RESEARCH ARTICLE OPEN ACCESS

Control of Suddenly Expanded Flow at Low Supersonic Mach Numbers

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ABSTRACT
In the present study the experiments were conducted to control the base pressure from a convergent-divergent nozzle at low supersonic Mach numbers to assess the effectiveness of active control mechanism in the form of micro jets at different expansion level. The parameters considered in the present study are the diameter ratio, length to diameter ratio (L/D), Nozzle Pressure Ratio (NPR), and the Mach number. The diameter ratio selected for the present study are 1.6, 1.8, 2.2, and 2.5. Experiments were conducted for nozzle pressure ratio (NPR) from 3 to 11. The L/D ratio of the enlarged duct was varied from 10 to 1, and results are presented for L/D 4, 3, 2, and 1. The Mach numbers of the present studies are 1.1, 1.2, 1.4, and 1.5. The results show that the Micro jets are very effective and are able to raise the base pressure value to a considerable level under the influence of favorable pressure gradient except at lower NPR 3. At NPRs 5 and 7 for some cases the trends differ due to the level of expansion, nature of waves present in the base region, relief available to the flow, L/D ratio of the enlarged duct and the Mach numbers. It is seen that most of the cases exhibit similar behavior for the L/Ds in the range 4 and 3, which means; that the back pressure has not adversely influenced the flow field in the base region as well as in the duct. The minimum duct length required for the flow to be attached is L/D = 2, even though in some cases flow is attached with duct wall. With this it can be stated that the micro jets can be an alternative for the for base pressure control.
***Keywords* -** Base pressure, Length-to-diameter ratio, Mach number, Nozzle pressure ratio, Sudden expansion

I. INTRODUCTION

In view of the developments in space flights and missile technology worldwide by all the developed nations as well as few developing countries, the base flows at high Reynolds numbers continue to be an important area of research. It is well known that the base pressure and consequently the base drag at transonic speed could be as high as 50 percent of the total drag during the jet off conditions, however, during the jet on (or power on) mode the effect of base suction will be negligible as the pressure at the base will be very high. Hence, if we are interested to control the base pressure and ultimately the base drag in case of blunt based projectiles and by doing so this would lead to significant increase in the range of the missiles or projectiles, and it will be of great help for defense applications. Presently the world is facing the energy crisis and any decrease in the value of the base drag will be a welcome step. Since, we have reached to a saturation stage as far as the optimization in skin friction drag and wave drag are concerned, there, is not much scope for further investigation is left and controlling the base pressure is the only area left to explore, hence, this study was undertaken to control the base pressure with micro jets. The prime objectives in this study are to control the base pressure, to have smooth development of the flow without oscillations in the duct, to minimize the total pressure loss; the studies are conducted keeping these features in mind. When we scan the literature available it is found that scientists have made attempts to control the base pressure by various passive means, like; ribs, base cavities, ventilated cavities at the blunt base, splitter plate, vortex locked device, stepped base, boattailed bases, and so on. Hence, in the present study the experiments were conducted to control the base pressure as well as the flow development in the enlarged duct was measured to ensure that there is no negative effect of the control on the flow field of the duct. It is well known that whenever either passive or active controls are used in the case of sudden expansion it mandatory on the part of researchers to ensure that the flow field in the enlarged duct is not aggravated and the flow field with and without control are identical.

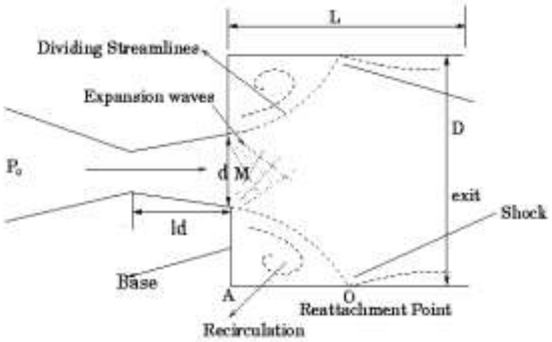


Fig. 1: Sudden expansion flow field

Flow field of abrupt axi-symmetric expansion is a complex phenomenon characterized by flow separation, flow re-circulation and reattachment. A shear layer into two main regions may divide such a flow field, one being the flow recirculation region and the other the main flow region. The point at which the dividing streamline Strikes the wall is called the reattachment point and the features of sudden expansion flow field are shown in Fig. 1.

II. LITERATURE REVIEW

Kidd et al. [1] conducted Free-flight tests of spin-stabilized projectiles and fin-stabilized missiles with various stepped, flat and boattailed bases at subsonic, transonic and supersonic Mach numbers. They got the results which indicate that sub sonically the addition of a stepped base can significantly reduce the aerodynamic drag over that a flat base. Khan and Rathakrishnan [2-6] 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. Ashfaq and Khan [7] presented the results of experimental studies to control the base pressure from a convergent nozzle under the influence of favourable pressures gradient at sonic Mach number. The area ratio (ratio of area of suddenly expanded duct to nozzle exit area) studied are 2.56, 3.24, 4.84 and 6.25. The L/D ratio of the sudden expansion duct varies from 10 to 1. They concluded that, unlike passive controls the favourable pressure gradient does not ensure augmentation of the control effectiveness for active control in the form of micro jets. Wall pressure was measured and it is found that the micro jets do not disturb the flow field in the duct rather the quality of flow has improved due to the presence of micro jets in some cases. Ashfaq et al. [8] presented the results of experimental studies to control the base pressure from a convergent nozzle to ascertain the effect of level of expansion in a suddenly expanded flow at sonic Mach number. From the investigation it was found that unlike passive controls the favourable pressure gradient does not ensure augmentation of the control effectiveness for active control in the form of micro jets. To study the influence of micro jets on the quality of flow in the enlarged duct wall pressure was measured and it was found that the micro jets do not disturb the flow field in the duct.

III. EXPERIMENTAL SETUP

The experimental set up of the present study is shown in the Fig. 2. There are eight holes at the exit periphery of the nozzle, four (marked m) were used for base pressure (P_b) measurement, four of which are (marked c) were used for control of base pressure. In the control chamber the pressure energy was drawn from the main settling chamber by employing a tube connecting the main settling chamber with the control chamber.

Further, the experimental setup was consisted of an axi-symmetric convergent-divergent nozzle having exit diameter as D_1 followed by a concentric axi-symmetric duct of larger diameter of diameter D_2, and the ratios of the diameter (i.e. D_2/D_1) are in the range from 1.6 to 2.5. At the exit, diameter of the nozzle was kept fixed (i.e. 10 mm) and the diameter ratio of the model were 1.6, 1.8, 2.2, and 2.5. Brass pipe was used to fabricate the suddenly expanded ducts. The duct has a maximum L/D = 10 and the lower L/Ds were achieved by cutting the length after testing a particular L/D. However, the results presented in this paper are for L/D = 4, 3, 2, and 1, though the experiments were conducted for L/D = 10 to 1.

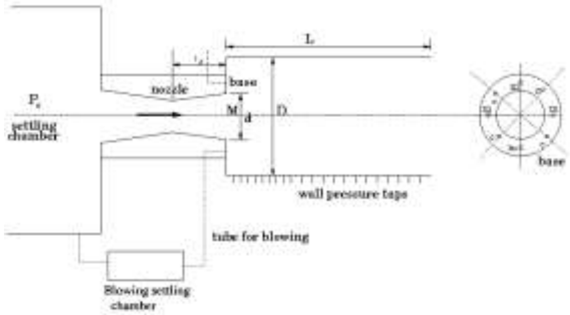


Fig. 2. Experimental setup

For measuring the pressure in the control chamber, the stagnation pressure in the main settling chamber and the pressure at the base, PSI model 9010 pressure transducer were used. It has 16 channels and pressure range is 0-300 psi. It displays the reading after averaging 250 samples per second. To interface the transducer with the computer, software is provided by the manufacturer. The user-friendly menu driven software obtains data and displays the pressure readings from all the 16 channels simultaneously on the computer screen.

The software is embedded with the facility to select the units of pressure from a list of available options, perform a re-zero/full calibration, etc. The transducer is capable of selecting the number of samples to be averaged, by means of dipswitch settings. It can function well, up to 95 per cent humidity and temperatures ranging from -20° to +60° Celsius.

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 were non-dimensionalized by dividing them with the ambient pressure (i.e. the back pressure). In the present study, the back pressure is the atmospheric pressure.

From the literature, it is found that in addition to area ratio and the NPR, the inertia at the nozzle exit has a very strong influence on the base pressure. To quantify the increase in base pressure achieved with control by micro jets, cross plots of base pressure in the form of non-dimensional base pressure with the non-dimensional step height of the suddenly expanded duct are used for presenting the results.

To highlight the effect of diameter ratio, cross plots of base pressure with diameter ratio as a function of jet Mach number and NPR are presented in Figs. 3((a) to (j)), for L/D = 4 and NPRs from 3 to 11. It should be kept in mind that, increase of diameter ratio simply means that the additional relief is available to the flow exiting from the nozzle. And, this kind of relief will make the shock/expansion waves at the nozzle lip to propagate comparatively easily with the increase of diameter ratio. This propagation of waves will result in change of reattachment point with the duct and hence the reattachment length. This variation in reattachment length will have a definite role to play in dictating the vortex strength at the base and hence on the base pressure level.

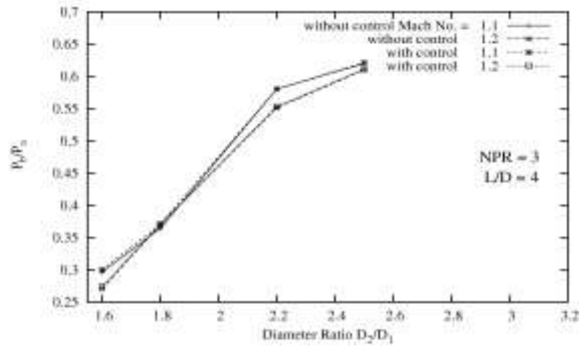


Fig. 3 (a)

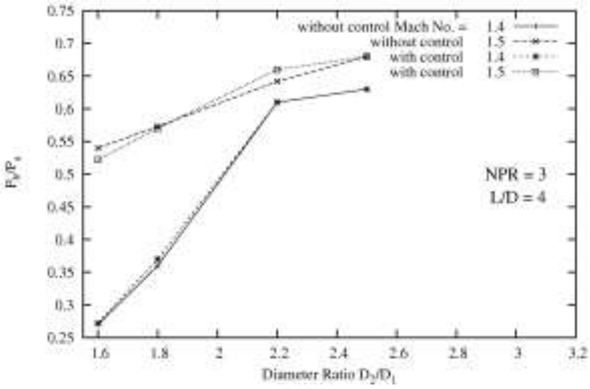


Fig. 3 (b)

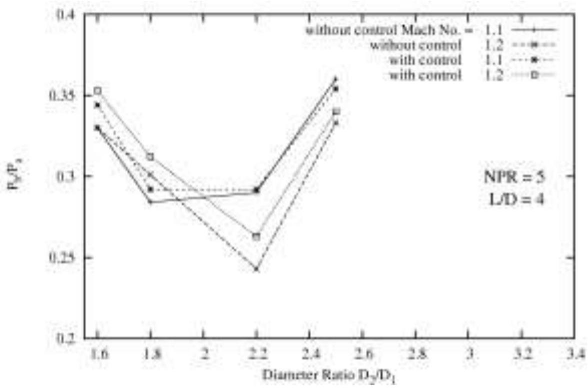


Fig. 3 (c)

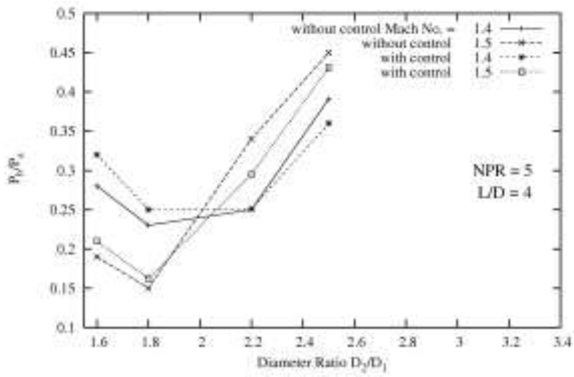


Fig. 3 (d)

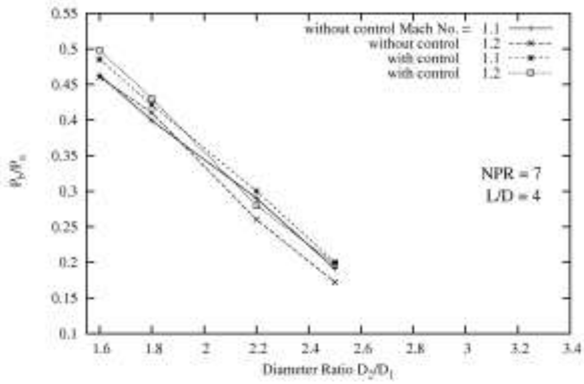


Fig. 3 (e)

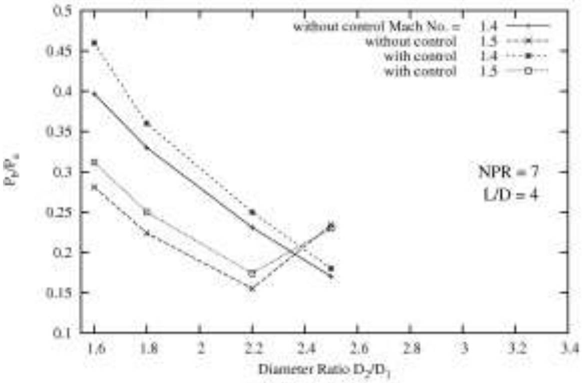


Fig. 3 (f)

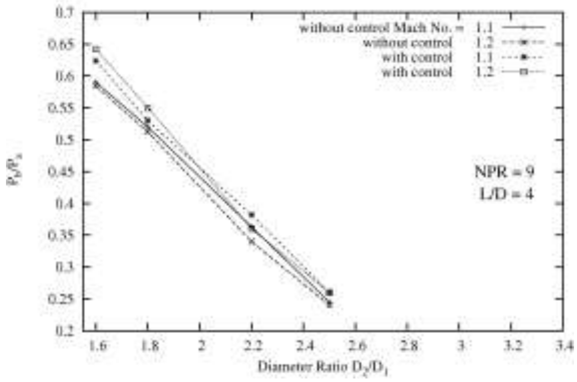


Fig. 3 (g)

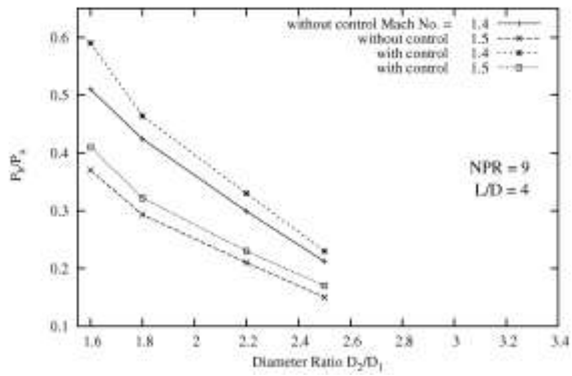


Fig. 3 (h)

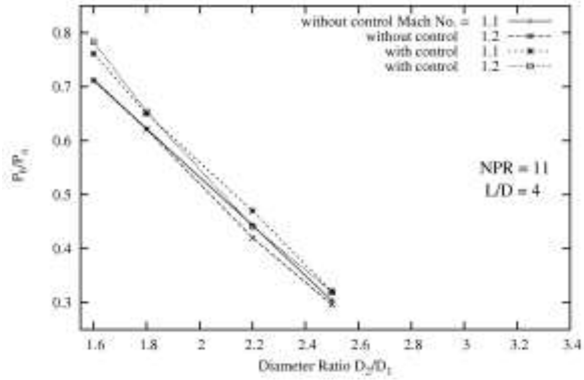


Fig. 3 (i)

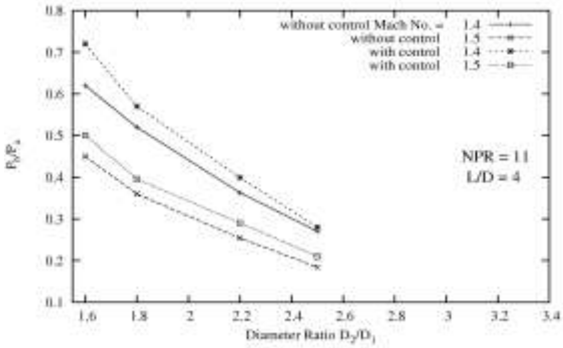


Fig. 3 (j)

Fig. 3. Base pressure variation with Diameter Ratio for L/D = 4

The results for NPR 11 are shown in Figs. 3((i) to (j)) for the Mach numbers in the range from 1.1 to 1.5 clearly reflect the effect of relief on the base pressure. All these jets are under expanded and hence the free shear layer from the nozzle exit passes through an expansion fan. In such situation increase in reattachment length due to increase of diameter ratio and hence the area ratio is seen to result in decrease of base pressure for all the parameters of the present study. Furthermore, the control is found to be effective for these Mach number range taking the base pressure to a higher value compared to the corresponding case without control cases as seen in Fig. 3(j) for Mach numbers 1.4 and 1.5. However, for the similar situation at lower Mach numbers namely 1.1 and 1.2 the trend of continuous decrease in the base pressure values continue but when micro jets were activated neither they are able to influence the flow field nor control results in substantial increase or decrease of base pressure. It is also seen that with increase in the Mach number from 1.1 to 1.2 results in increase of base pressure this trend is on the expected lines. It is well known from the literature that the base pressure will increase with increase in Mach number.

Similar results for NPR 9 are shown in Figs. 3((g) to (h) for Mach number ranges 1.1 to 1.5. Here again the base pressure behavior with diameter ratio is similar to that for NPR 11, excepting that the magnitudes of base pressure has come down as compared to the values at NPR 11 when NPR comes down from 11 to 9.

Base pressure results for NPR 7 are given in Figs. 3((e) to (f)) for Mach number ranges 1.1 to 1.5. Here, at lower NPR namely at NPR = 7 the level of expansion has changed considerably as compared to the NPRs 9 and 11. And for higher NPRs in the range 11 and 9 the jets were highly under expanded and it is found in the literature that whenever the jets are under expanded control in the form of either passive or active control becomes very effective and in the present study also the same trend has been observed. Further, it is seen that this effectiveness also, decreases with the decrease in the Nozzle Pressure Ratio. The effect due to the transition from high level of under expansion to a lower level of under expansion is clearly seen here. As seen from Fig. 3(f) that for Mach 1.5 the decreasing trend is arrested at diameter ratio 2.2 and control effectiveness becomes marginal. For lower Mach numbers 1.1 and 1.2 the control effectiveness is only marginal.

Results for NPRs 3 and 5 at L/D = 4 are shown in Figs. 3(a) to (d)). Here for Mach numbers 1.1 and 1.2 the flow is under expanded. Once the level of under expansion has come down significantly the trend of decrease in base pressure which was observed for higher NPRs is no more visible, however, up to diameter ratio 1.8 the similar trends are maintained as earlier as seen in Fig. 3(d) for Mach 1.5 and control reversal also takes place at the same point whereas, the same behavior of the flow takes place at diameter ratio 2.2 for Mach 1.4. From Fig. 3(c) it is seen that at Mach 1.1 control reversal takes place at diameter ratio 2.2, and there is progressive growth in the value of the base pressure from diameter ratio 1.8 to 2.2 and beyond the value of the base pressure shoots up, but the decreasing trend in the base pressure is reversed at the diameter ratio 2.2, in case of Mach 1.2, the trend of decrease in base pressure is the same except between diameter ratio 2.2 there is sudden increase in the value of the base pressure and control results in increase of base pressure for all the parameters of the present study.
For NPR 3 the results are shown in Figs. 3((a) to (b)). There is continuous increase in the magnitude of the base pressure for Mach 1.1, 1.2, 1.5 and 1.4 as seen in Fig. 3((a) to (b)), this change in trend is due to the effect of level of expansion, length to diameter ratio, and inertia level at the nozzle exit.

The strong effect of diameter ratio and area ratio when the jets are almost correctly expanded is clearly seen from these results exhibiting a mixed trend reflecting both under and over expanded situation. This is because when the jets are correctly expanded there is an expansion fan at the nozzle exit due to the increase in diameter ratio. This expansion fan has control over the base pressure depending on the relief it enjoys due to the diameter ratio.

From the results for L/D = 4 it is clear that the control is effective when jets are under expanded and the control effectiveness decreases with decrease in the level of under expansion. These results indicate that the control becomes effective in a field when there is favorable pressure gradient exists. This is in good agreement with the argument of available literature as stated for the case of passive control.

Results for L/D = 3 are shown in Figs. 4((a) to (j)). They show similar results for NPR 9 and 11 as it was seen for L/D = 4, the only difference between the present result and in the previous one is that all the variables are same except that the L/D ratio has been decreased from L/D = 4 to 3 as seen in Figs. 4((g) to (j)). When the jets are operated at this decreased length of L/D ratio = 3, the back pressure will influence the flow in the suddenly expanded duct and may marginally influence the base region. This marginal influence is clearly seen as the nature of the graphs are on the similar lines as that of at L/D = 4 with marginal increase in the magnitude of the base pressure.

Fig. 4(f) presents the results for NPR 7 at Mach 1.4 and 1.5. For Mach 1.4 the results are same as that of higher NPRs, whereas, for Mach 1.5 the trend is similar up to diameter ratio 2.2 then there is sudden increase in the value of the base pressure for the reasons as explained above. Figs. 4((a) to (e)) presents the results for NPR 7 at Mach 1.1 and 1.2 Fig. 4(e) and NPR 3 and 5 are shown in Figs 4((a) to (d)) for Mach 1.1, 1.2, 1.4, and 1.5 they are representative of the similar results as that of higher NPRs.

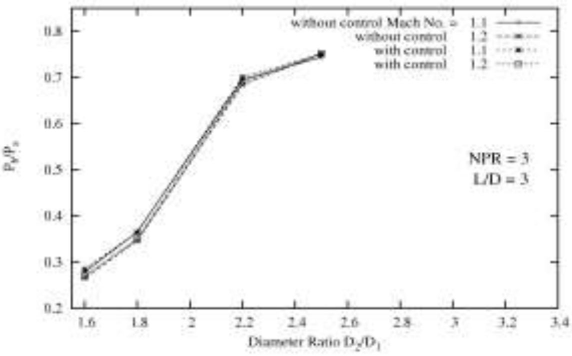


Fig. 4 (a)

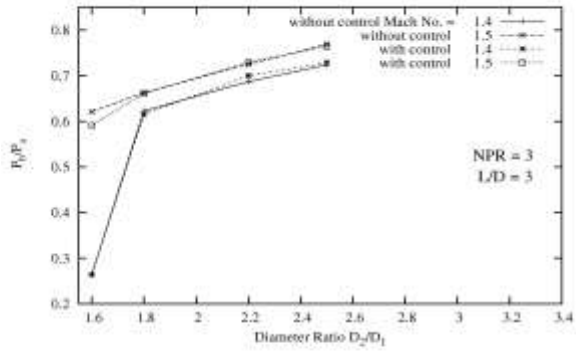


Fig. 4 (b)

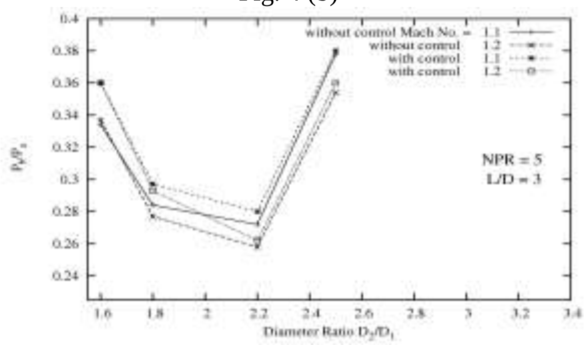
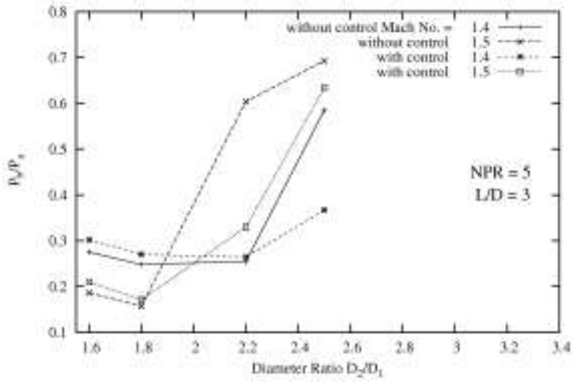


Fig. 4 (c)



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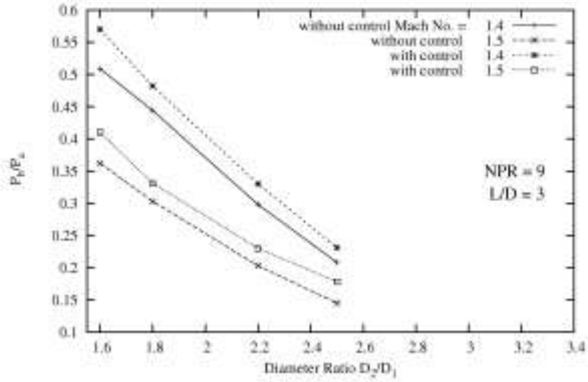

Fig. 4 (h)

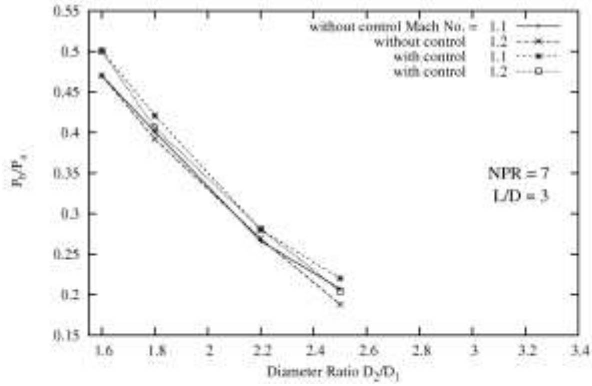

Fig. 4 (e)

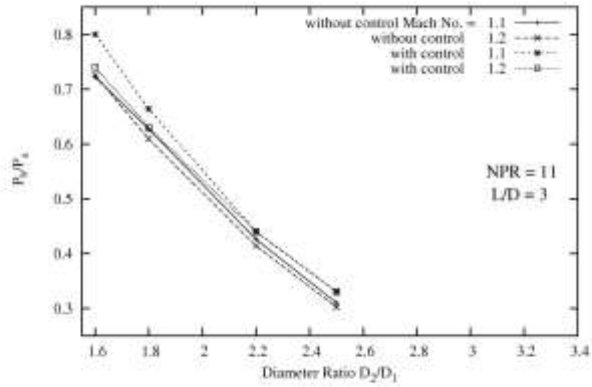

Fig. 4 (i)

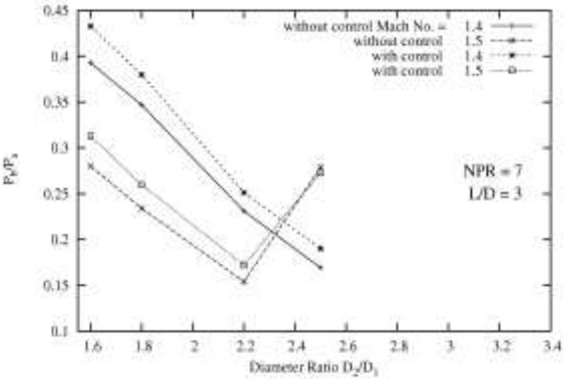

Fig. 4 (f)

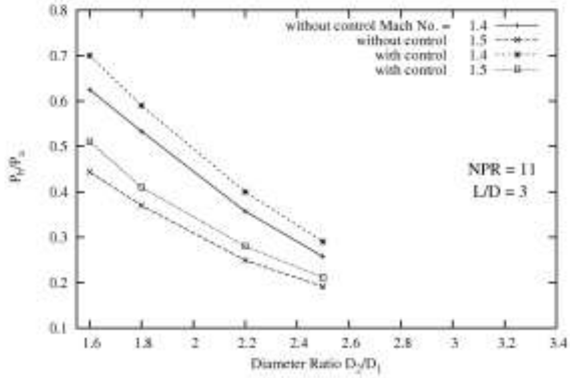

Fig. 4 (j)

Fig. 4. Base pressure variation with Diameter Ratio for L/D = 3

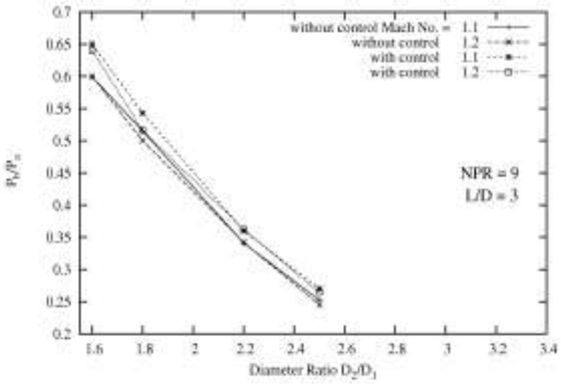

Fig. 4 (g)

Base pressure results for L/D = 2 in the NPR range 11 to 3 are given in Figs. 5((a) to (j)). The general behavior of base pressure with increase of diameter ratio is similar to that for L/D = 4 for NPR 9 and 11 for NPR 7 at Mach 1.1 and 1.2 as shown in Figs. 5((g) to (j)) and Fig. 5(e). However, the control effectiveness is strongly influenced by the L/D, as seen from these Figs. With decrease in L/D it is interesting to see that the control has become very effective in reducing the base pressure without control case and when control were activated they result in increase of base pressure for all the parameters. Fig. 5(f) presents results for NPR = 7 at

Mach 1.4 and 1.5. From the figure it is seen that for Mach 1.4 the results are the same as we have discussed earlier for higher NPRs and the control results in increase of the base pressure, whereas, for Mach 1.5 also the same trend of decrease in the base continues till the diameter ratio 2.2 and then base pressure abruptly increases. The primary reason for this behavior is the level of expansion and the low length to diameter ratio. Results for NPR 3 and 5 are shown in Figs. 5((a) to (d)) and they represent the similar results as we have discussed above for higher NPRs namely 7, 9 and 11.

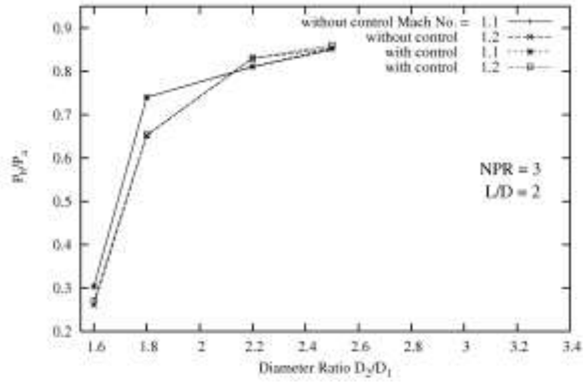

Fig. 5 (a)

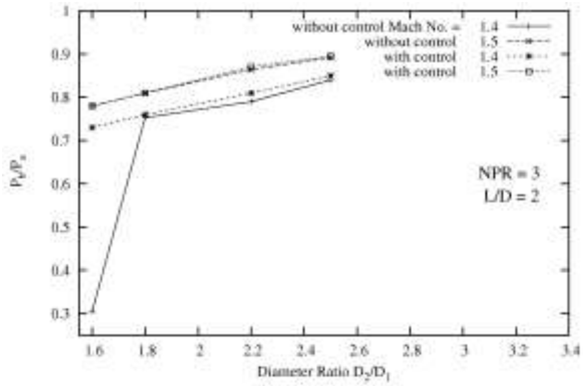

Fig. 5 (b)

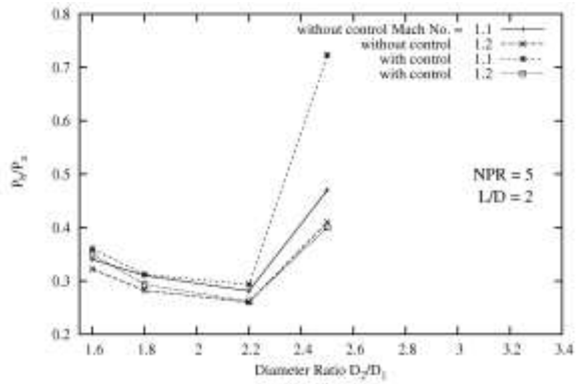

Fig. 5 (c)

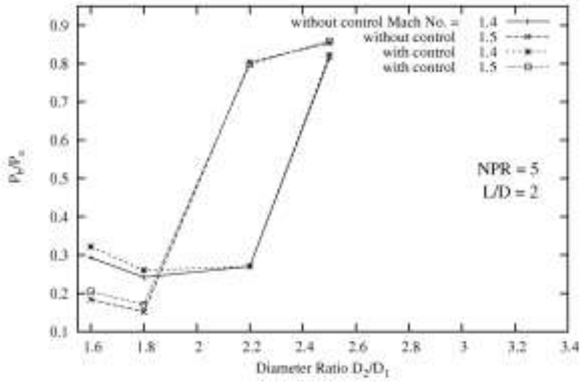

Fig. 5 (d)

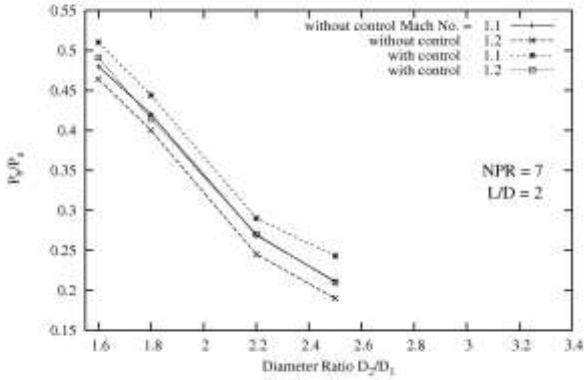

Fig. 5 (e)

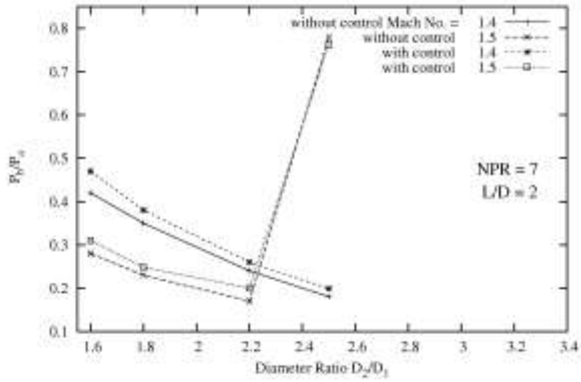

Fig. 5 (f)

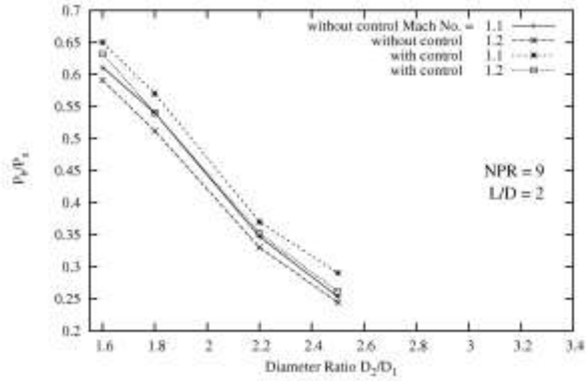

Fig. 5 (g)

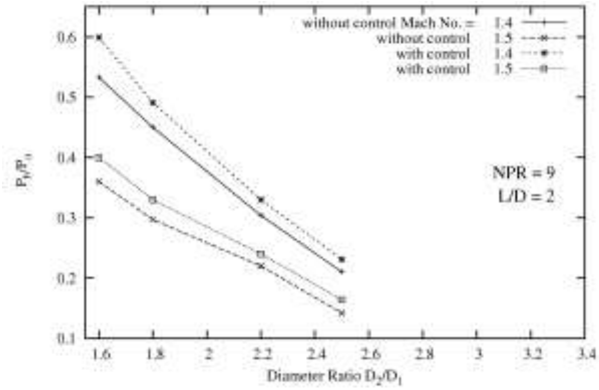

Fig. 5 (h)

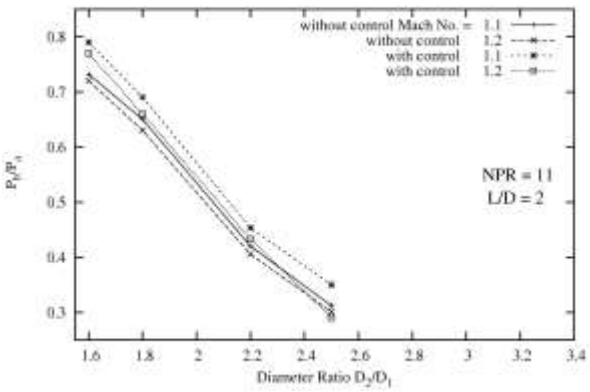

Fig. 5 (i)

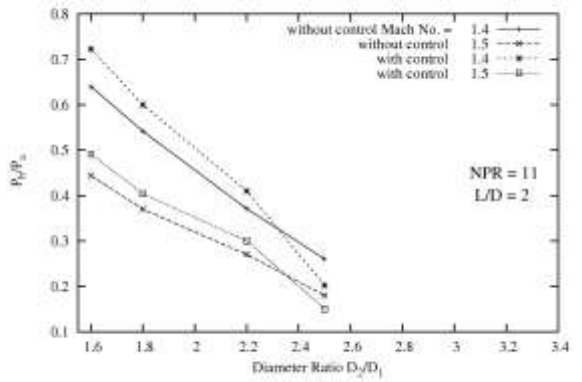

Fig. 5 (j)

Fig. 5. Base pressure variation with Diameter Ratio for L/D = 2

The results for L/D = 1 are shown in Figs. 6((a) to (j)) for NPRs 3 to 11. From the figure it is evident that at NPRs 9 and 11 exhibit similar results as seen earlier for L/D = 2 at NPRs 9 and 11.

Figs. 6((e) to (f)) shows the results for NPR 7 at Mach 1.1, 1.2, 1.4 and 1.5. From the figure it is evident that the results for Mach 1.1, 1.2, and 1.4 are in no way different to that of for higher NPRs as discussed above, whereas, for Mach 1.5 trend is same to that of lower Mach number up to the diameter ratio 2.2 and beyond there is sudden jump in the value of the base pressure and this result clearly indicates that the this length is not sufficient for the flow to be attached with the duct wall and then up to diameter ratio 2.2 control results in increase of base pressure.

For NPR 5 the base pressure results are shown in Figs. 6((c) to (d)). From the Fig. 6(d) it is seen that at Mach 1.4 and 1.5 up to diameter ratio 1.8 the base pressure decreases with increase in the diameter ratio then there sudden jump in the value of base pressure, this clearly indicates that the flow is no more attached with the enlarged duct whereas, for Mach 1.1 and 1.2 that the base pressure decreases up to diameter ratio 1.8 then there is marginal increase in the base pressure value and then sudden increase in base pressure, which indicates that flow is detached with the enlarged duct and control is only marginal for all the cases in the present case. At NPR 3 Fig. 6(b) for Mach 1.4 trend is same as discussed earlier but at Mach 1.5 there is continuous increase in the value of base pressure and flow is no more attached with the duct wall. Similar results are seen in Fig. 6(a) and flow seems to be no more attached with the duct wall.

However, the results for lower NPRs behave in similar manner as those for L/D = 4, excepting that the control effectiveness is very strongly influenced by the reduced enlarged duct length. This is because the base pressure is dictated by the free shear layer reattachment and the reverse flow to the base region from the boundary layer which grows downstream of the reattachment point. Therefore, the duct length which has got a very strong effect on boundary layer growth has a definite influence on the base vortex as well flow pattern at the base area which dictates the base pressure level.

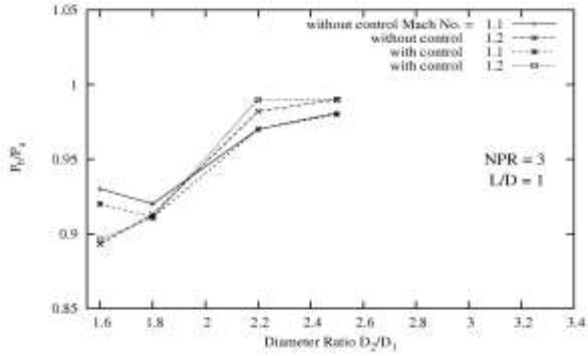

Fig. 6 (a)

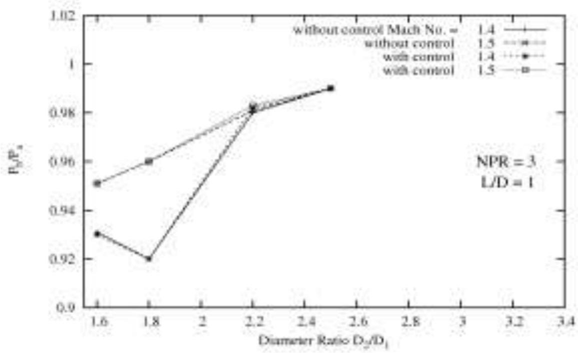

Fig. 6 (b)

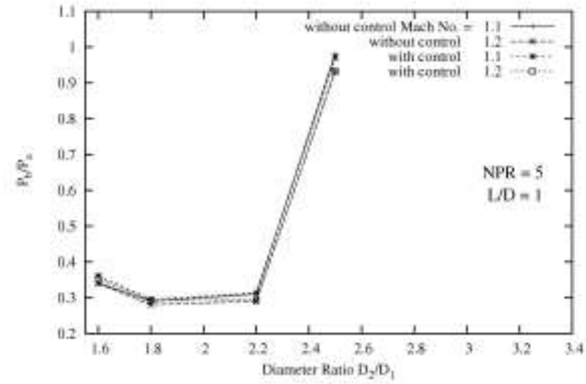

Fig. 6 (c)

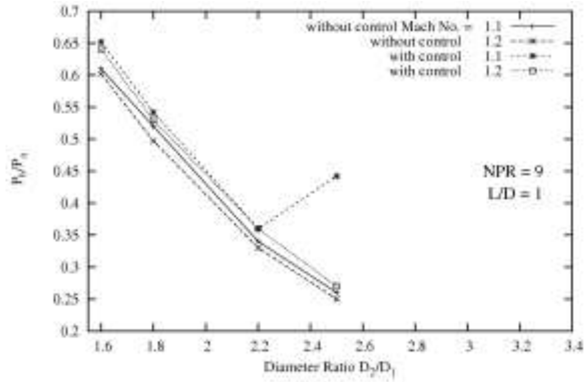

Fig. 6 (g)

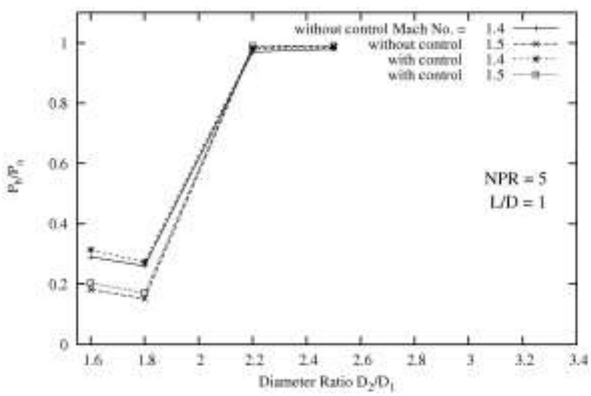

Fig. 6 (d)

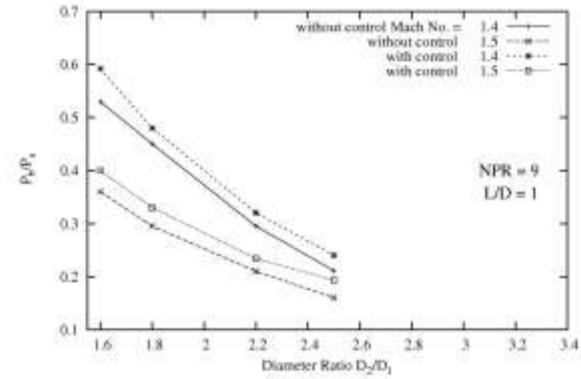

Fig. 6 (h)

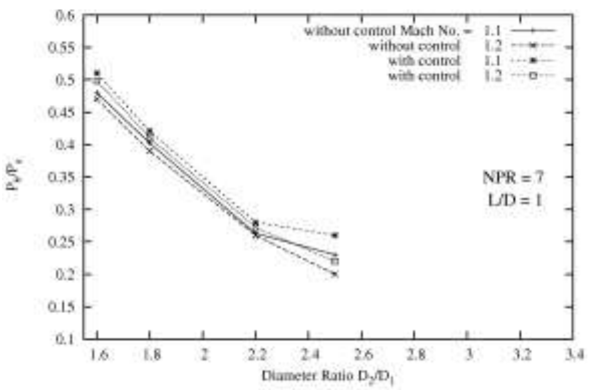

Fig. 6 (e)

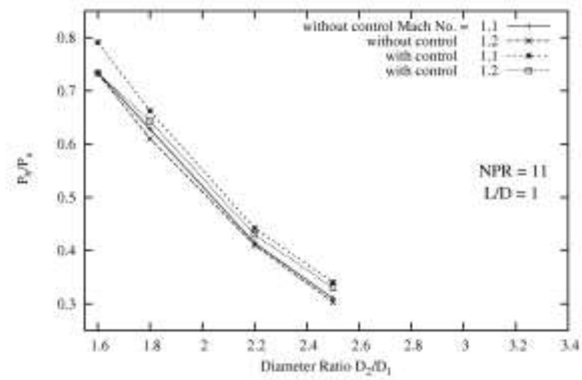

Fig. 6 (i)

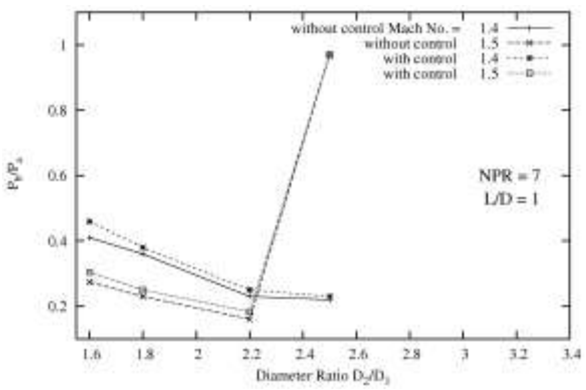

Fig. 6 (f)

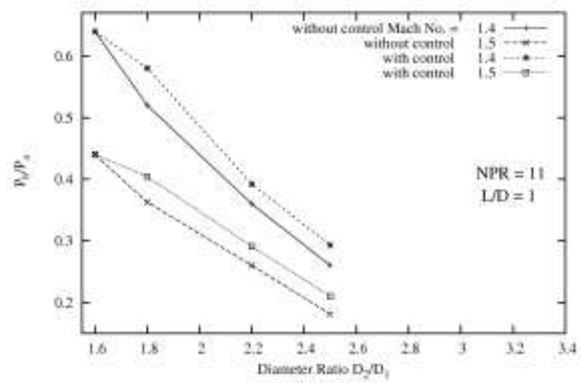

Fig. 6 (j)

Fig. 6. Base pressure variation with Diameter Ratio for L/D = 1

V. CONCLUSION

The results show that the effectiveness of the Micro jets is marginal for some cases in controlling the base pressure even under the influence of favorable pressure gradient at lower NPRs namely 3 and 5. An important point to be observed that, unlike passive controls the favorable pressure gradient need not give desired results for active control in the form of micro jets. However, for higher values of the NPRs namely 9 and 11 the active control by micro jets results in increase of base pressure for all the values of the diameter ratios of the present studies. At NPRs 5 and 7 the trends are different due to the level of expansion, nature of waves present at the base, relief available, L/D ratio and Mach numbers.

It is seen that most of the cases exhibit similar behavior for higher as well as the lower L/Ds, and at lower NPR and Mach numbers which means; that the back pressure has not adversely influenced the flow field in the base region as well as in the duct for L/D = 4 and 3.

The minimum duct length required for the flow to be attached with the enlarged duct seems to be L/D = 2, for all the cases of the present study, it is also found that for some combinations the flow attached with the duct wall even at L/D = 1.

Hence the present results are case sensitive and their behavior changes due the change in the shock wave pattern when we alter the NPR, the Mach number, L/D ratio and the diameter ratio.

All the non-dimensional base pressure presented in 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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