# Investigation of efficacy of low length-to-diameter ratio and nozzle pressure ratio on base pressure in an abruptly expanded flow

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**Abstract.** This study has been carried out to assess the efficacy of the flow regulations in the form of tiny jets to regulate the pressure in the base region of an abruptly expanded duct. Four tiny jets of 1mm diameter placed at 90° intervals at 6.5 mm distance from the main jet in the wake region of the base were employed as flow management mechanism. The experiments were conducted at the inertia level of M = 2.5 & 3.0. The jets from the nozzles were expanded abruptly into a circular duct with four cross-sectional areas of 2.56, 3.24, 4.84 and 6.25. The L/D ratio of the enlarged duct considered was from 10 to 1 and experiments were conducted for Nozzle Pressure Ratio (NPR) from 3 to 11. Since the jets Mach numbers are high and the highest NPR tested was 11 which imply that the flow remains over expanded, even though, with increase in the NPR, the level of over expansion will decrease. It is well known that for over expanded nozzles an oblique shock will be formed at the nozzle lip, which in turn will result in the increase of the base pressure once it passes through the shock wave. From the results it is observed that for the NPRs 3 and 5 there is no appreciable gain in the base pressure, and hence, control employed as tiny jets are not effective, however, at NPR 7, 9, and 11 there is remarkable change in the base pressure values. This clearly indicates that NPR plays a significant role to decide on the magnitude of the base pressure and the control efficacy of the flow regulation mechanism as the tiny jets. It is found that the present method of flow regulation mechanism can be used as effective regulator of the base flows in an abruptly expanded duct. The control does not alter the nature of the flow in the enlarge duct.

**Keywords.** Base pressure, active control, abrupt expansion, nozzle pressure ratio.

## 1 Introduction

Base Flow instabilities are a grave concern to the design of high performance aerodynamic vehicles and efficient propulsive systems (rockets, aircraft bodies, re-entry vehicles, ramjet, and thrust augmenting ejectors). The base flow is characterized by large flow separations, resulting in the low pressure circulation zone at the base, which have many dispensable outcomes. The transonic/supersonic flow proceeding over the body of the vehicle collaborates with the exhaust nozzle jet in such a way that the turbulent layer and re-circulatory shock system deteriorates the performance of the vehicle, and the base flow is the cue. For the prospective aerodynamic vehicles (re-entry vehicles, scram-jet), advanced nozzles and propulsion systems, the performance turns more pertinent to the external flow, and therefore the base flow plays even greater role. In order to comprehend the parameters of base flow aerodynamics, more experiments are carried out and new applications are chosen. In case of flow separation, the pressure in the wake region is usually substantially smaller than the free stream ambient pressure, and the flow will get separated and will reattach with the solid wall of the enlarged duct. The reattachment point and reattachment length will depend upon the Mach number, the diameter ratio, Nozzle Pressure Ratio (NPR), length-to-diameter ratio and the type of the boundary layer at the nozzle exit. The flow field at the base which is very complex is one of the significant and complex problems in fluid dynamics. The flow at the base will be wave dominated consisting of diamond shock and barrel shock. When the flow at the nozzle exit is under the influence favorable pressure gradient there will be an expansion fan located at the nozzle lip, where as in the case of correctly expanded case still waves are bound to be there at the nozzle exit, however, for correctly expanded case these waves are weak. The enquiry that befalls is the influence of pressure gradient on the base drag. From the previous studies, it has been shown that at lower Mach numbers, base drag comprises only of the ten percent of the total drag of the body, whereas at Transonic/Supersonic Mach numbers, the major contribution of the total drag comes from base drag, which is sixty percent of the total drag. Hence, the slight increment in the base pressure could induce substantial decrease in the base drag; therefore enhancing the performance and reduce the fuel consumption.

| Nomenclatures | |
|---|---|
| $P_b$ | Base Pressure |
| $P_w$ | Static Pressure |
| L/D | Length to Diameter ratio |
| NPR | Nozzle Pressure Ratio |
| $A_2/A_1$ | Area Ratio |

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### 1.1 Literature review

To study and define the given flow phenomenon, various experiments have been conducted by the researchers. In order to simplify the understanding of base flow analysis, the comprehensive study of approaching free stream Mach numbers, character of expansion phenomenon and nozzle characteristics is achieved by our experimental study. To further increase of the base pressure, which decreases the base drag, one can think of different geometrical modifications, like boat-tails, additional cavities, sting and discs, or application of base bleed and base combustion. However, the studies of base drag reduction with active control has not been studied much, therefore we will study the problem with an internal flow.

Viswanath[1] explored experimentally the estimation of drag for various models like multi-step after-bodies that considers the idea of managed separated flows in the transonic as well supersonic Mach numbers. The significant geometrical variables which are influencing the drag of such after-bodies were considered to be of interest, and their influences were tested through an experimental study by considering various variables. Their outcome indicate that multi-step after-bodies can be designed that give considerable decrease in the net drag and it may go beyond 50 % in comparison to the cases having blunt bases; nevertheless, in comparison to the bodies with the boattailed after-bodies cases of a given base area, the multi-step after-bodies have resulted into higher drag. Therefore, the certain flow behavior involving the flow separation as well as the reattachment on multi-step after-bodies was considered based on flow visualization studies.

Singh and Rathakrishnan[2] concluded from their research the efficacy of various tab parameters on the flow exiting from the converging nozzle at Mach M = 1. They concluded that the passive control in the form of tabs are greatly efficient to control the center line decay and hence the core length of the jets, and they observed that the tabs can reduce the core length by 80 per cent. Asymmetric flows in symmetric ducts with sudden expansion were induced by the disturbances engendered at the edge of the expansion and augmented in the shear layers(Vijayaraja, Senthilkumar et al.)[3]. Also, they demonstrated that the strength of fluctuating energy in the low Reynolds number can be greater than the counterpart turbulent flow. The study of closed-cavity laminar flows at adequate Reynolds number was carried out by Acrivos [4]. They observed that the flow becomes real turbulent once the critical Reynolds number is exceeded. Experimental analysis of the flow field in suddenly expanded combustion chamber was studied by Khalil.[5] For highly turbulent flow field, they verified the eminency of laser Doppler anemometer for measuring the reverse flow.

Khan and Rathakrishnan([6]-[9]) did experimental examination to assess the effectiveness of micro jets for various level of expansion to regulate the base pressure in abruptly expanded ducts at moderate and high supersonic speeds. The result thus produced showed that on the positive side the highest enhancement is152 % percent at Mach M = 2.58. The result also indicated that the control mechanism does not augment the nature of the flow field. Lovaraju et al. [10] conducted the experiments to study the efficacy of tabs and a wire which is projecting normally into the flow at the nozzle exit, as a passive control on the characteristics of an axi-symmetric sonic jets which were operated at various level of expansion, and their studies suggests that the efficacy of passive controls either in the form of cross-wire or the tabs on the under expanded sonic jet shows that, both the passive controls are effective in decreasing the core length significantly.

Rathakrishnan, Ahn et al. [11] presented the outcome of an experimental studies on the flow from a converging-diverging nozzle and its behavior for slanted entry at a 15º at the inertia level of M = 2.94 and later the flow was exposed to various supersonic Mach numbers in the range from M = 1.6, 1.8 and 2.0.

## 2. Experimental Setup
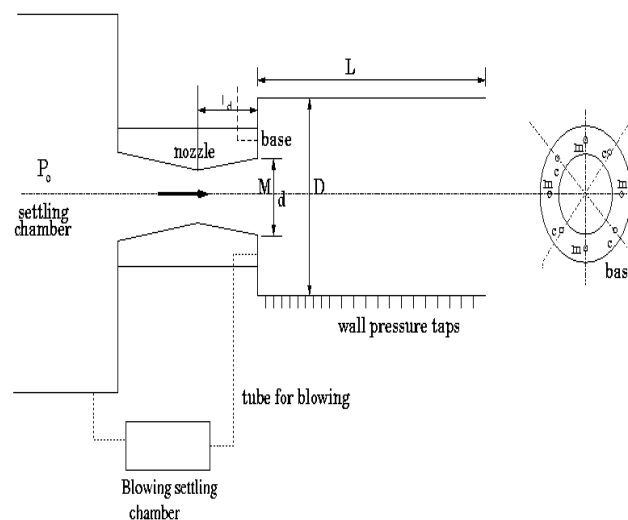


**Fig. 1.** Experimental setup

The investigation was performed with a full scale experimental model consisting of pipelines, pressure transducers and the settling chamber. In order to expand the gas through the experimental model, it is first allowed to go through regulating valves. The experimental model is a nozzle with an augmented duct. The flow leaving the model is subjected to ambient air. Figure 1 depicts the experimental setup.In the outlet boundary of the nozzle, 8 holes of 1mm diameter each are drafted. In the present arrangement the regulation of the pressure the separated region was accomplished by injecting the air through control chamber.

**Fig. 2.** Experimental Apparatus

## 3 Results and discussion

The measured values consisted of the base pressure ($P_b$), the static pressure ($P_w$) along the wall of the duct and the NPR in the main settling chamber as well as the control pressure. The obtained pressures were transformed to non-dimensional data by multiplying them with the inverse of the ambient pressure. The percentage change in base pressure as a function of L/D ratio was shown in the Fig.3 ((a) to (j)). The effect of area ratio with Mach number and the NPR on the percentage change in base pressure were presented in the Figure 3 ((a) to (j)). Further, while analyzing the results it should be kept in mind that the jets exiting from the nozzles were over expanded and hence an oblique shock will be present at the nozzle lip. Even though there was a reduction in the level of adverse pressure gradient with the increase in nozzle pressure ratio. It could be visualized that, when there was an oblique shock positioned at the nozzle exit the shear layer coming out of the nozzle will be deflected towards the nozzle center line rather than towards the base region. This will results in enhancement of the base/wall pressure after the shock and also this will delay the reattachment of the flow with the duct wall, which in turn will result in a longer reattachment length as compared to a case without a shock. It was well known that the reattachment length was a parameter strongly influencing the base vortex, the increase or decrease of reattachment length will modify the base pressure flow field. It was also, evident that increases in area ratio and in turn increase in relief to the flow simply indicates that relaxation space existing for the flow was increasing. This sort of relief will make the shock waves at the nozzle lip to spread relatively more freely with the increase of relief at the lip of nozzle and the area ratio as shown in (Fig. 3 (a) - (j). From the results it is seen that at the NPR 3 and 5 the micro jets were ineffective as shown in the Figs 3 (a) to (d).
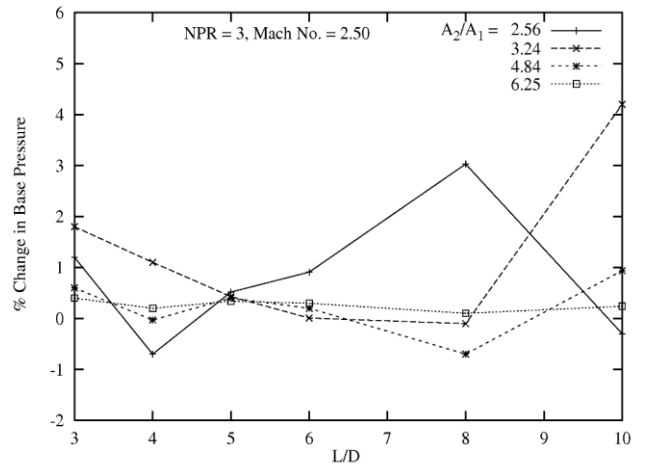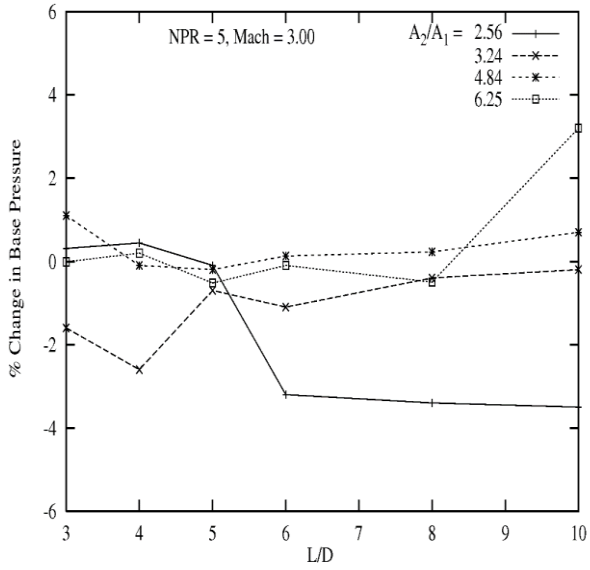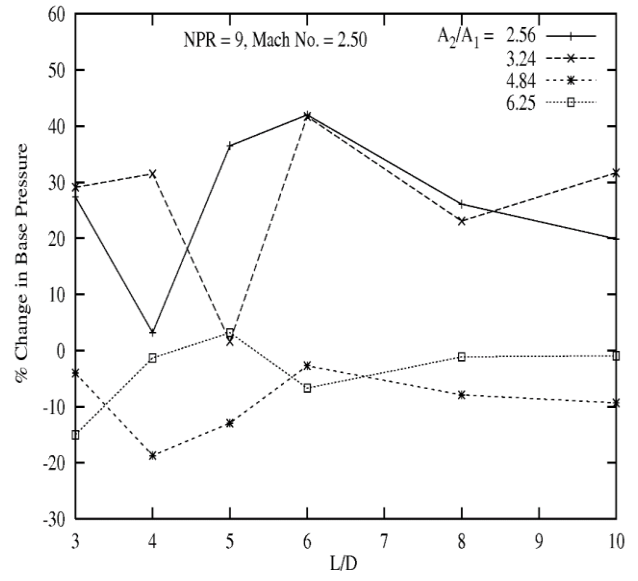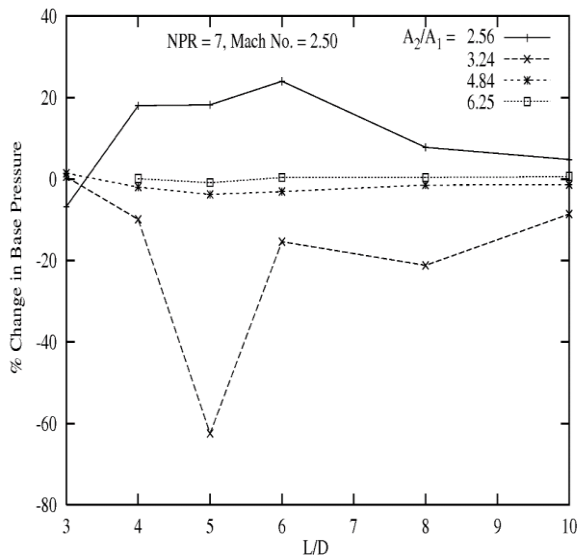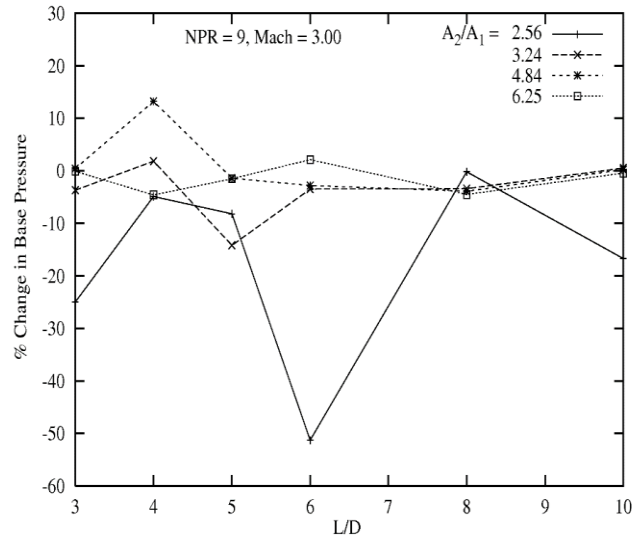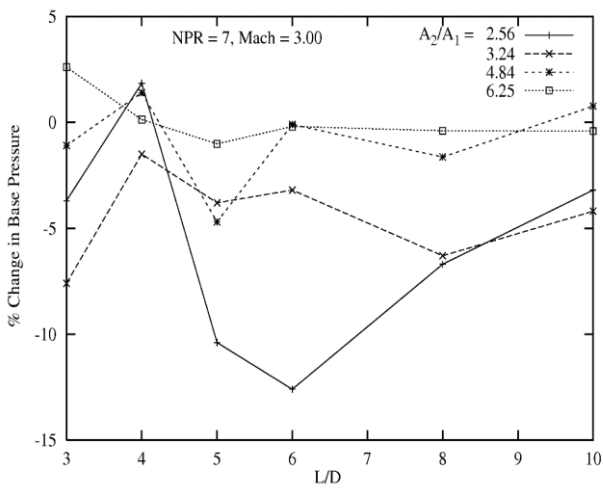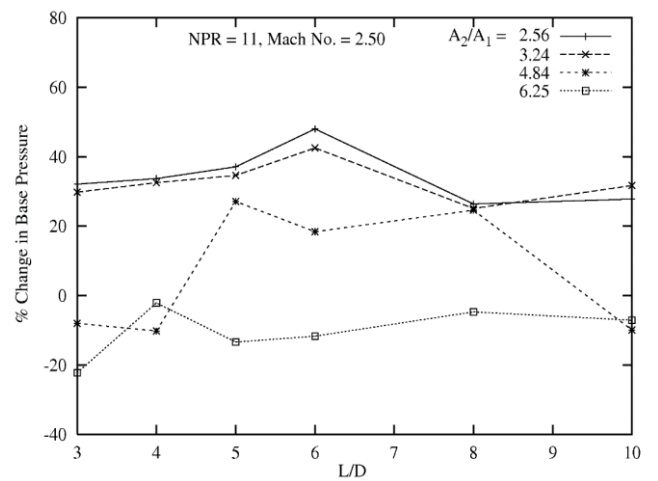


(a)
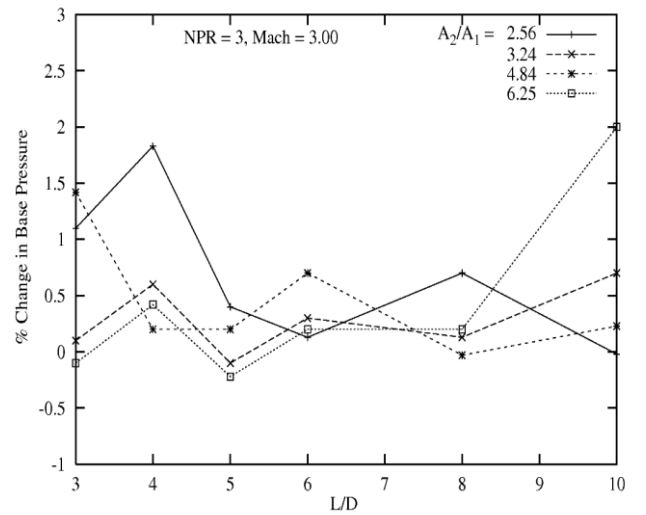


(b)
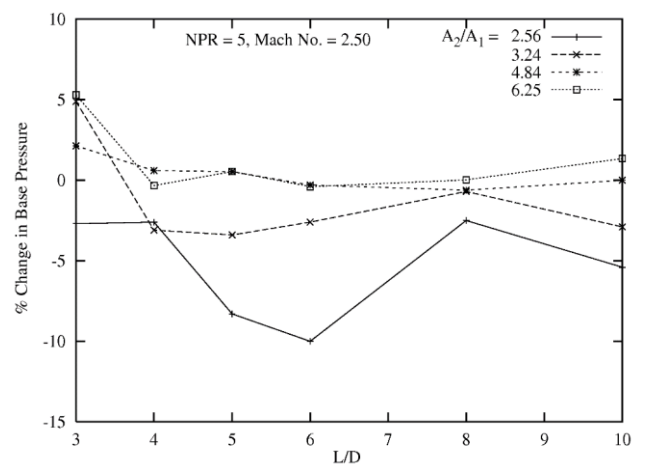


(c)

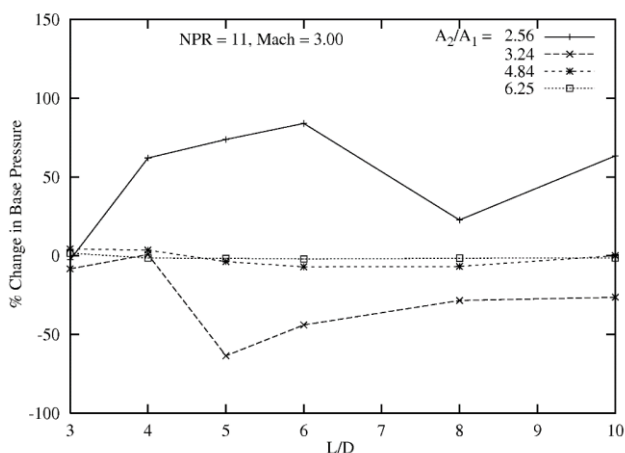(d)



(g)



(e)



(h)



(f)



(i)

(j)

**Fig. 3.** Percentage change in base pressure with L/D ratio

The results for the NPR 7 were shown in the Figures 3(e) to (f)). From the results it was observed that for lower area ratios namely 2.56 and 3.24, even at NPR 7 the micro jets had become effective and more so for lowest area ratio namely 2.56. This effectiveness results in decreasing the base pressure and for the higher area ratios 4.84 and 6.25, while the control mechanism in the form of tiny jets were not at all effective. The reason for this trend may be due to the larger area avaialble to jet and vortex positioned at the base was unable to make any significant effect on the base flow field.Under these conditions when control was activated they were unable to alter the base flow field, rather they go unnoticed since for these higher area ratios the micro jets were closed to the main jet and away from the base region.

The Results for the NPR 9 were shown in the Figs. 3 (g) to (h). They exhibit the similar results as discussed above for NPR 7. In this case due to increase in the NPR, the level of over expansion had marginally come down and the same had been reflected in the magnitude of the per cen tage change in the base pressure which had marginally improved. It was also seen for the highest area ratios namely 4.84 and 6.25, the gain had increased as compared to the NPR 7 for same area ratio. These results clearly reflect the impact of NPRs on the base pressure level in the base region, reattachment point/length, and the flow establishment in the duct.

The results for the NPR 11 were shown in the Figs. 3(i) to (j). This was the highest NPR for which the tests were conducted, tests were unable to be conducted at higher NPR or for correct and under expanded case due to the limitation of the experimental set up. From the Fig. 3(i) it was seen that at Mach 2.5 for area ratio the maximum gain was forty eight percent at L/D = 6, and at other L/Ds it remains between thirty to forty percent range. For area ratio 3.24, this gain remains in the range between twenty to thirty eight percent. One interesting observation was that the micro jets which were not effective for the area ratio 4.84 and 6.25 now became effective at the NPR 11 due to the reduction in the level of over expansion, which had resulted in the reduction

of strength of the oblique shock wave. For area ratio 4.84 as high as forty percent increase had been achieved. In the case of the highest area ratio namely 6.25, the gain was on the negative side and remains between ten to twenty percent. This may be due to the further increase in the area ratio leading to the weakening of base vortex, and incresae in reattachment length, which was small for lower area ratios. Since the NPR remains the same and due to increase in the relief, this trend was expected.

Another point to be noted that the with the change in the enlarged duct, the back pressure also will influence the flow field in the base area, and hence, the magnitude of the base pressure will significantly altered. As it was evident from the above discussion that the flow was dominated by the presence of shock waves of variable strength, hence, dealning with this type of flow one had to take note on a case to case basis generizing the conclusions.

The results for Mach 3.0 are presented in the Figure 3(j). Here, again the effffectiveness of the control in the form of micro jets were observed only for lower area ratios, whereas, for the larger area ratios 4.84 and 6.25 it remains ineffective. This could be due the level of expansion at the Mach number as the NPR for correct expansion was quite high as compared to the Mach 2.5 while all other parameters remain the same.

Finally, in view of the above, we can conclude that apart from the effect of shock or expansion wave at the nozzle exit, the relief available due to variation of area ratio, location of micro jets, level of expansion and L/D ratio will affect the base pressure. Furthermore, it should be kept in mind that in case of lowest area ratio 2.56, the micro jets in the base region were located at middle of the base area, whereas for area ratio 3.24 (and also for area ratios 4.84 and 6.25) the micro jets were closer to the main jet. This was due to the pitch circle diameter for the control mechanism was kept same for all the area ratios. This was also the reason for peculiar trend in the above discussed results.

## 4 Conclusions

From the above results it could be concluded that in supersonic regime, the inertia level had a very strong effect on the base pressure. For a fixed value inertia level, the NPR, which controls the level of expansion had a major role to play on the control efficacy of the tiny jets. Also, it was seen that with further increase of the NPR, the flow regulation mechanism becomes more efficient in enhancing the base pressure with Mach number. In view of above, it could be said, the control mechanism in the present study to control base pressure was effective for Mach M = 2.5 for NPRs 7, 9, and 11 for lower area ratios. The effectiveness of the micro jets was only marginal for higher area ratios namely 4.84 and 6.25, for all the inertia levels and nozzle pressure ratios of the present investigation. Further, it was concluded that the results were required to be analyzed on the case by case basis, hence, no definite rule could be established. One had to study on case by case basis and also on what is needed and to identify the set of

parameters which will lead to maximum increment or decrement of the base pressure.

The flow field in the suddenly expanded duct was dominated by the presence of the waves both strong as well as the weak waves, since the jets exiting the nozzles are over, under and correctly expanded, and hence, no definite trend can be drawn. The reflection of the waves from the wall, recompression and recombination will continue to take place in the base region of the duct wall. Thereby, making the flow oscillatory for some combinations of parameters, that would otherwise exhibit similar trends as expected when compared with and without control cases of the wall pressure field. The micro jets had demonstrated that they could be considered as efficient active controllers of the suddenly expanded flow field. Hence, increasing or decreasing the base suction to appreciable level for range of variables of the present study. From the results it was seen that the nozzle pressure ratio (NPR) plays a key role in deciding the magnitude of base pressure with and without control, in the supersonic regime too. All the non-dimensional measured values exhibited in the present study are within an uncertainty range of 2.6 % on the either side. All the tested values are reproducible in the range of 3 per cent on the either sides.

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