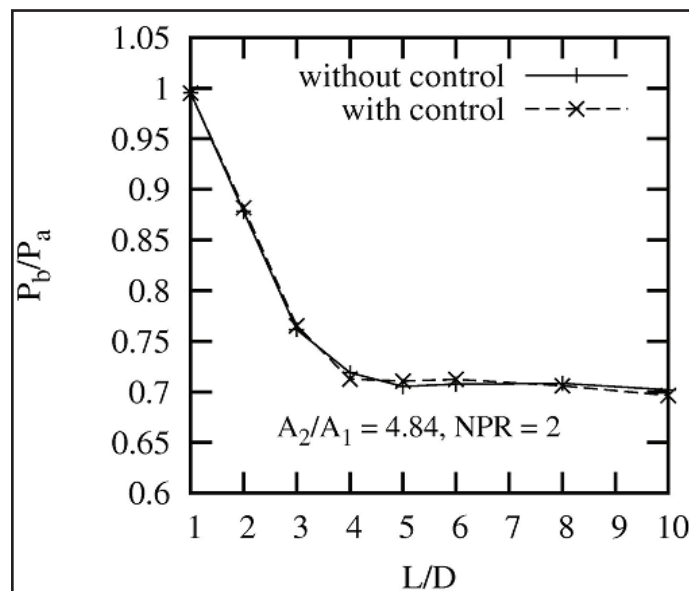


Fig. 5: Base Pressure Variation with L/D

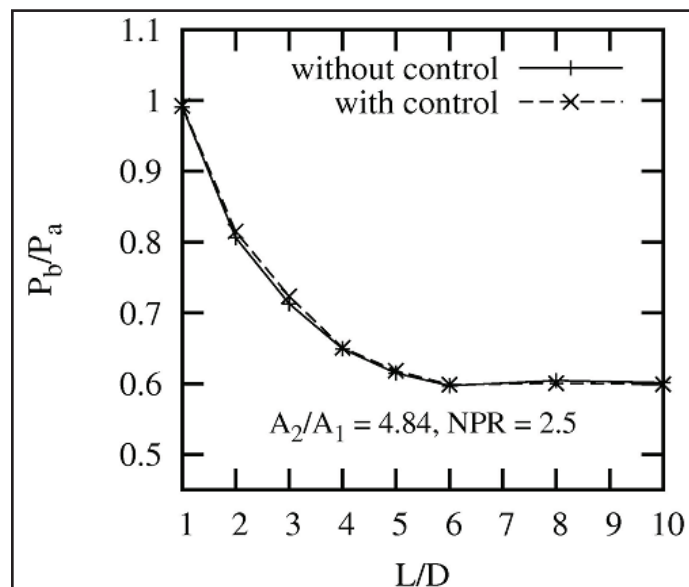


Fig. 6: Base Pressure Variation with L/D

Fig. 6 presents base pressure results for NPR = 2.5, it is seen that with further increase in NPR, it will result increase in inertia and the non-dimensional base pressure value for without control case has further decreased and this value is 0.6 and the percentage decrease in the value is around 14 percent and as compared with NPR = 1.5, this decrease in the value is 27 percent and the control effectiveness is only marginal. The physical reasons of this behavior may due to the presence of a complex field at the base region, variation in the inertia which; in turn lead to variation in the shock strength, boundary layer effect, the reverse flow at the duct wall, and the interaction with free shear layer.

Fig. 7 presents the base pressure results for the Highest NPR tested in the present study. It is seen that there is further decrease in the base pressure without control case. The non-dimensional base pressure value has further decreased to the level of 0.5 resulting in 17 percent reduction as compared to the previous value that is present at NPR = 2.5, and an overall reduction in the base pressure with reference to the lowest value of NPR tested that is NPR = 1.5 is 40%.

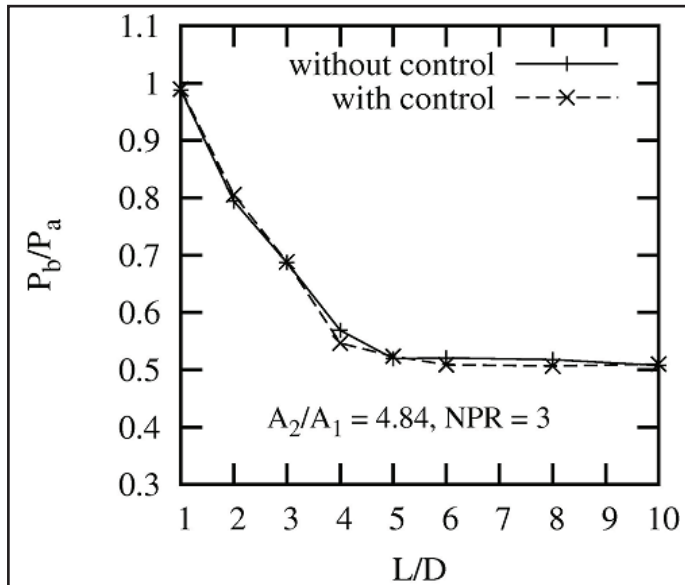


Fig. 7: Base Pressure Variation with L/D

This reduction in the base pressure value is simply because of increase in the inertia value which will create a powerful vortex at the base, and other interactions as discussed earlier.

From these results it is evident that area ratio which governs the relief effect has got a definite role to play on the level of base pressure. When the relief increases due to increase of area ratio, the shear layer from the nozzle exit has a tendency to attach later compared to lower area ratio. This result in higher suction at the base compared to lower area ratio when the duct length is above some limiting value. When duct length is less than this limit, the expanding flow has got a tendency to relax more than what it would be for low area ratio, thereby not establishing the powerful suction at the base.

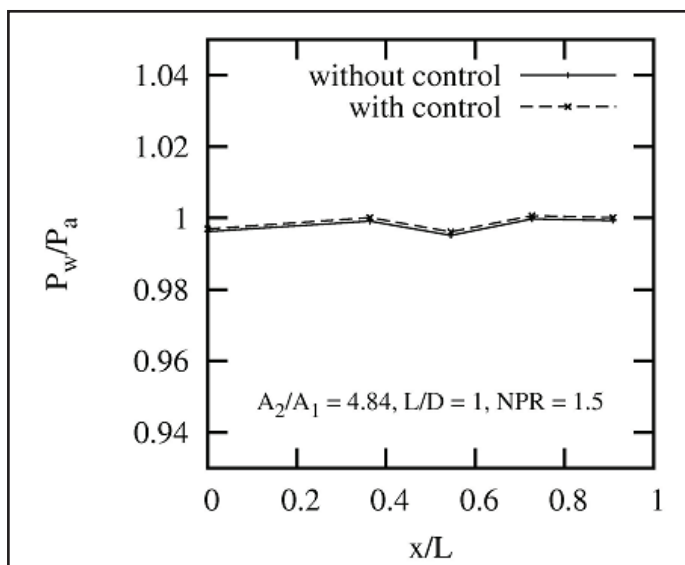


Fig. 8: Wall Pressure Distribution

Figs. 8 to 11 present the wall pressure results for L/D = 1 and NPRs 1.5 to 3, the wall pressure with and without control is identical, wall pressure assumes very high value as the flow is detached from duct wall.

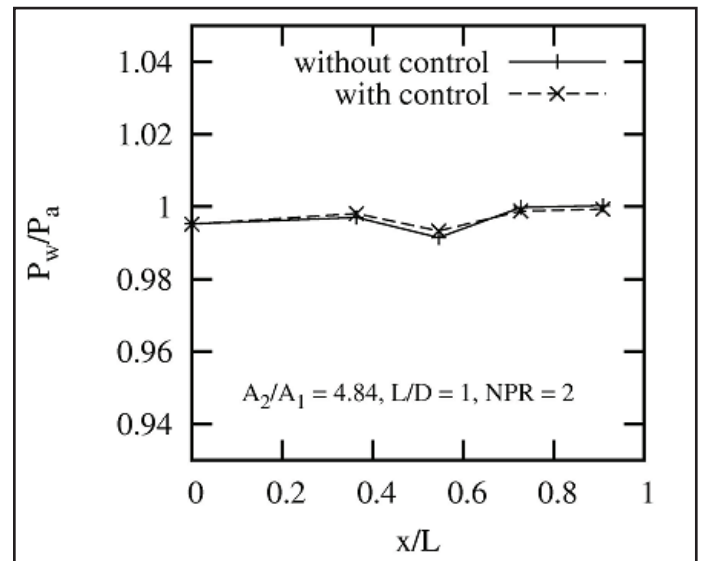


Fig. 9: Wall Pressure Distribution

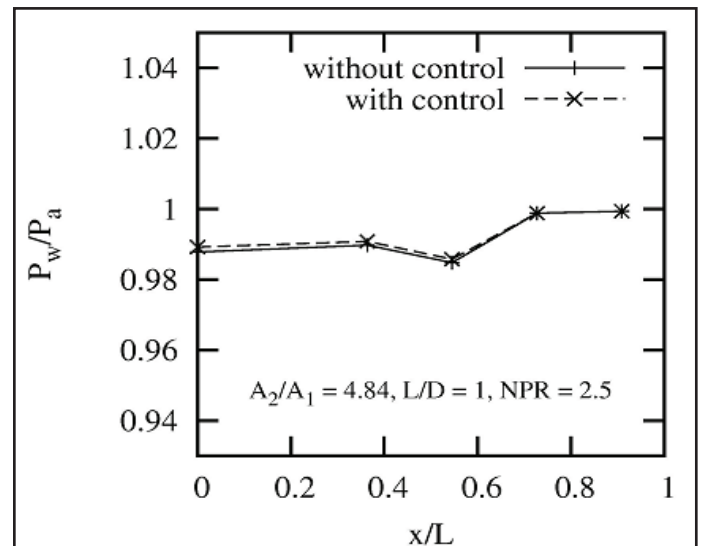


Fig. 10: Wall Pressure Distribution

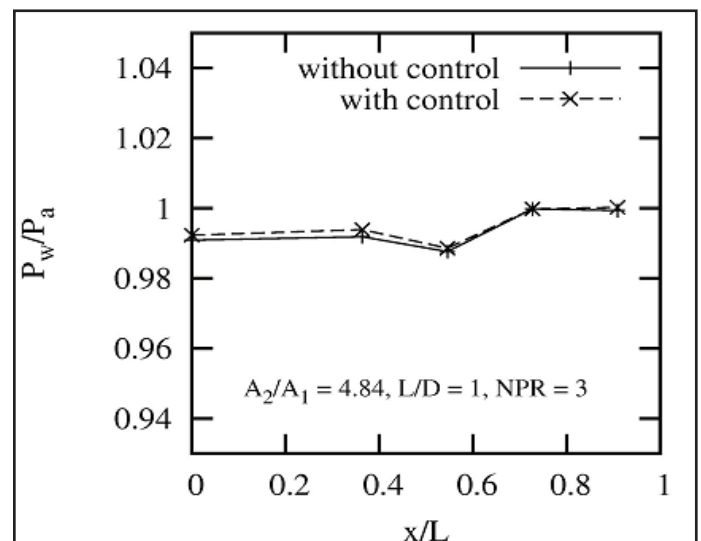


Fig. 11: Wall Pressure Distribution

Figs. 12 to 15 presents wall pressure results for all the NPRs tested for $L/D = 2$. The difference between the results for $L/D = 2$ and 1 is that wall pressure for $L/D = 1$ the magnitude of the wall pressure is almost equal to the atmospheric pressure or in other terms the non-dimensional wall pressure value is almost equal to one, the physical reason may be due to the detached flow at the duct wall, however, for $L/D = 2$, the wall pressure assumes lower values compared to $L/D = 1$, even though the flow is still not attached with the duct wall. Even for $L/D = 2$ there are variation in the magnitude of wall pressure and this value varies from 0.94 to 0.8, resulting in 15 percent decrease in the wall pressure just because of increase in NPR from 1.5 to 3. The wall pressure flow field remains unaltered with and without control case, and the control results in increase of the wall pressure.

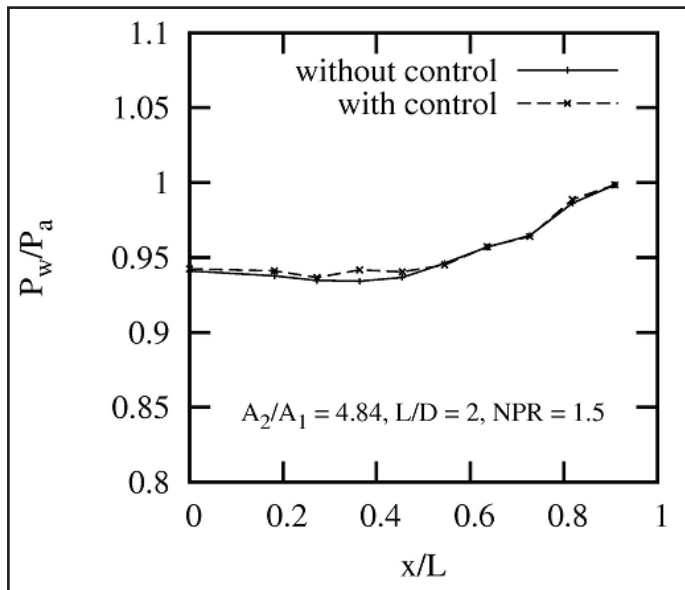


Fig. 12: Wall Pressure Distribution

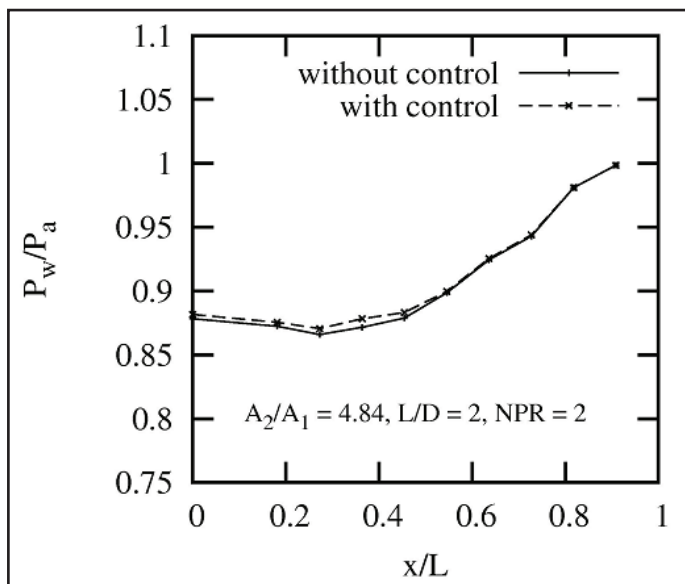


Fig. 13: Wall Pressure Distribution

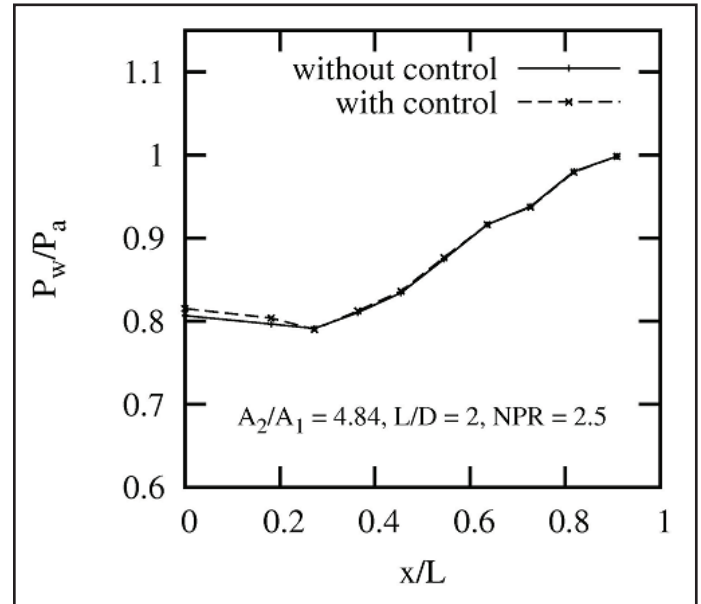


Fig. 14: Wall Pressure Distribution

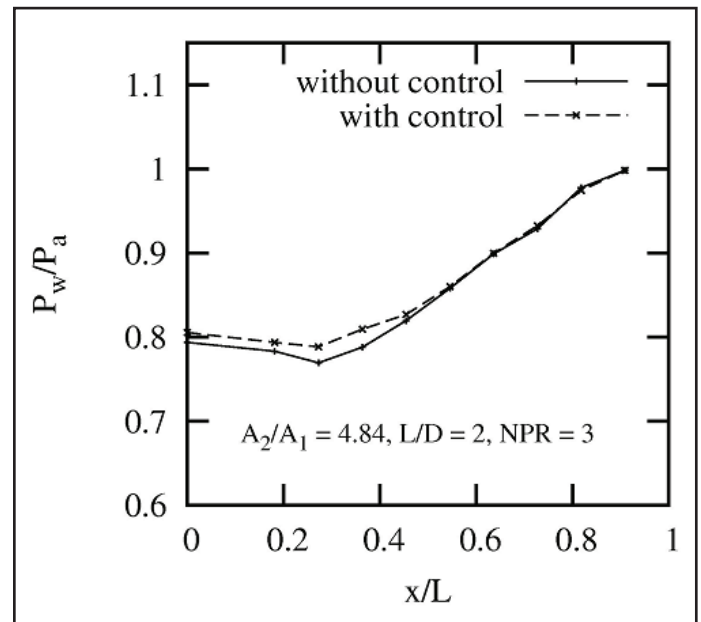


Fig. 15: Wall Pressure Distribution

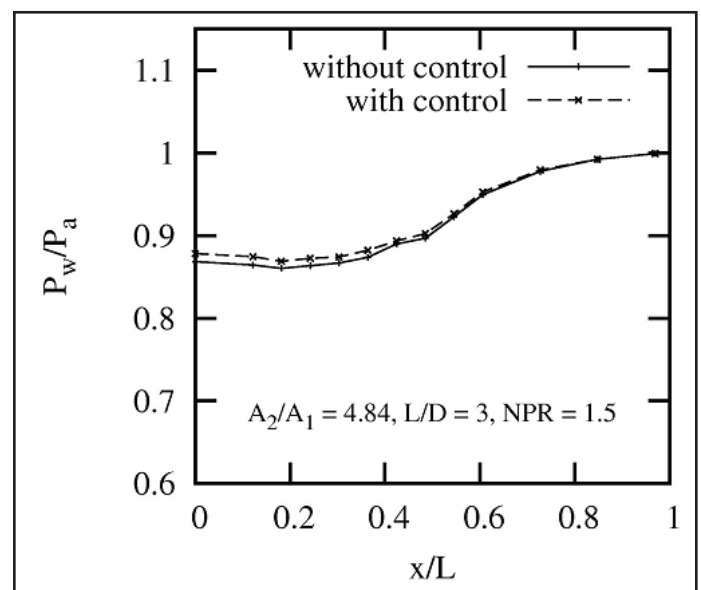


Fig. 16: Wall Pressure Distribution

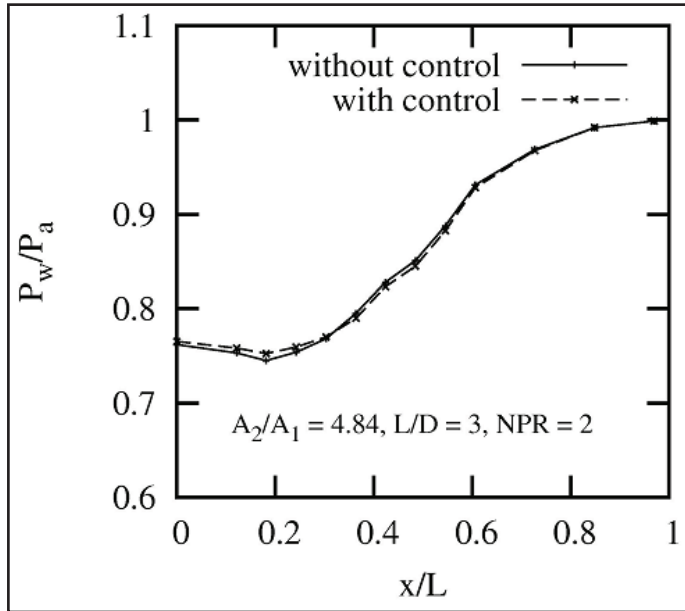


Fig. 17: Wall Pressure Distribution

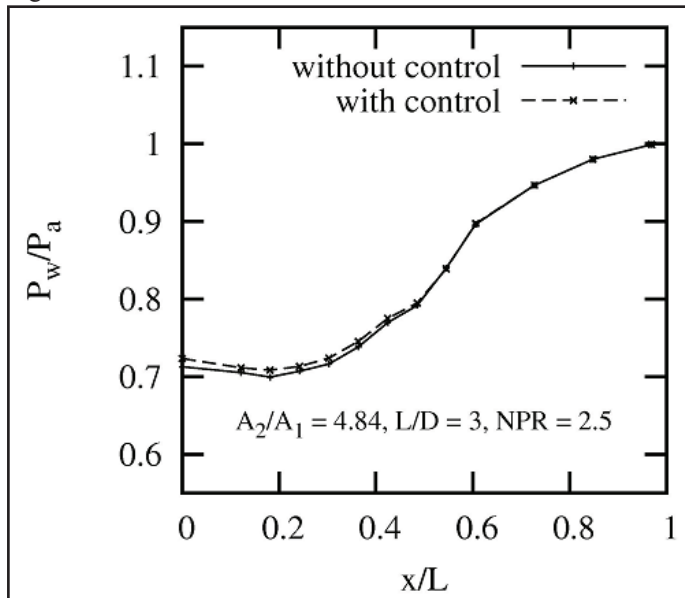


Fig. 18: Wall Pressure Distribution

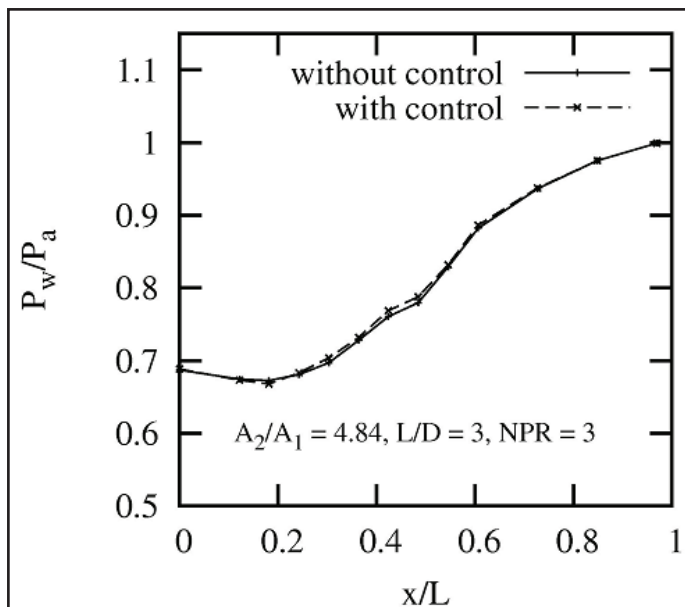


Fig. 19: Wall Pressure Distribution

Similar results for $L/D = 3$ are seen in Figs. 16 to 19. Here, once again there progressive decrease in the wall pressure value and this value has come down from 0.88 to 0.68 resulting in 22 % reduction in wall pressure for the L/D being the same and this reduction is observed due to the change in the level of expansion at the nozzle exit. The flow field in the duct with and without control is the same; however, there is a marginal increase in the wall pressure.

Wall pressure results for $L/D = 4$ and all the NPRs tested are shown in Figs. 20 to 23. From these results it seen that for $NPR = 1.5$ (Fig. 20), the control results in increase of the wall pressure within the reattachment length and for the flow beyond the reattachment length the recovery in the wall pressure is very smooth and the flow field with and without control are the same. Figs. 21 and 22 present identical results, and further, it seen that due to the increase in NPR from 1.5 to 2.5 there is a 23 % reduction in wall pressure value for the same $L/D = 4$. Fig. 22 presents results for the highest value of NPR, the decrease in the wall pressure value is around 36 percent for the $L/D = 4$, it is also seen that within the reattachment length the control results in decrease of wall pressure where as in the downstream the control results in increase of wall pressure.

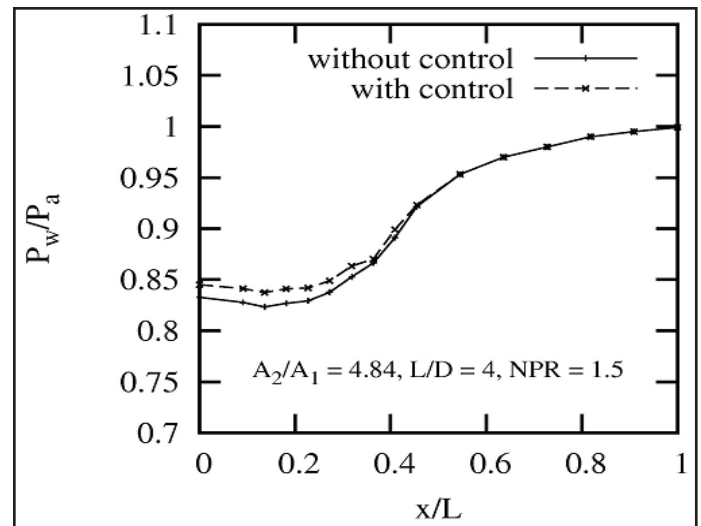


Fig. 20: Wall Pressure Distribution

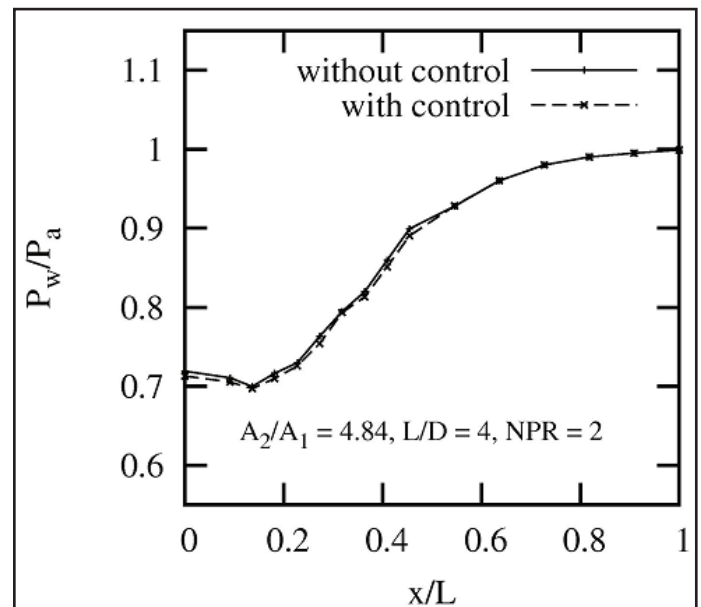


Fig. 21: Wall Pressure Distribution

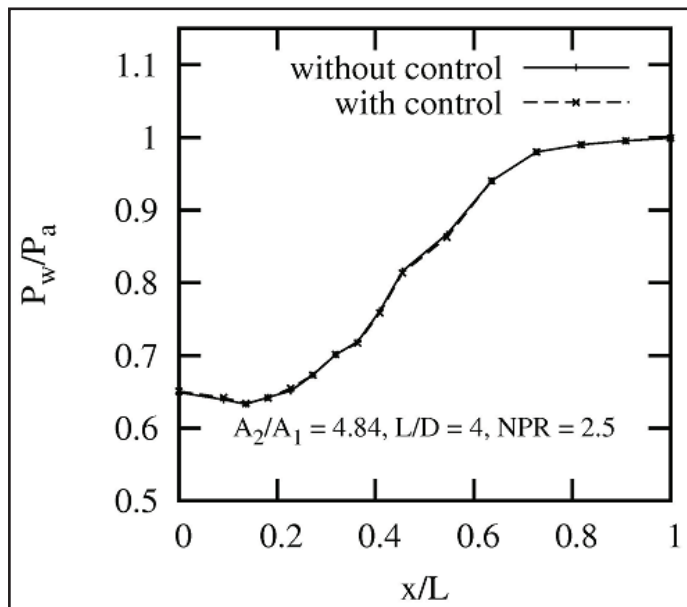


Fig. 22: Wall Pressure Distribution

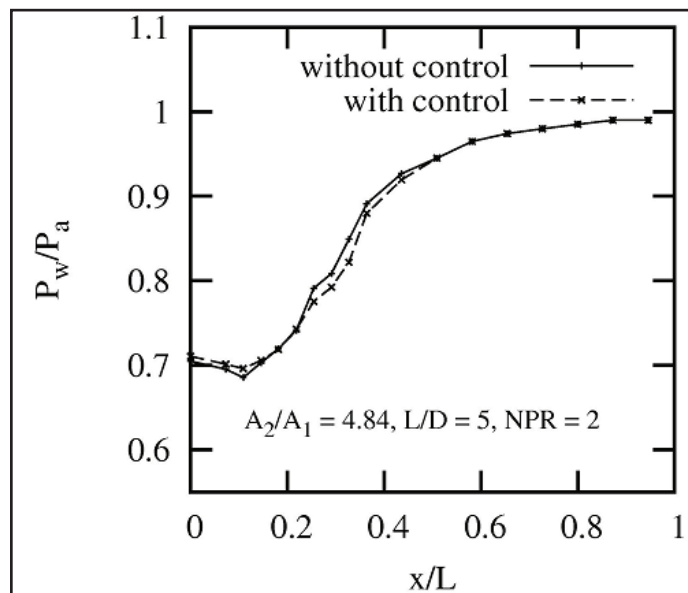


Fig. 25: Wall Pressure Distribution

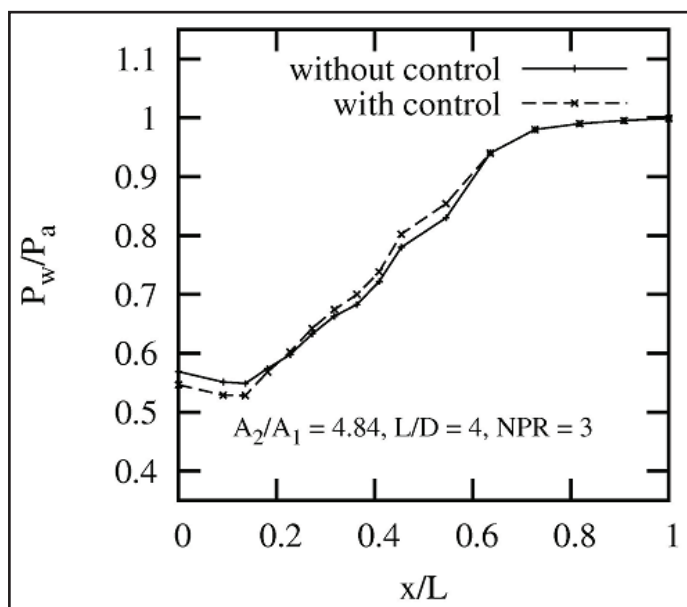


Fig. 23: Wall Pressure Distribution

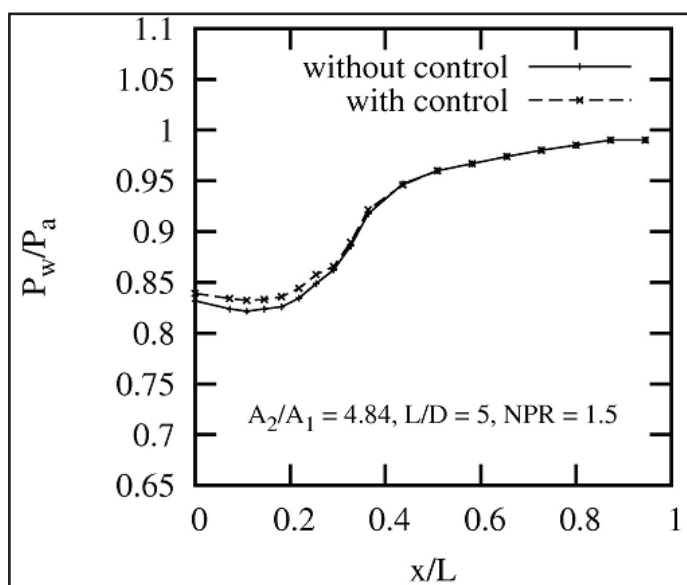


Fig. 24: Wall Pressure Distribution

Fig. 24 presents wall pressure results for $L/D = 5$, these results are similar as shown in Fig. 20. Fig. 25 presents results for $L/D = 5$ and $NPR = 2.0$, here within reattachment length there is waviness in the wall pressure field in the duct and control results in marginal decrease in the wall pressure. Fig. 26 presents similar results as shown in Fig. 22 and there is a further decrement the wall pressure value, the wall pressure flow field in the duct with and without control remains the same. Fig. 27 shows results for $L/D = 5$ and $NPR = 3$, here again control results in decrease of wall pressure and further downstream the recovery in wall pressure flow field is smooth. This further decrease in the wall pressure is attributed to the following reasons; the flow is attached, the pressure gradient is favorable, and due to the high value of L/D ratio it will result in increase of suction at the base region.

Fig. 28 shows the wall pressure results for $L/D = 6$ and $NPR = 1.5$, in this figure the flow field in the enlarged duct with and without control are identical, it is also seen that for the duct length beyond the reattachment length there is smooth recovery of wall pressure. For $NPR = 2.0$, and $L/D = 5$ the wall pressure results are shown in Fig. 29. It is well known that the NPR required for choked flow condition is 1.89 for isentropic flow, however, for the real situation of the flow at $NPR = 2$, the flow at nozzle exit definitely expected to choke, and when at this situation the wall pressure are measured in the duct, in this region there could be nominal fluctuations in the wall pressure values and the control results in decrease of wall pressure within the range of reattachment length. Similar results are seen in Fig. 30 for $L/D = 6$ and $NPR = 2.5$, only initial value of wall pressure has decreased with small fluctuations and the general behavior remains the same. The reasons for this trend are the large length of the duct and high inertia at the nozzle exit available to the flow.

Fig. 31 presents results for $L/D = 6$ and $NPR = 3$, it is seen from the figure that the control results in increase of wall pressure and the wall pressure in the base region is decreased by 50 percent.

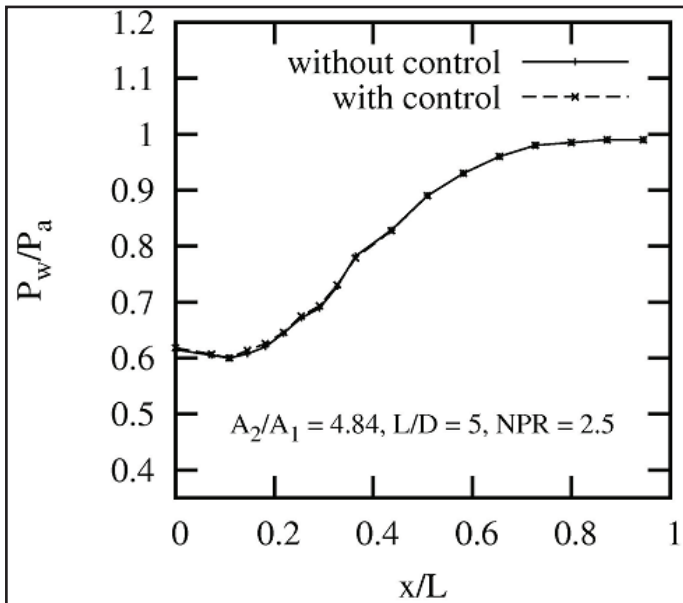


Fig. 26: Wall Pressure Distribution

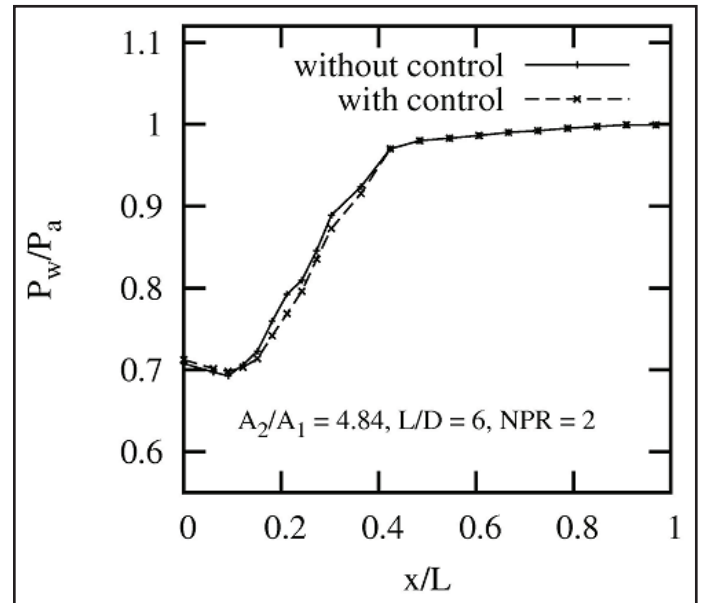


Fig. 29: Wall Pressure Distribution

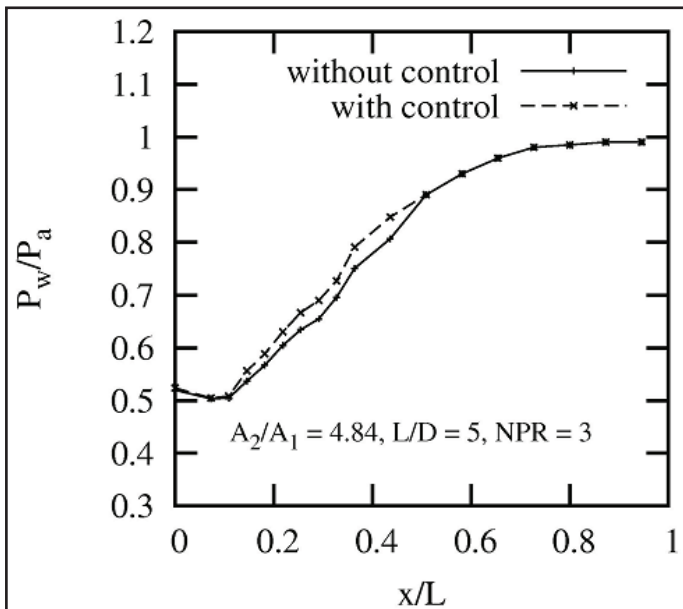


Fig. 27: Wall Pressure Distribution

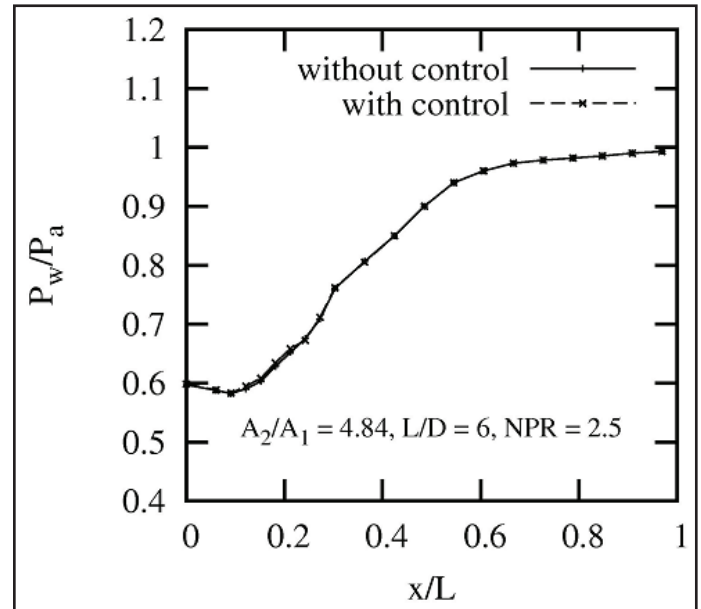


Fig. 30: Wall Pressure Distribution

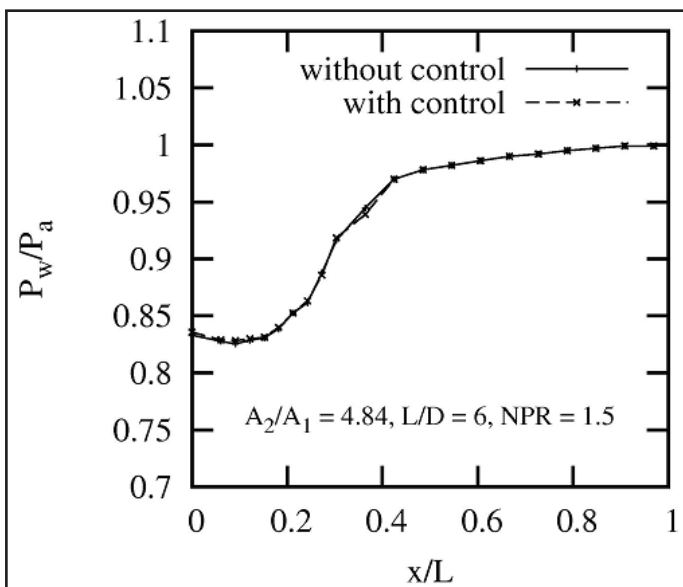


Fig. 28: Wall Pressure Distribution

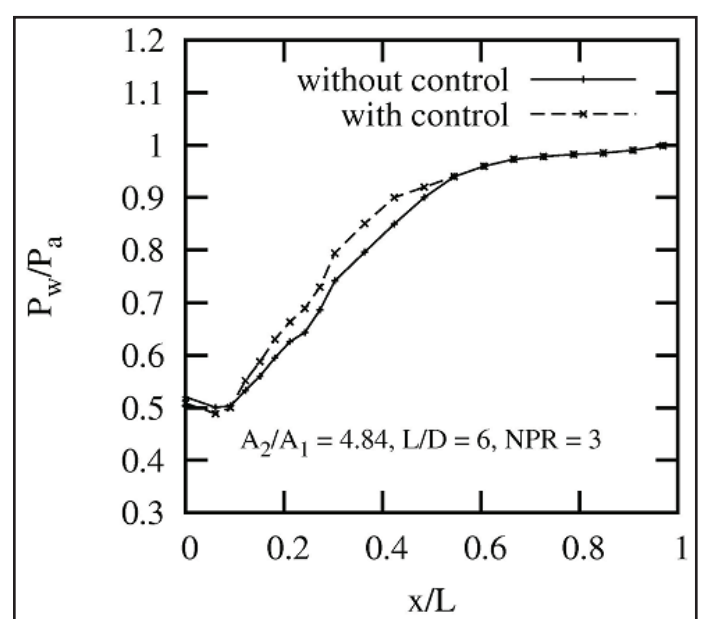


Fig. 31: Wall Pressure Distribution

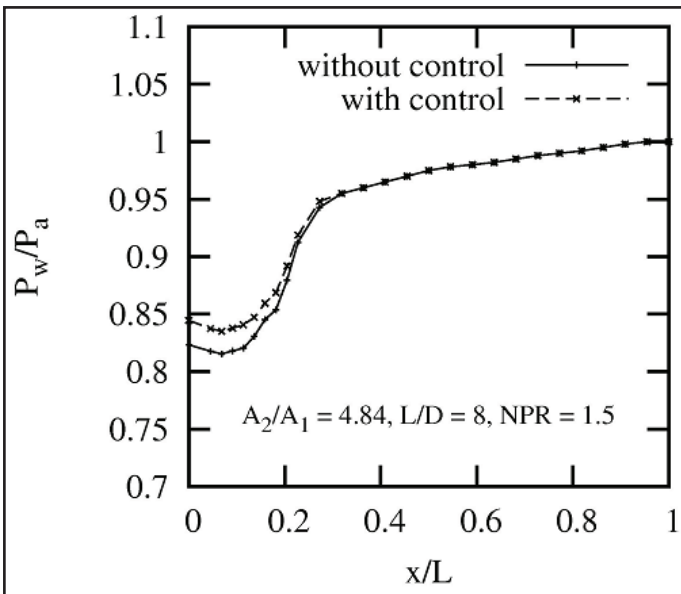


Fig. 32: Wall Pressure Distribution

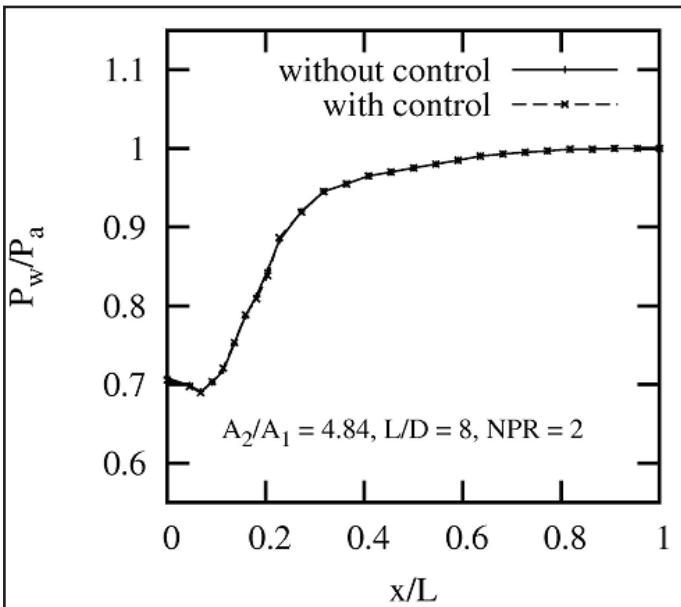


Fig. 33: Wall Pressure Distribution

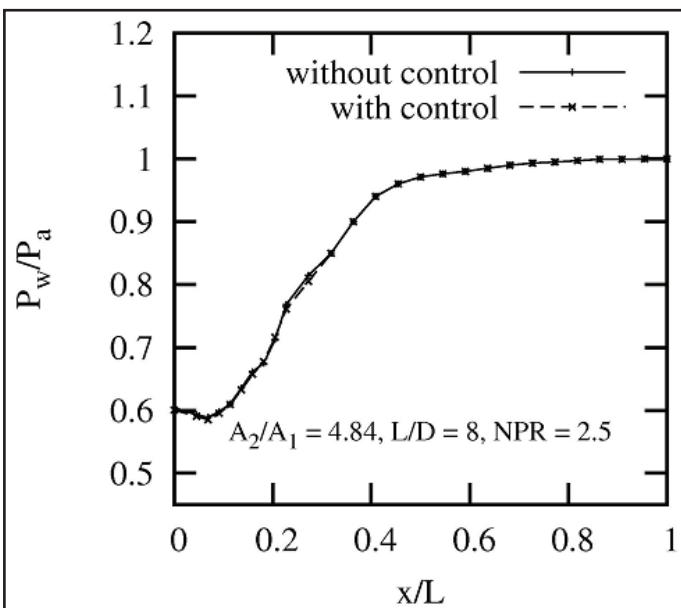


Fig. 34: Wall Pressure Distribution

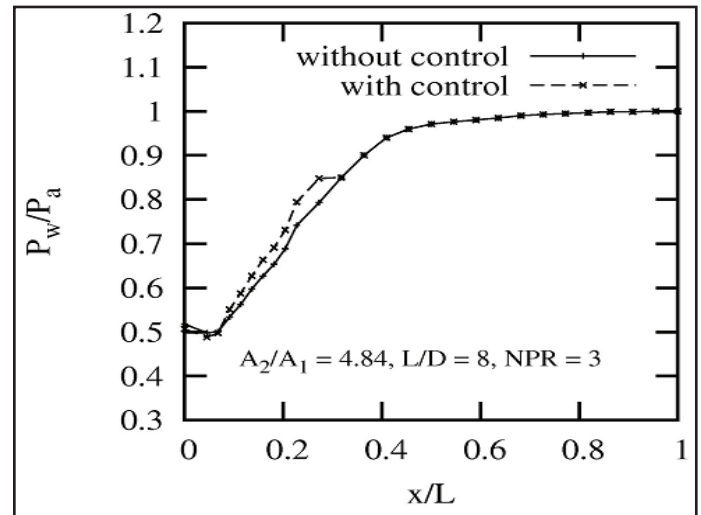


Fig. 35: Wall Pressure Distribution

Results for $L/D = 8$ are shown in Figs. 32 to 35 for NPRs from NPRs 1.5 to 3. In Fig. 32 for $NPR = 1.5$ in the base region the control results in decrease of wall pressure and this decrease happens in the region around 30 percent from the leading edge of the duct, and further, downstream of the duct wall the pressure recovery is smooth. Similar results are shown in Figs. 33 and 34 for NPRs 2.0 and 2.5, here the only difference from the previous case is the initial value of the wall pressure comes down from 0.85 to 0.7 and then 0.6 and this decrease in the wall pressure is due to increase the inertia of the flow and hence; the level of expansion, the flow field in the enlarged duct is identical for the cases with and without control. However, in Fig. 35 when we consider the case for $NPR = 3$, the starting value of wall pressure has further reduced and the control results in increase of wall pressure in the base flow region. The reason for further decrease in the base pressure is due to the presence of expansion fan at the nozzle exit which will flow further downstream of the duct.

Results for $L/D = 10$ are shown in Figs. 36 for $NPR = 1.5$, it seen that these results are similar to that of for $L/D = 8$ however, some oscillations are observed at the base region and control results in decrease of base pressure. Similar results are seen in Figs. 37 and 38 for $NPR = 2, 2.5$. The wall static pressure assumes low value for initial two taps; however the flow field is unaltered for both with and without control cases. Fig. 39 presents wall pressure results for $NPR = 3$, it is found that within the base region

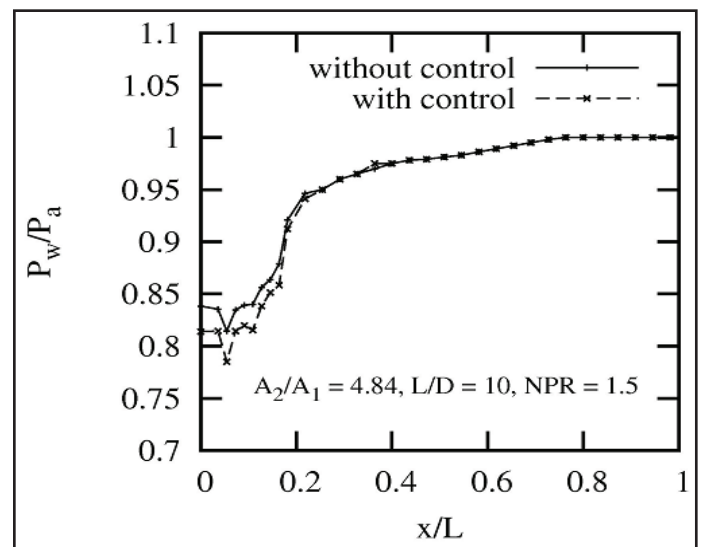


Fig. 36: Wall Pressure Distribution

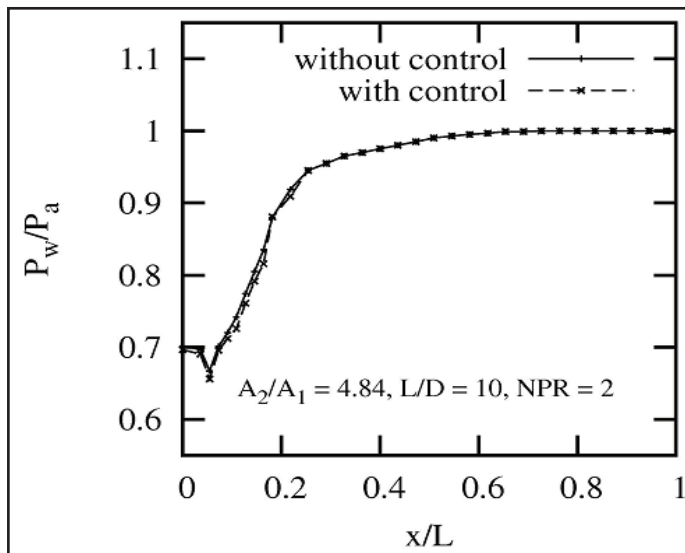


Fig. 37: Wall Pressure Distribution

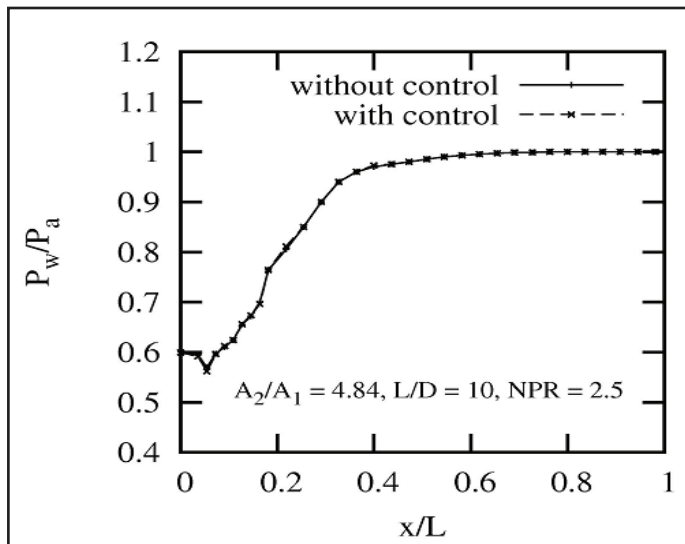


Fig. 38: Wall Pressure Distribution

the wall pressure assumes very low value and control results in increase as well as decrease of the wall pressure when the flow is moving from the leading edge of the duct towards the end of the base region and further, downstream of the duct wall, and this recovery in the wall pressure

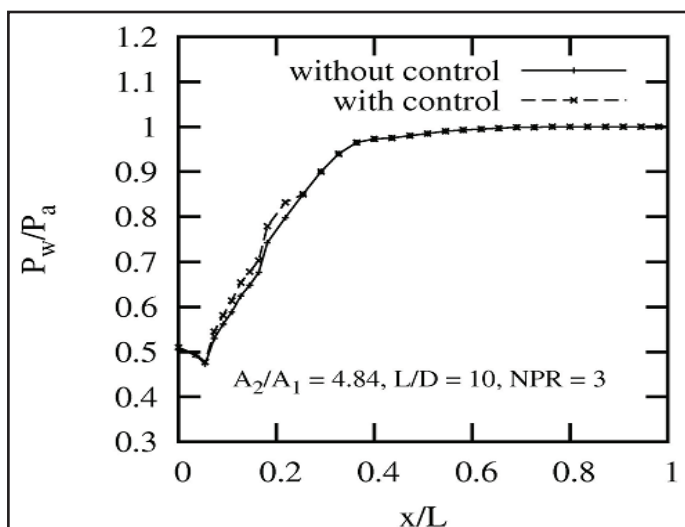


Fig. 39: Wall Pressure Distribution

is achieved within the 30 percent of the length from the leading edge which; is happens to be the reattachment length for the particular case.

V. Conclusion

From the above results the following conclusions can be drawn:

1. From these results it is evident that area ratio which governs the relief effect has got a definite role to play on the level of base pressure value.
2. Whenever the relief increases due to increase of area ratio, the shear layer from the nozzle exit has a tendency to attach with duct wall at a later stage as compared to lower area ratios. This result in higher suction at the base region as compared to lower area ratios when the duct length is above some limiting value.
3. When duct length is less than this limiting value, the expanding flow has got a tendency to relax more than what it would be for lower area ratio, thereby not establishing the powerful suction at the base region.
4. The wall pressure distributions in the wall duct are identical for both cases i.e. for with and without control.
5. It is found that for lower NPRs the wall pressure assumes higher values and with the increase in NPR and thereby by increasing the inertia at the nozzle exit the base suction will increase and as high as 50 percent decrease in the wall pressure has been achieved.
6. The present results are case sensitive, and very carefully one has to take the decision, hence, if for example if the application is for combustion chamber where the requirement is the lowest base pressure value, whereas, for the flow at the blunt base of the external flow the base pressure should be as high as possible to reduce the base drag and hence increase in the range of the projectile and missiles.
7. Experimental results of the present work are a technology demonstration and the data base has to be used very carefully.

All the non-dimensional base pressure presented in the 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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