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# Active Control of Wall Pressure Flow Field at Low Supersonic Mach Numbers

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***Abstract:*** *This paper presents an experimental study of airflow from convergent-divergent nozzles discharged into enlarged duct, focusing attention on the flow development in the duct. To investigate the influence of active control on the flow field developed in the duct, the micro jets of 0.05 mm radius orifice placed at $90^0$ interval along the base at 6.5 mm from the main jet were employed. The Mach number of this study was 1.3. The area ratio of the present study was 2.56. The NPR presented are from 3, 5, 7, 9, and 11 respectively. The L/D ratio of the duct was varied from 10 to 1. The level of expansion at the nozzle exit influences the wall pressure very strongly since in the present case all the NPRs of the tests are under expanded. For all the L/D the entire flow field in the duct is full of waves, the few shock wave is so powerful that the wall pressure is equal to the atmospheric pressure or more. At L/D = 3, it is seen that due to the influence of the back pressure the number of compression and expansion waves have reduced drastically. The flow field with and without control is identical.*

## I. Introduction

Researchers in the field of external Aerodynamics have long been wondering with the problem of back ward facing step as well as the external compressible flow at the base of missiles.Researchers were interested to correlate the phenomena of low base pressure at the base area with the boundary layer thickness, its type. The experiments conducted as well as the aerodynamic data extracted from the Radar revealed that the base pressure at the base will very low, and due to this low base pressure will contribute significantly to the base drag. From their test they observed that base drag is very high in the transonic zone. It could be in range of 60 % of the total drag as compared 10 % of the skin friction drag in sub-sonic flow. From the earlier study it was found that the study of base flow with internal apparatus has got distinct advantage over the usual external ballistic test. This is also well established that when the flow is sub-sonic the flow will get affected all along, when Mach number is 1 it divides the flow field in to two region, one is being zone of action and the other one is the zone of silence. When the Mach number is greater than 1 there will be an oblique shock at the nose of the projectile which will the flow in the zone of action and zone of silence. So for the flow over axi-symmetric bodies in case of external flow it flows inward whereas, in case of internal flow it will be out ward. We will be utilizing this phenomena of the flow to study by internal flow.

Borda [1] studied experimentally the flow field of circular duct with water. Crocco and Lee [2], Chapman [3]and Kurzweg [4] from their investigation found that the base is very much related with the upcoming Boundary layer, its locations and the type. In view of chapman Chapman [3] concluded that the boundary layer thickness immediately upstream of the corner decidesthe pressure at the base region for missiles and a variable that was the L/D ratio, be divided by the Reynolds Number to the $1/5^{th}$ power to correlate his experimental results. The effect of boundary layer on sonic flow with sudden expansion was studied experimentally by Wick [1]. He concluded that the pressure in the base corner of expansion was function of the boundary layer type at the expansion. They thought that the boundary layer as a source of fluid for theflow in the base corner. Whereas, in view of Hoerner [5] the boundary layer acts as an insulating air that reduces the efficiency of the flow from the nozzle as a pump. Primary source of flow was the boundary layer flow around the corner and the secondary source was backflow in the boundary layer along enlarged duct. The reason for this reverse flowwas due to the pressure gradient along the shock wave emanating where the flow hits the duct wall. In his opinion the mechanics of internal and external flow was technically the same and base pressure phenomenon in external flow could be studied comparatively with ease by experiments with as compared to the internal flow. Rathakrishnan and Sreekanth [6]conducted experiments through circular pipes and from their tests they found that the pressure in the base area is a function of area of enlargement of the duct, the level of expansion and the inertia level.

Khan and Rathakrishnan [7-14] investigated the efficacy of the tinyjets as the flow regulator in the base corner for flows from C-D nozzles under the circumstances that at the exit of the nozzle adverse pressure gradientpersists for Mach numbers 2.0, 2.5, and 3.0. A maximum gain of 80 % in the base pressure was accomplished. The static wall pressure in the duct with and without control were identical.The experimental outcome to study the effects of micro jets under the influence of various level of expansion was done to control the base drag by Khan and others[12-19]. The result was very effective in terms of percentage, as micro jets reduced the base drag without affecting the wall pressure distribution. It is found that many techniques can be used to reduce or even suppress the flow separation.

## II. Experimental Procedure

The fringed nozzle-enlarged duct is fixed at the end of the settling chamber by a slot holder arrangement. The base pressure taps and wall pressure taps are measured matching the channels of pressure sensors connected on bread board to a data logger at a time in each run for different Mach numbers and expansion levels. Pressure sensors used for this experiment are Honeywell TruStability® Board Mount Pressure Sensors, HSC Series - High Accuracy, Low Pressure Sensors - HSCDANN015PAAA5 (Absolute) and HSCDANN010BGAA5 (Gauge). Data acquisition is done with the help of Graphtec MIDI LOGGER GL820, with a 20- channel input. The model area ratio (D2/d2) is varied in the range from 1.5 to 4. The L/D ratio is another variable parameter 4, 5, 6 for pipe diameters 19 mm, 16 mm, and 13 mm respectively. NPR can be calculated accurately, while Mach number can be estimated from isentropic relationships. The measurements include the stagnation pressure of the settling chamber, the base pressure, and the wall pressure distribution along the length of the duct. All of the pressures are measured using absolute pressure sensors, except for the settling chamber pressure, which is measured using gauge pressure sensor. A data logger is used for data acquisition. Tests done using pressure sensors and data logger for a particular case with repeated testing for the same, showed that it was repeatable within ±2~3% accuracy with the previous results of the same case.

## III. Results and Discussion

One of the major difficulty encountered while working in the area of sudden expansion is that the flow field in the duct becomes oscillatory because of the “Ejector Pump” action at the base region i.e. the vortices are getting formed at the base because of expansion of the shear layer from the nozzle and getting ejected to the main flow continuously. In the literature this action was known as the ***“Jet Pump action”.*** This action renders the flow in the duct to become oscillatory. Therefore, it is mandatory on the part of a researcher working in this area to monitor the flow development in the duct. In other words when we employ a control to regulate the flow at base and in the duct. It is mandatory on our part to ensure that the control might alter the nature of the flow in the duct. To take care for this undesirable effect using pressure transducer and the multi-tube manometer was used to record the static pressure in the duct for all the L/Ds and NPRs of the present investigation. Before we analyze the results let us discuss the conditions for this Mach number of 1.3. The NPRs of the present tests are such that the flow at the exit of the nozzles experiences favorable pressure gradient for all the NPRs. The NPR for correct expansion is 2.77. Which means that with the change in NPR only the level of favorable pressure gradient will be changing at different NPRs. Results for L/D = 10 for NPRs 11, 9, 7, 5, and 3 are presented in figures 1((a) to (e)). From Fig. 1(a) to (d) it is seen that at NPR = 11, 9, 7, and 5 the entire flow field in the duct is full of waves, the few shock wave is so powerful that the wall pressure is equal to the atmospheric pressure for NPR 7 and 5 whereas, for NPRs 11, and 9 initially it is equal to ambient pressure later it get enhanced 45 and 20 percent and then through the next shock the wall pressure assumes equal to the value of the atmospheric pressure. At NPR = 3 there is oblique shock which results in steep rise in pressure and later flow gets expanded and again getting compressed then it becomes smooth. Since the flow is highly under expanded the initial values of the wall pressure at x/L = 0 are 0.8, 0.7, 0.58, 0.4, and 0.38 for NPRs 11, 9, 7, 5, and 3 respectively, the reason for the variations in the initial values is the change in the level of under expansion. Flow field with and without control remains the same.

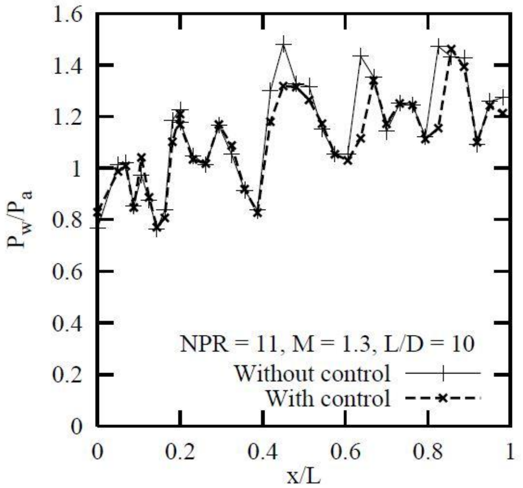



**Fig. 1 (a)**

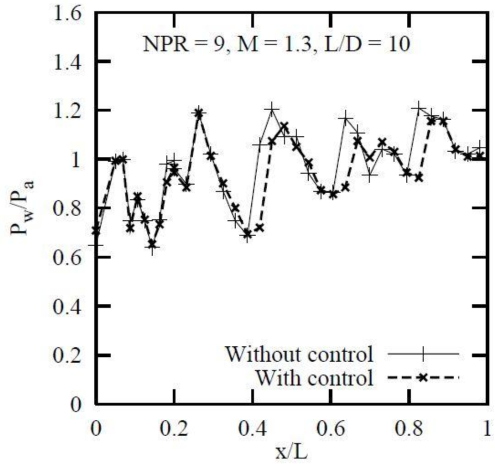



**Fig. 1(b)**

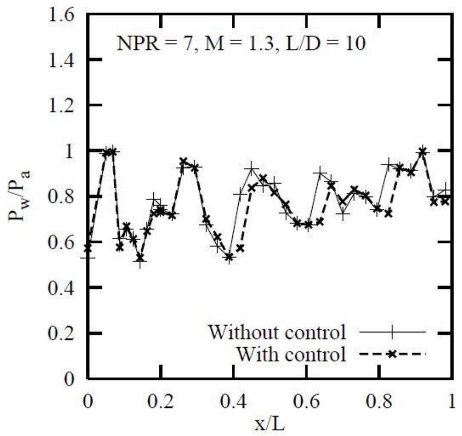



**Fig. 1 (c)**

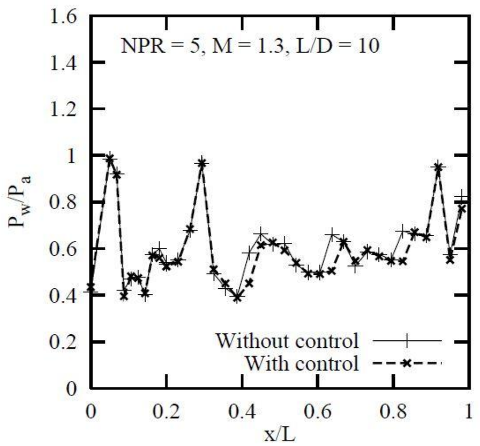



**Fig. 1(d)**

Fig. 2((a) to (e)) depict the experimental outcome of the investigations for duct length of 8D as observed above for the case of L/D = 10, the wall pressure flow field is associated with the compression and expansion waves for NPRs11, 9, 7, and 5 and for NPR 3 no such trend is seen. Further, due to decreased L/D, the initial jump in the wall pressure has gone up by 20 % and 40 % for NPRs11, 9 and 7. Some fluctuations in wall pressure with and without controls are observed for higher NPRs 11, 9, 7, and 5 towards the end of the duct due to back pressure effect.

Figs. 3((a) to (e)) show the outcome of the investigation for L/D = 6 it is seen that for the same NPRs, for NPRs 11, 9 and 7 there is a sudden jump in the initial wall pressure and it has gone up by 85 %, 55 % and 20 % respectively for NPRs 11, 9 and 7, however, for NPRs 5 and 3 the trend is the same as discussed earlier. Another phenomenon observed is that number waves have reduced considerable due to the short duct length and flow is likely to become smooth with further reduction in duct length.

Results for NPRs 11, 9, 7, 5 and 3 for L/D = 5 are shown in Figures 4((a) to (e)), they similar results as discussed earlier for NPRs 11, 9 and 7 for this L/D = 5 as well, but when we see the results for NPRs 11, 9, 7, and 5 there is marginal change in the terms of shock strength and number of waves due to the reduction in the duct length. Also it is seen that the initial jump has further increased to the level of 80 %, 50 %, and 20 % for NPRs 11, 9 and 7. Rest of the behavior remains the same. Results for L/D = 4 and are on the similar trends as that of L/D = 5 as shown in Figs. 6((a) to (e)). Even though trend is same but the strength of the shock is the highest for the L/D = 4, and the jump is 95 %, 60 %, and 25 % for NPRs 11, 9, and 7. This trend may be due to the combined effect of the NPR, Mach number, duct length, and the influence of the back pressure.

Never the less in the of L/D = 3, due to the influence of the back pressure the number of compression and expansion waves have reduced drastically, but for higher NPRs 11, 9, 7, and 5 it has aggravated. There is a reduction in the percentage increase which is 78 %, 50 %, and 15 % for NPRs 11, 9, and 7 respectively. However, for L/D = 3, with a number of oblique shock waves the flow recovery takes place.

Figs. 7((a) to (e)) show the results for L/D = 2 and trend of the flow field remains the as that of L/D = 3 for NPRs 11, 9, 7 and 5, but at NPR = 3, without control the suction which was created for all the L/Ds NPRs was created is no more visible when active controls are employed and the value of wall pressure increases from as low as 0.3 to 0.75, this behavior is due to the overall effect of NPR, L/D, and due to the influence of ambient atmospheric pressure.

Figs. 8((a) to (e)) show outcome of investigation for lowest duct length (i. e. L/D = 1) the flow is no more attached at NPR = 3 as seen in Fig. 8(d). Another observation is that when were employed there is marginal increase in wall pressure for all the NPRs in the range 11, 9, 7,and 5 for L/D = 1. We can neglect the results for NPR = 3, as the flow is detached with the duct wall.

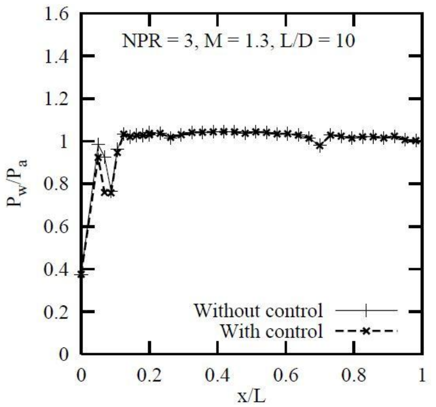



**Fig. 1 (e)**

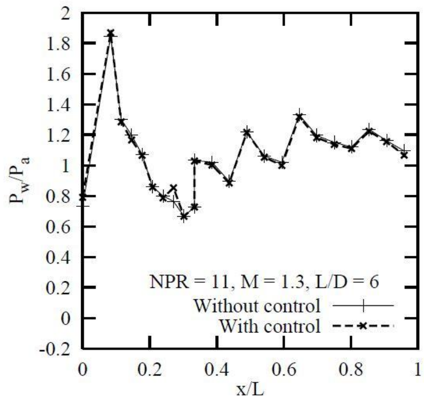
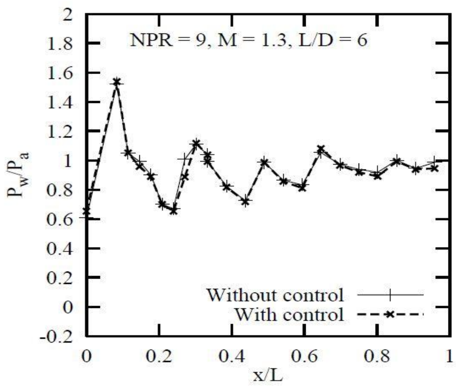



**Fig. 2 (a)**

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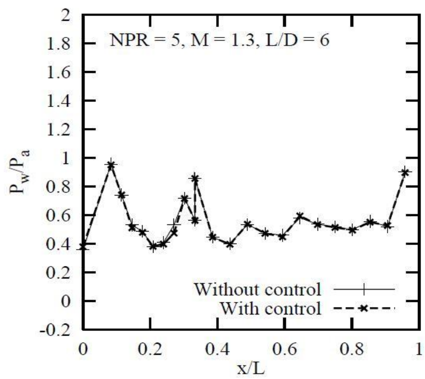



**Fig. 2 (c)**

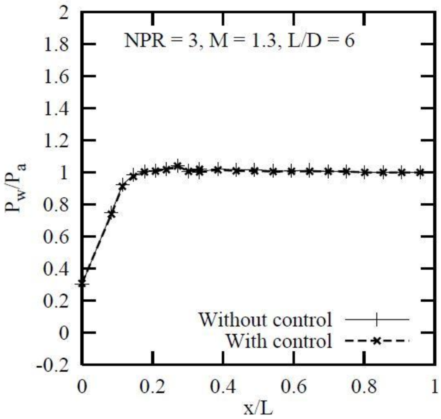



**Fig. 2 (e)**

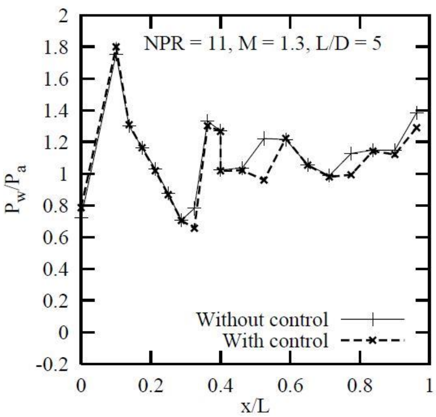



**Fig. 3(a)**

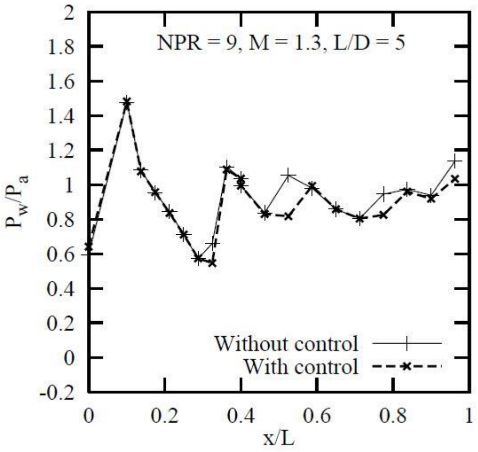



Fig. 3 (b)

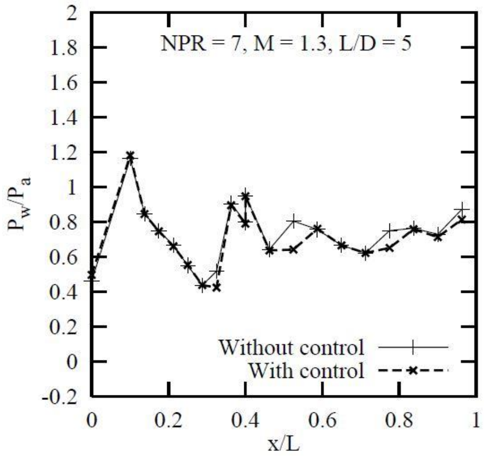



Fig. 3(c)

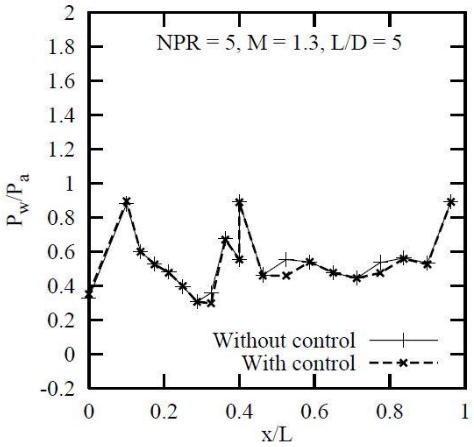



Fig. 3 (d)

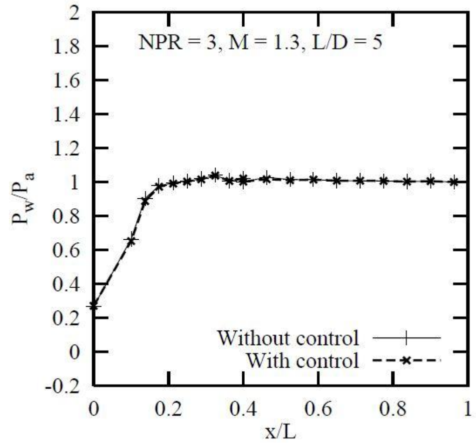



Fig. 3 (e)

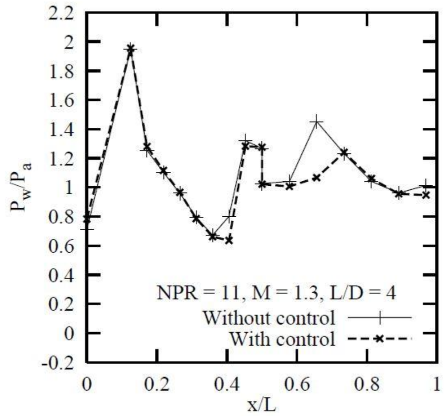



Fig. 4 (a)

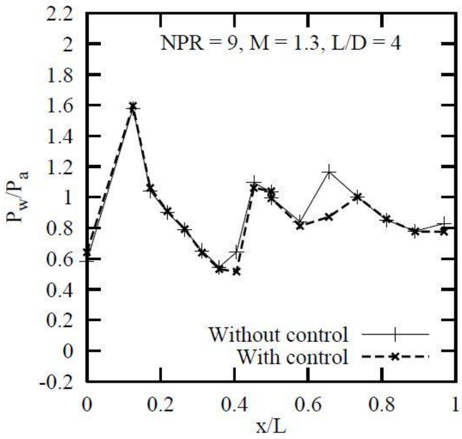



Fig. 4 (b)

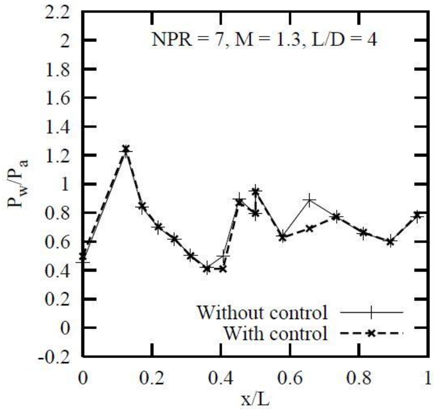



**Fig. 4 (c)**

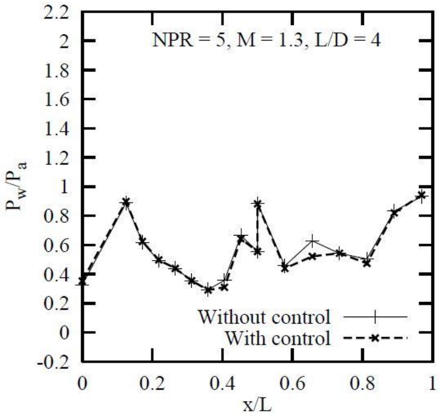



**Fig. 4 (d)**

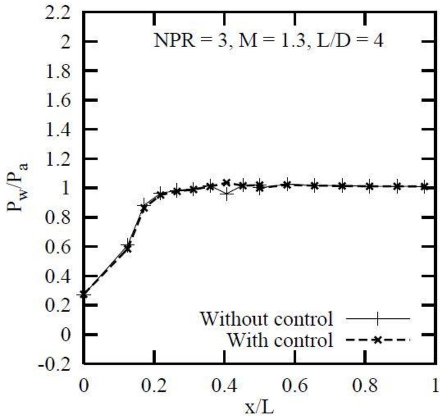



**Fig. 4 (e)**

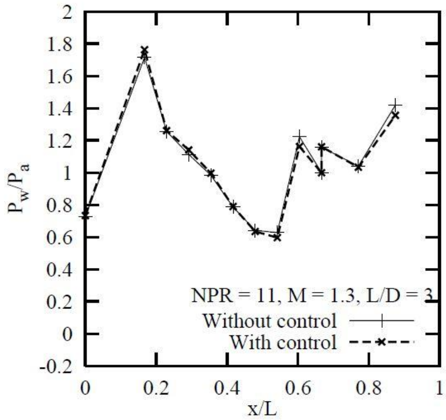



**Fig. 5 (a)**

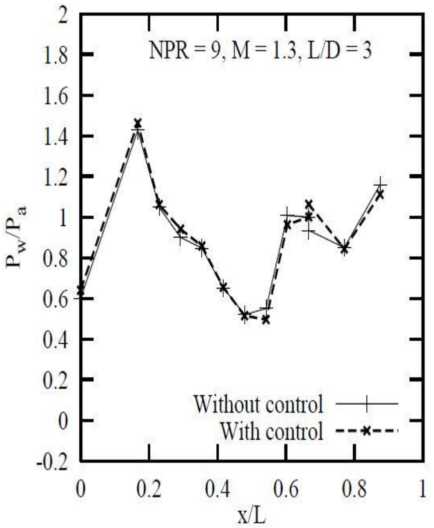
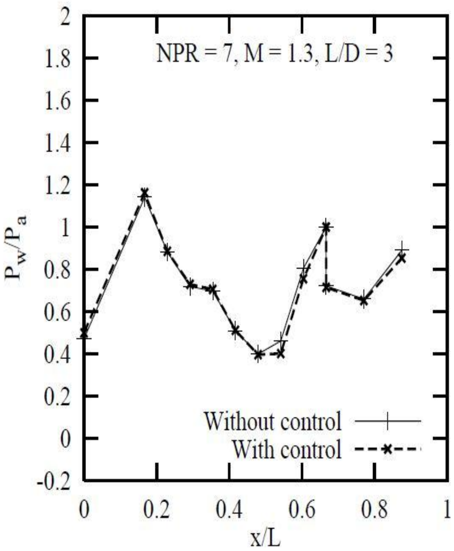



**Fig. 5 (b)**

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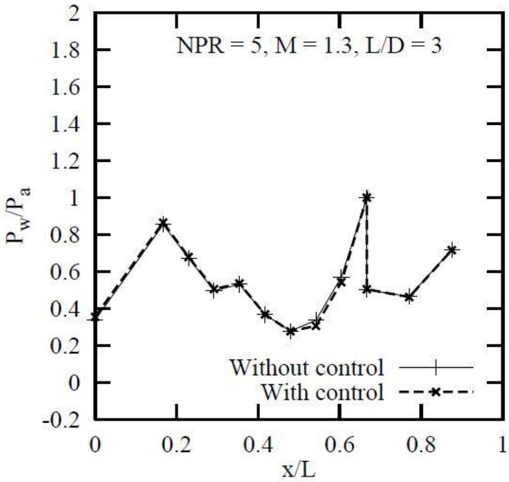



**Fig. 5 (d)**

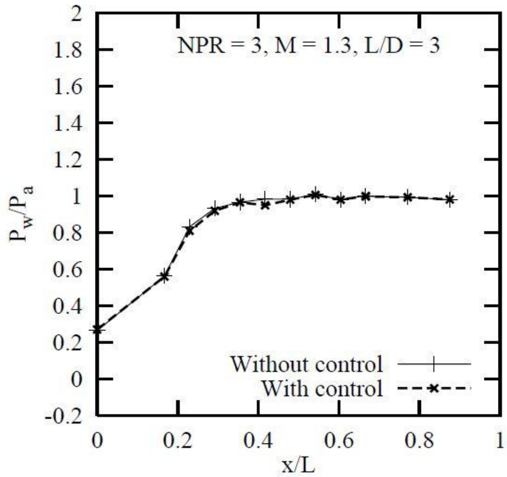



**Fig. 5 (e)**

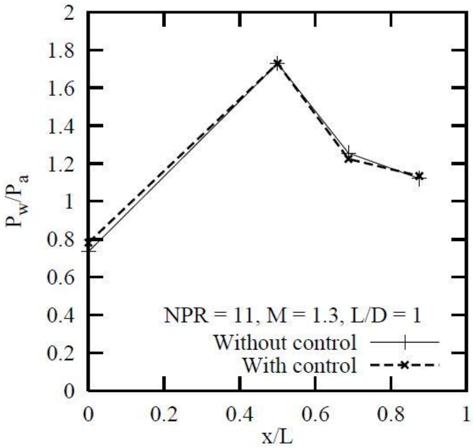
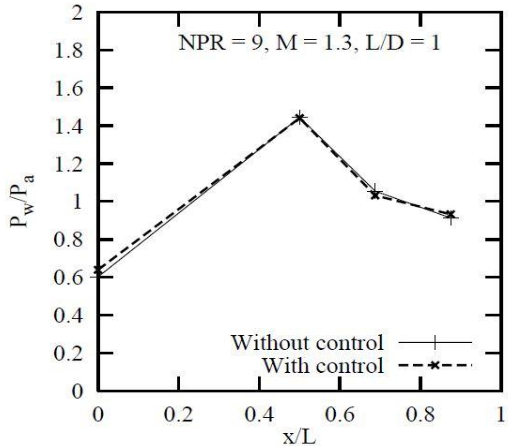



**Fig. 6 (a)**

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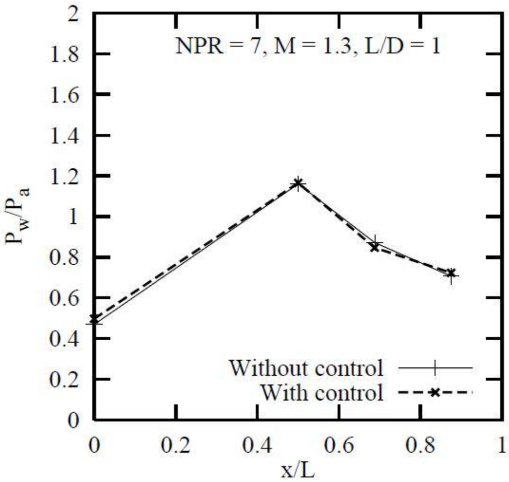


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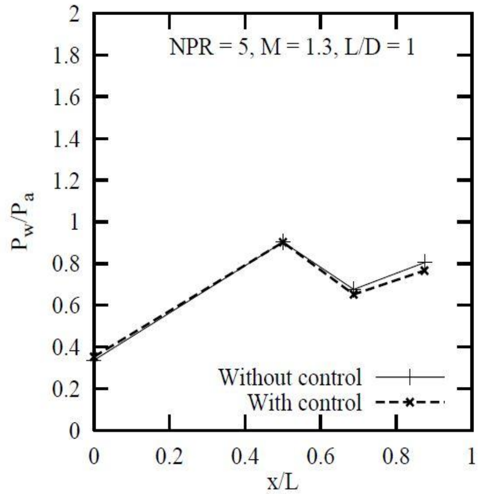


**Fig. 6 (d)**

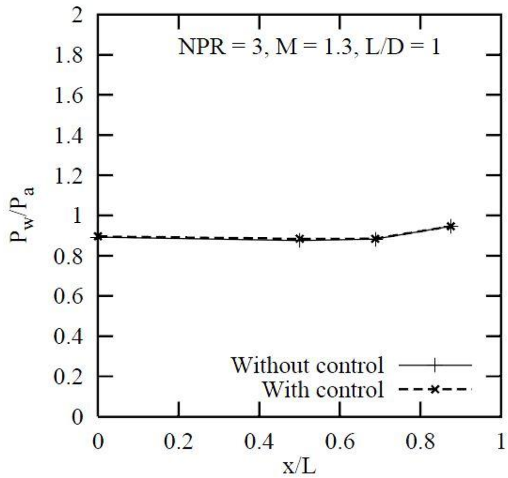


**Fig. 6 (e)**

## IV. Conclusions

- The NPRs of the present tests are such that the jets remain under expanded for all the NPRs. The NPR for correct expansion is 2.77. Hence only the level of under expansion is changing at different NPRs.
- For all the L/D the entire flow field in the duct is full of waves, the few shock wave is so powerful that the wall pressure is equal to the atmospheric pressure or there is as high as 100 %, to 20 % increase in the initial wall pressure value is recorded, the reason for the variations in the initial values is the change in the level of under expansion. Flow field with and without control remains the same for all the cases of the present tests.
- For L/D = 6 there is a sudden jump in the initial wall pressure. Another phenomenon observed is that number waves have reduced considerable due to the short duct length and flow is likely to become smooth with further reduction in duct length.
- When L/D = 3, it is seen that due to the influence of the back pressure the number of compression and expansion waves have reduced drastically, but for higher NPRs 11, 9, 7, and 5 it has aggravated. There is a reduction in the wall pressure value. However, for L/D = 3, with a number of oblique shock waves the flow recovery takes place.
- In case of L/D = 2 at NPR = 3, with and without control the suction which was created for all the L/Ds and NPRs was created is no more visible when active controls are employed and the value of wall pressure increases from as low as 0.3 to 0.75, this behavior is due to the combined effect of NPR, L/D, and due to the influence of ambient atmospheric pressure. We can neglect the results for NPR = 3, as the flow is detached with the duct wall.

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