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Research Article

Controlling The Base Pressure Of A Supersonic Body Subjected To Sudden Expansion Flow Using Micro Jet

Mohammed Aneeque[a], Maughal Ahmed Ali Baig[b], Mohammed Avvad[c]

[a]Mechanical Engineering, P A College of Engineering, Mangalore, India, kmaneeque@gmail.com
[b]Mechanical Engineering, CMR Technical Campus, Hyderabad, India, mabaig09@gmail.com
[c]Mechanical Engineering, P A College of Engineering, Mangalore, India, cmavvad@gmail.com

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Abstract: Researchers involved in the area of external aerodynamics have been particularly bothered with the issue of the sudden expansion of the flow at the rear end of the projectile and its relationship to the base pressure. One specific issue particularly of concern is that the pressure at the base of the projectile is less than the ambient pressure. The base pressure control method mentioned in most of the earlier studies is passive control methods, providing sufficient scope to research the impact of active control methods. The present study is experimental research, conducted on the sudden expansion of the flow in a supersonic nozzle. The study focuses on the effectiveness of controlling base pressure using micro-jets (active control method). It aims to highlight the variation in base pressure, with the control method and without it. The parameters considered are area ratio, length-to-diameter (L/D) ratio, and nozzle pressure ratio (NPR). We used area ratios that were not used earlier for Ma = 2.58. The effect of the above parameters on the base pressure is presented. The result suggests that at a higher NPR and higher L/D ratio, the reattachment of the flow occurs with the use of micro-jets. Also, for a constant area ratio with variation in L/D ratio and NPR, it is found that the base pressure considerably decreases.

Keywords: microjets, base pressure, area ratio, L/D ratio, NPR, nozzle

1. Introduction

In the field of aerodynamics (rockets, aircraft, missiles, and projectiles), objects subjected to higher Mach number leads to form a recirculation zone with low pressure to the vicinity of the base. Investigators working in the field of external aerodynamics have studied the problem associated with the abrupt expansion of flow at the backside of the projectile and its relationship with base pressure and found that free stream atmospheric pressure is higher than the base pressure[1]. In this way, for the subsonic stream where wave drag will not be there, the base drag is just 10 percent of the skin contact drag. Whereas for transonic speed, it is up to two-third of aggregate drag, and for supersonic speeds, it is around one-third caused due to difference in pressure. In order to reduce base drag, methods like base burning, base bleed, and boat tailing were used early. Many investigations have been carried out using the passive control method, but a very less number of studies has been done using the active method. Here we are investigating the problems related to the internal flow in an abrupt expansion flow field. The study shows that there is a huge number of advantages as compared to the other test procedures used for rocket launching. One important advantage of using internal flow is that here we can get complete measurements of static pressure and surface temperature in the entrance as well as wake region. Here a large amount of air supply is needed to conduct an experiment as the text section is large, and there should be no disturbance due to wall interference.

When a body moving with a certain speed subjected to suddenly expanded flows, on the external force of the body, flow recirculation, reattachment, and separation of flow may take[s place. When a flowing fluid over a body detached, it forms a region between the fluid and a body, this region with low pressure behind the body in which recirculation and backflow take place is known as a separated region. When a separated streamline strikes the body, then it is called a reattachment point, as shown in Fig. 1.

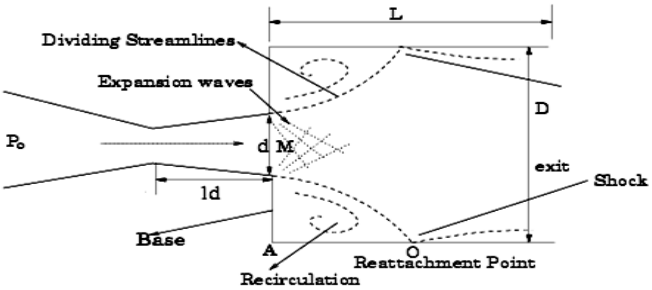


Fig.1 Sudden Expansion Flow Field

The significant features of the flow are similar both in laminar as well as turbulent but differ in detail. When the enlargement section begins, an area of divided streams formed quickly downstream of the section for all Reynolds numbers. There may be an expansion fan or an oblique shock at the nozzle exit, depending on whether the stream is extended or over-expanded, assuring that nozzle exit Mach number is supersonic. At the nozzle exit, there will be an expansion fan for correct expansion, but for under expanded flows, the strength of the fan will be lesser. Before reaching the base region, the nozzle flow will have to pass through these waves. In supersonic flows, because of the sudden extension and stream turning (toward the center line by oblique shock and away from the center line by expansion fan), the combined relief effect will dictate the strength of the base vortex and thus the base pressure value

2. Literature Review

When a body moving with a certain speed subjected to suddenly expanded flows on the external force of the body, flow recirculation, reattachment, and separation of flow may take place. Plenty of work has been done on bodies subjected to sudden expansion problem. However, the available research on this problem is restricted for particular flow and geometrical parameters. In the present literature, the focus is given on a particular problem associated with sudden expansion flow. Some of the literature pertinent to the present investigation is briefly highlighted. Nusselt [2] was the first to conduct experiments on ducts with sudden expansion in the cross-sectional area. The flow of gas with high velocity is discharged through the duct. The major outcome of his experiment says that the pressure at the entrance region plays a critical role, and it is observed that for subsonic flow ($M<1$), the base pressure is equivalent to the pressure at the entrance region. However, for supersonic flow ($M>1$), these two pressures may not equal but vary. However, Nusselt's analysis fails to evaluate the factors controlling the base pressure. The investigation says that the base pressure study for internal flow is easier to conduct in comparison to external flows. An experimental investigation conducted by Wick [3] mainly focused on flow with Mach number equal to one in which there is a drastic change in the area of the duct.

A two-dimensional sonic flow with boundary layer effects was studied by Korst [4] experimentally. He compared his experimental results with theoretical results available in the literature and found to be under the good agreement. In another study Korst [5] experimentally determined the supersonic flow problems related to base pressure. The investigation reported by Badrinarayanan [6] shows the significance of flow separation and flow reversal. The pressure increases significantly due to the effect of air injection at the base. A study related to features of internal flow has been reported by Ackeret [7]. Throughout his analysis, he found that in the case of internal flow, three-dimensional boundary layers would appear. He also concluded that the equation of continuity plays an important role if compressibility is present. The turbulence in base pressure of supersonic flow is analytically found out by Mueller [8], and according to their studies, the pressure at the base is categorized based on the assumption of rising or fixed pressure in the jet mixing zone. Experiments conducted by Anderson and Williams[9], revealed the noise level produced by the sudden fluid expansion in a duct. They also stated that the noise level would be reduced due to sudden loss in the base pressure, which primarily depends on the specifics of the nozzle and area to duct ratio of the nozzle. Heskestad [10] studied the sudden enlargement flow by applying the suction scheme. He found that for fixed geometry and Reynolds number, there is a gradual increase in suction rate and increases due to the increase in pipe diameter, and a point is reached where the suction is critical. A study based on the effect of the injection rate at the entrance section of conical diffusers has been reported by Nicoll and Ramaprian [11]. They also studied the diffuser geometry on pressure recovery and sudden pressure loss. They came to the conclusion that even at moderate rates of injection, the diffuser performance is significant. The flow direction at the entry region and its impact on base pressure is investigated by Mueller [12]. His results along with experimental data of Ried and Hastings [13] shows good agreement for values $\gamma = 1.4$, $T_b/T_{0a} = 1$, $M_j = 2.0$, and $r_b/r_c = 0.58$. An experimental investigation conducted by Bar Haim and Weihs [14]mainly dealt with submerged bodies. They reported that drag reduction in submerged bodies could be controlled by managing the boundary layer. They came to the conclusion that separation of flow can be controlled, and the drag of axis-symmetric bodies can reduce by boundary layer suction. Khan et al. analyzed the experiments for a fixed value of under expansion with Mach numbers 1.25-1.6 for under expanded case [15-20]. In their study, they found out that under expanded flow, microjets are very effective. Control effectiveness is stated to be at its best when there is a favorable pressure gradient, whether it is active or passive. In one of the studies [21], it is found that for Mach numbers 1.25-1.6, microjets are not effective for a properly expanded case, and there is a slight change in base pressure. Also, they found that there is a formation of waves, which is not supposed to happen for the correctly expanded case. The study based on the area ratio of 2.89 at Mach number 2.4 in a suddenly expanded flow from the nozzle is reported by Pandey and Kumar [22] by using a fuzzy set theory. They noticed that parameters like base pressure, static wall pressure, and total pressure loss is responsible for smooth flow at $L/D = 4$. Pandey and Kumar [23] evaluated the results using the fuzzy-set theory for an optimal L/D ratio. They observed that for Mach numbers of 1.58, 1.74, 2.06, 2.23, L/D ratio = 6, which is close to experimental results for base pressure. From their analysis, they concluded that an optimum of L/D=6 is needed for better results. Alam et al. [24] carried out an experiment for supersonic flow using a method known as passive control, which includes a cavity which is partially filled by a solid surface. By using the passive control method, they came to the conclusion that there is a reduction in amplitude in the mainstream region and also in the internal part of the cavity in case of control flow. Khan and Rathakrishnan [25] and other similar papers [26-28] reported the study based on the control effectiveness and expansion intensity in a suddenly expanded flow. Studies on various NPR's, ranging from 3 to 11, were carried out considering, over, under and proper extended nozzle for four area ratios. It was discovered that an increase in base pressure with area ratio for the given nozzle pressure ratio, length-to-diameter ratio, and Mach number.

From the above survey, it shows that there is a large number of literature available on problems of sudden expansion, but most of them studied without any control. And the number of studies that has been reported with control, it is by using passive control such as grooves, cavities et cetra. Hence there are only few studies available that has looked into the active control method. In this paper, an attempt is made to study the flow regime in a supersonic flow and investigate the control effectiveness of microjets on the base pressure when compared to no control mechanism. It intends to study the effect of various area ratios (1.6, 3.62 and 10.08) for the given Mach no—2.58, which is not found in the literature. Also, an effort is made to find the optimum L/D ratio (9, 10, 11, 12) and the effect of NPR (2, 4, 6) on the base pressure. The combination of L/D ratio, NPR and Area ratio considered here is different from those available in literature.

3. Methodology

A. Experimental Setup

The experiments are carried out at supersonic Aerodynamics Laboratory, Mechanical Engineering Department, Bearys Institute of Technology, Mangalore. Figure 2 represents the experimental setup used for the conduction of the experiments. The present investigation is based on an active control method wherein the air is used as a blowing purpose. Eight holes of one mm diameter are drilled at the base of the nozzle. By using a pressure manometer, four holes are used to reduce vortex formation by blowing through the control chamber, and the remaining holes are used for calculating the base pressure. The control chamber has the same pressure as the pressure of the settling chamber when the air moves from the main settling chamber to the control chamber.

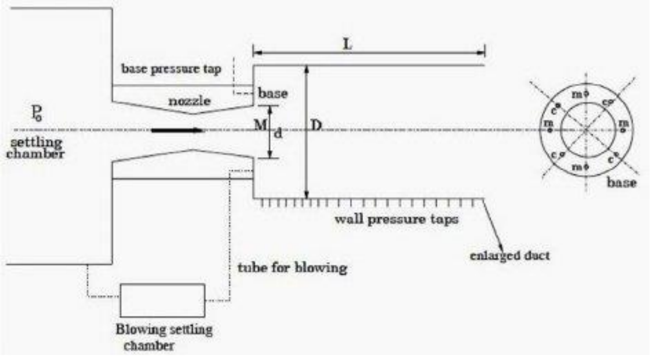


Fig. 2. Experimental Setup

Compressed dry air is produced and stored in a large storage tank. This air is passed to the settling chamber through a pipe connection using valves. A mixing length is constructed between the valve and the settling chamber to ensure the stagnation condition in the settling chamber is achieved. With a wide-angle diffuser, the flow from the mixing length pipe is enhanced. To attain a stagnation state and to reduce flow turbulence level, wire meshes are provided in the settling chamber. As the fluid reaches equilibrium in the settling chamber, it is extended freely to the suddenly enlarged duct through the nozzle. With the help of the valve, the air contained in the storage tank is controlled to flow into the settling chamber. When the flow is free of turbulence and the state of stagnation is reached, then the pressure is recorded in the settling chamber. With manometers, the base pressure and the pressure of the control chamber in the secondary chamber are also recorded. These readings are repeated by blowing the air through the orifice, and the influence of microjets is recorded. When the measurements are recorded for a specific L/D ratio of the duct, for the given area ratio and the NPR, and with and without control mechanism, the L/D is adjusted to the next lower L/D. The measurements are repeated for various L/D ratios. Then the experiment is repeated by changing area ratio, and all the measurements are recorded. This procedure is continued until all expected data for all the area ratios are acquired.

B. Outline of the Present Work

The present study is based on three area ratios (ratio between the enlarged duct and nozzle exit area), which were not used in the previous studies for the nozzle of Mach number 2.58. The flow from the settling chamber flows is made to flow from from the enlarged duct, which is actually connected to the nozzle on the other side to study the base effect. Also, microjets are used wherein the air is blown through it to the base of the duct. For the flow to be attached with a duct optimum, L/D ratio will be found out accordingly from 12 to 9. Experiments are performed for different L/D's (12 to 9), area ratios (1.6, 3.62, and 10.08), and NPR's (2, 4, and 6). The nozzle is made up of brass, whereas the enlarged duct is made up of GI pipe. The nozzle used in the experiment is fabricated for Mach number 2.58.

4. Results and Discussion

The present research focuses on the analysis of base pressure, wall pressure, and NPR using microjets. Different measurements were conducted to comprehend the effect of the area ratio, the L/D ratio, and the NPR on the base pressure. Other Flow parameters considered in the present research are the NPR and such geometrical parameters as area ratio and the L/D ratio of the enlarged duct. It is also to be noted that all the measured pressures are non-dimensionalized with back pressure (so-called ambient pressure). In the present study, area ratios used are 1.6, 3.62 & 10.08; and NPRs are in the range 2, 4 & 6. By applying the following formula, the percentage gain in the base pressure is obtained.

$$\begin{array}{c}\text{Change in}\\ \text{Base}\\ \text{Pressure, } \mathrm{P_B}\\ \text{(Percentage)}\end{array} = \frac{\mathrm{P_{Bcontrol}} - \mathrm{P_{Bwithoutcontrol}}}{\mathrm{P_{Bwithoutcontrol}}} \times 100$$

A. Effect of Area Ratio on Base Pressure

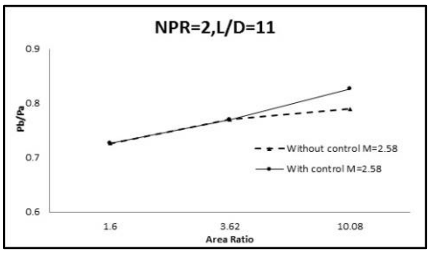
The main purpose of this research is to find the effect of microjets in regulating the base pressure for the whole range of area ratios, i.e., 1.6, 3.62, & 10.08 for Mach number 2.58. An increase in the area ratio tends to increase the room for relaxation available for the flow that leaves the nozzle. As stated earlier, an increase in the flow region will tend to propagate shock waves freely at nozzle lip. Thus it results in a change of reattachment location, and it will assume a decisive part in directing vortex quality at the base and subsequently on the base pressure level. The expansion level at the nozzle exit and by the L/D duct for a given area ratio controls the base pressure level [16]. In order to determine the impact of varying area ratio on base pressure, cross plots of base pressure with area ratio are presented as an NPR variable.

Figure 3 shows the relationship between base pressure ratio and the area ratio for the given L/D ratio (12) and different NPR (2, 4, and 6). These results are plotted with the control mechanism and without it. The results reflect the consequence of relaxation on base pressure. Results for NPR 4 and 6, it is observed from Fig. 3(b) that, in the case of using a control mechanism, the magnitude of the base pressure decreased, although in small quantity, compared to the magnitude without control.

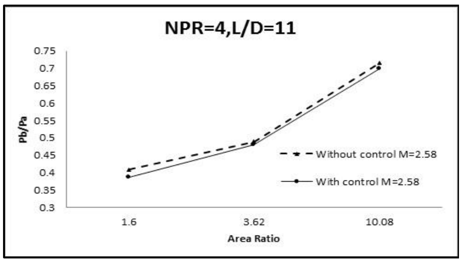
Fig. 3. $\mathrm{P_B}$ vs. Area Ratio

However, the level of over-expansion has come down relatively with an increase of NPR, and also the variation of base pressure has come down. Here the influence of microjets is observed clearly as the base pressure with the control mechanism differs from without control. Initially, the microjets have good influence at lower area ratio, but for higher area ratios, there is no such observation.

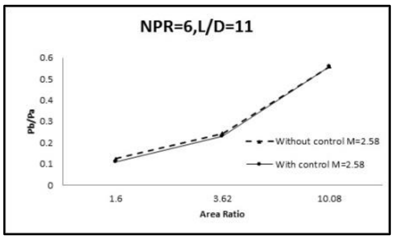
Results for NPR = 2, 4 and 6 with L/D = 11 are shown in the Fig 4. It can be seen that, except for a few observations, most of the results for L/D=11 and L/D = 12 are similar.



(a) NPR=2



(b) NPR=4

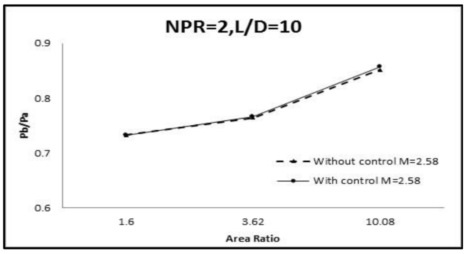


(c) NPR=6

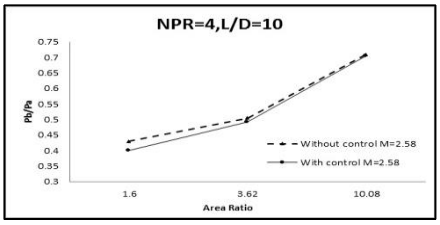
Fig. P_B 4. vs. Area ratio (L/D=11)

In Fig. 4(b), there is little change at the area ratio of 10.08 as the influence of microjets is still present at a higher area ratio. But, in Fig. 4(c), at area ratio 1.6, the base pressure is less, although not significantly with the microjets.

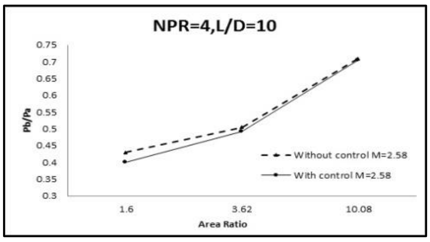
Fig. 5 represent the plot of base pressure for L/D = 10 with NPR 2, 4, and 6. The general base pressure behavior with an increase in area ratio is the same as that for L / D = 12 and 11. As seen in Fig 5(c), for L/D=10, initially, microjets have good control over the effectiveness of base pressure. However, for uncontrolled situations, the base pressure is high compared to higher L/D ratios, and there is a steep rise in base pressure for higher area ratios.



(a) NPR=2



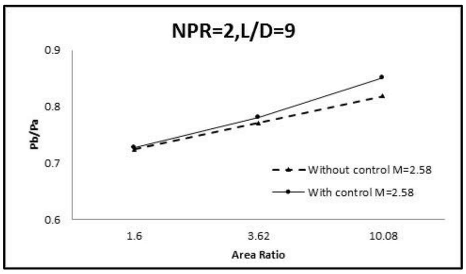
(b)NPR=4



(c) NPR=6

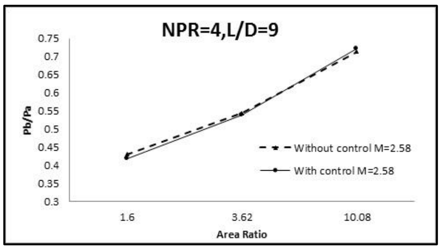
Fig. 5. P_B vs. Area ratio (L/D=10)

For L/D = 9 and NPR 2, 4 & 6, it is evident from Fig. 6 that there is a significant effect of microjets in the control of base pressure. Also, the results for NPR = 6 & L/D = 9 shows that base pressure is less with the use of microjets up to 3.62, but tends to decrease between area ratios 3.62 and 10.08.

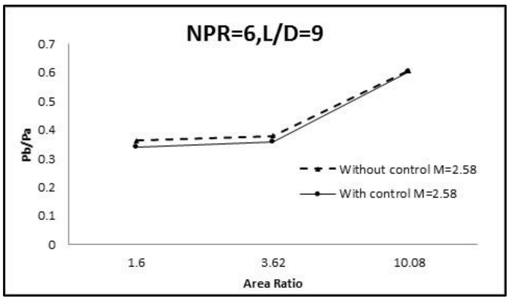


(a) NPR=2

Fig. 6. P_B vs. Area ratio (L/D=9)



(b) NPR=4

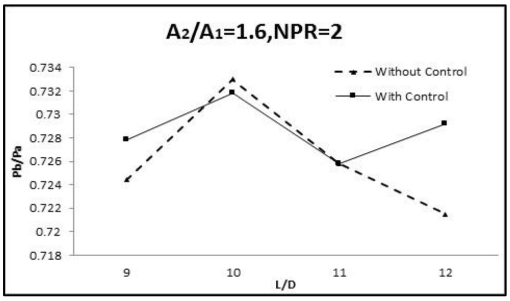


(c) NPR=6

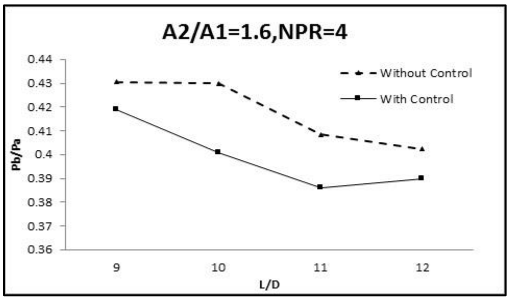
Fig. 6. P_B vs. Area ratio (L/D=9)

B. Effect of L/D ratio on base pressure.

In this section, we are investigating the variation of base pressure at different L/D ratios, and the influence of microjets on base pressure for different NPR's. To study the effect of NPR and area ratio for various L/D ratio, on the base pressure, the graphs are plotted, as shown in Fig. 7 to Fig.10. For Area ratio=1.6, with a higher L/D ratio for all NPRs, the base pressure effectively decreases. Also, there is evidence of the effect of microjets on base pressure than without the control mechanism. It can also be observed from the figures that the maximum effect is up to the L/D of 11, and at L/D=12, the flow is assumed to be attached.

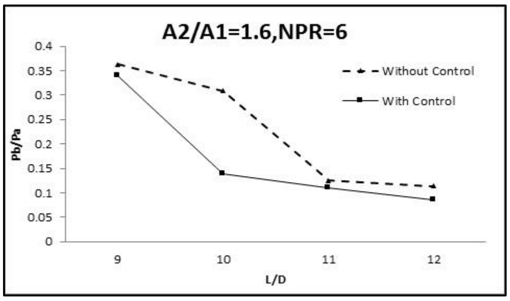


(a) NPR=2



(b) NPR=4

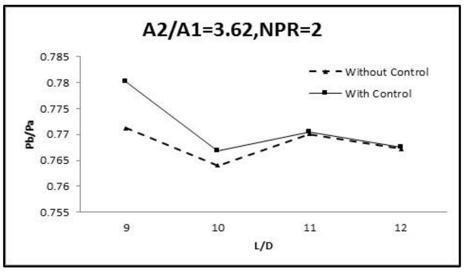
Fig. 7. P_B vs. L/D (Area ratio=1.6)



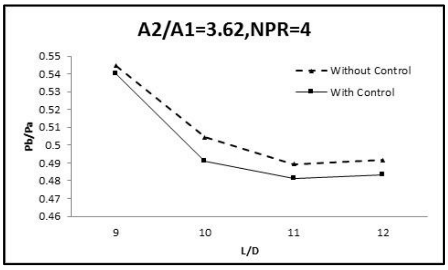
(c) NPR=6

Fig. 7. P_B vs. L/D (Area ratio=1.6)

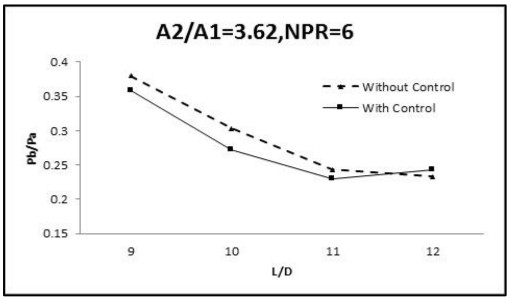
Fig 8(a) through Figure 8(c) shows the effect of different NPR and L/D ratio for area ratio=3.62 on base pressure. At low L/D, the base pressure is initially high, and as the L/D increases, the L/D tends to decrease base pressure. The microjets tend to reduce base pressure for with and without control for L/D's up to L/D = 11, and then the flow is assumed to be attached flow.



(a) NPR=2



(b) NPR=4

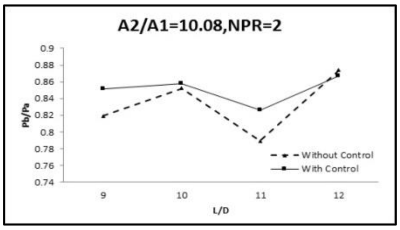


(c) NPR=6

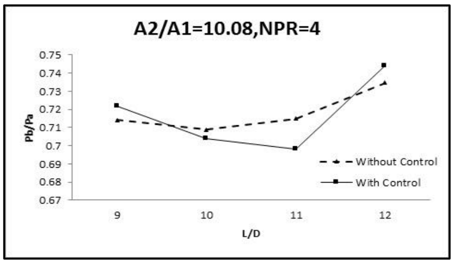
Fig. 8. P_B vs. L/D (Area ratio=3.62)

From Figures 9(a) to 9(c), it is observed that initially for NPR=2 and L/D up to 11, the microjets does not have any influence on the base pressure value, as its value is high. Moreover, the base pressure starts reducing for both with and without control as L/D increases. However, again at L/D = 12, the base pressure increases marginally. Here at L/D = 11, the behavior is different for with and without control for NPR 2 and NPR 4. Without control of microjets, the base pressure variation was low as compared to control.

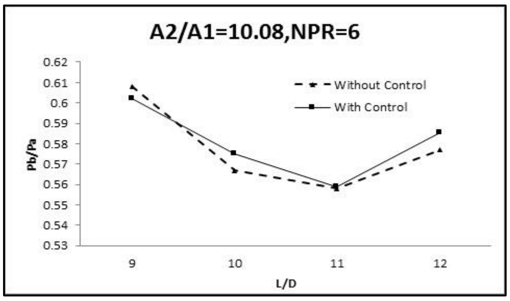
It is also observed that L/D has a good influence on base pressure. Initially, the base pressure was high at low L/D, and as the L/D increases, the base pressure decreases up to L/D = 11 for both with and without control. But at L/D = 11, the base pressure starts to increases marginally as the jets are over expanded.



(a) NPR=2



(b) NPR=4



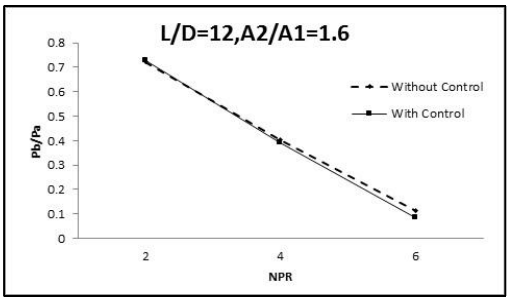
(c) NPR=6

Fig. 9. P_B vs. L/D (Area ratio=10.08)

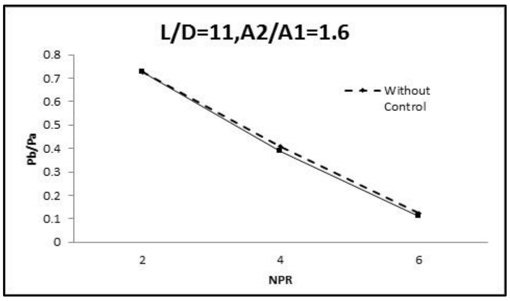
C. Effect of NPR on base pressure.

The change in base pressure concerning various nozzle pressure ratios and for different L/D's maintaining a constant area ratio are as shown in Fig. 10(a) to Fig. 10(c). For area ratio 1.6, with the increase in NPR, base pressure value gradually decreases as indicated in the graph. Also, it is clearly seen that area ratio and duct L/D are the two main criteria on which base pressure depends. It is also noted that the functional dependency of the base pressure with NPR is unchanged for most of the L/D ratio due to the control mechanism. However, base pressure tends to decrease more with the use of control methods. While analysing the effect of the L/D ratio on base pressure, it is observed that at L/D=10, the control is more effective from NPR 6 to NPR 8 as the base pressure decreases.

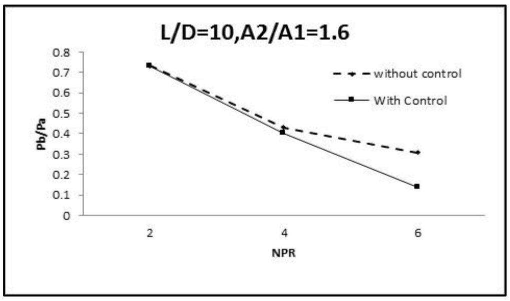
For area ratio 3.62, as observed in figure 11, it is noticed that the base pressure variation with and without control is nearly the same for all cases. Hence, control effectiveness is not appealing, but as soon as NPR increases, the base pressure decreases. We can state that, for Area ratio 3.62, microjets are effective for NPR 3 onwards, and it decreases its effectiveness as NPR increases.



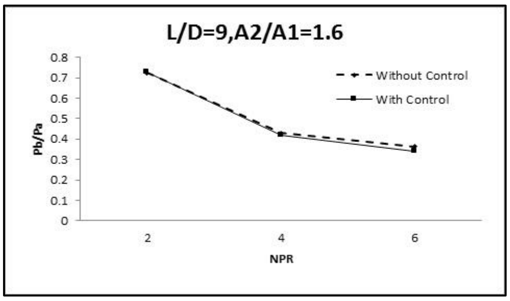
(a) L/D=12



(b) L/D=11

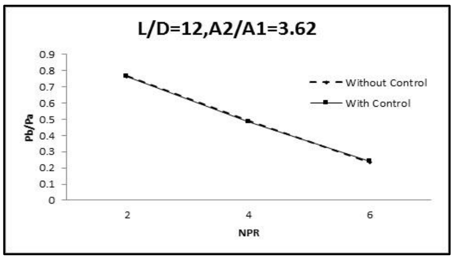


(c) L/D=10



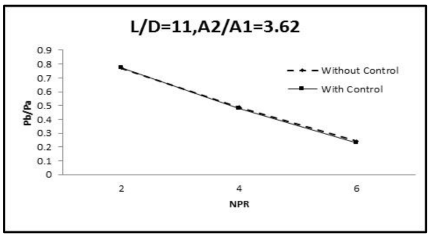
(d) L/D=9

Fig. 10. P_B vs. NPR (Area ratio=1.6)

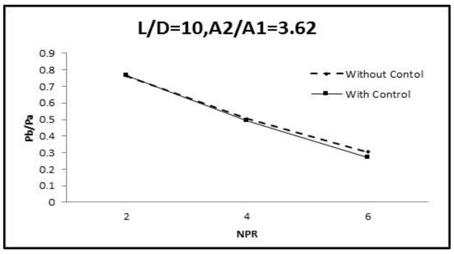


(a) L/D=12

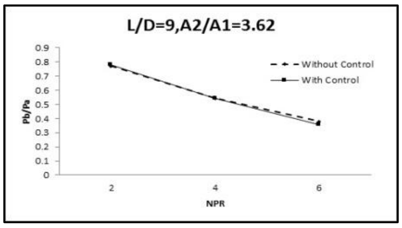
Fig. 11. P_B vs. NPR (Area ratio=3.62)



(b) L/D=11



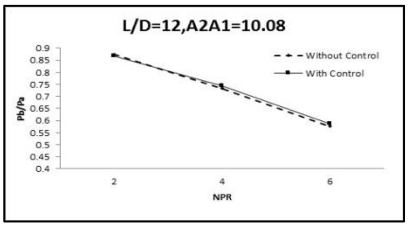
(c) L/D=10



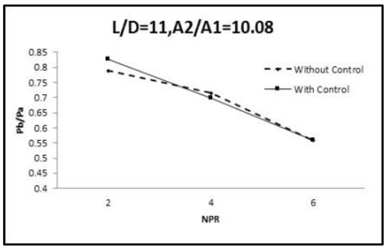
(d) L/D=9

Fig. 11. P_B vs. NPR (Area ratio=3.62)

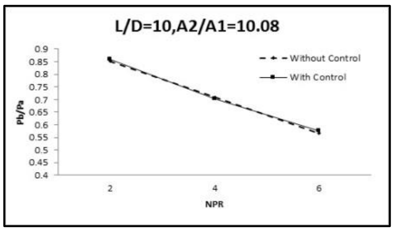
In Fig 12, for area ratio 10.08, as in previous cases with low NPR, the value of the base pressure stays the same with and without control, and then the effectiveness decreases. It is also shown that the base pressure value is the highest in this case relative to other area ratios. This is because when area ratio increases, then the discharge from the nozzle tends to attain greater reattachment length as compared to the optimum length required for strong vortex at the base. This is why the impact of NPR on base pressure is negligible.



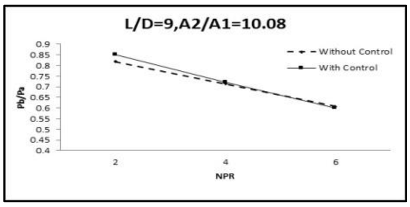
(a) L/D=12



(b) L/D=11



(c) L/D=10



(d) L/D=9

Fig. 10. P_B vs. NPR (Area ratio=10.08)

5. Conclusion

It is revealed from the above experimental study that, the base is greatly affected by the L/D ratio, area ratio, and nozzle pressure ratio. The optimal L/D ratio of the duct can be determined for a given area ratio, Mach Number, and nozzle pressure ratio, which will result in the output plane total pressure at the nozzle tip. For a fixed value of area ratio with variation in NPR and L/D ratio, the base pressure behaves differently with and without microjets, and for higher values of L/D ratio, the base pressure is reduced drastically as reported by Baig et. al [17]. At Mach number 2.58, for the given area ratios with variation in NPR and L/D, the base pressure is found to be optimum at lower area ratio (1.6), and higher NPR (6) and L/D ratio (11 and 12). At a higher NPR and higher L/D ratio, it is observed that the reattachment of the flow occurs with the use of microjets. So it is stated that NPR greatly influences the base pressure. Further, to find the influence of the L/D ratio on base pressure with variation in area ratio and NPR, it is observed that microjets have a great effect on the control of base pressure. It is also found that the optimum base pressure ratio is found at L/D (12) for lower area ratio (1.6) and maximum NPR (6). With respect to the effect of NPR on base pressure, it is found that the effect is not much significant with or without a control mechanism. However, as NPR increases, base pressure decreases significantly.

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