Control of suddenly expanded flow for area ratio 3.61

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ABSTRACT

Airflow from convergent axisymmetric nozzle expanded suddenly into circular duct of larger cross-sectional area than that of nozzle exit area were studied experimentally, focusing attention on the base pressure and the flow development in the duct. The flow parameters considered in this investigation are Mach number at the nozzle exit and the nozzle pressure ratio. The geometrical parameters considered are the area ratio between the sudden expansion duct cross-section and the nozzle exit area and the length to diameter ratio of the duct. To investigate the influence of active control on base pressure as well as on the flow field developed in the duct, the micro jets of 1 mm orifice diameter located at 90^0 interval along a pitch circle diameter (pcd) 1.3 times the nozzle exit diameter were employed as the controller of base pressure. The area ratio of the present study is 3.61. The nozzle pressure ratio (NPR) used were from 1.5 to 3, in steps of 0.5 and experiments were conducted for NPR 1.5, 2.0, 2.5 and 3.0. The length to diameter ratio of the enlarged duct was varied from 10 to 1, and tests were conducted for L/D 10, 8, 6, 5, 4, 3, 2 and 1. The experimental investigation on suddenly expanded flow field covering the above flow and geometrical parameters revealed that the base pressure is strongly influenced by the geometrical parameters viz length to diameter ratio, Mach number and the nozzle pressure ratio (NPR). The level of expansion at the nozzle exit (i.e. before sudden expansion) influences the base pressure very strongly.

Key words: Micro jets, Base pressure, Sudden expansion, Control pressure, Mach number

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INTRODUCTION

Due to the importance of the problem connected with fluid dynamic drag, a vast number of investigations, both theoretical and experimental, considering base pressure and base drag have been performed. The rapid growth of interest in supersonic drag problems associated with the development of supersonic aircraft, projectiles, missiles, and spacecraft was one

reason for the fact that the theory made greater advances at high Mach numbers than at low speeds and that more experiments were performed in this velocity range to verify the theoretical results. Because of it's vide applicability; suddenly expanded flows have studied extensively. Many researchers attempted to control the base pressure with passive means and some of the works relevant to the present study are reviewed in the section to follow. Therefore, in the present study an attempt is made to investigate the base pressure control with active control in the form of micro jets.
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.

LITERATURE REVIEW

The effect of boundary layer on sonic flow through an abrupt cross-sectional area was studied experimentally by Wick [1]. He observed that the pressure in the expansion corner was related to the boundary layer type and thickness upstream of the expansion. He considered a boundary layer as a source of fluid for the corner flow. Anderson J. S. et al. [2] found that the most significant is the base-pressure type, where the variations in pressure are large. James A. Kidd et al. [3] conducted Free-flight tests of spin-stabilized projectiles and fin-stabilized missiles with various stepped, flat and bottailed 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. Viswanath P. R. [4] investigated experimentally the zero-lift drag characteristics of multi-step after-bodies that utilize the concept of controlled separated flows at transonic and supersonic speeds. The important geometrical parameters affecting the drag of such after-bodies were identified, and their effects were examined through a parametric study. Their results show that multi-step after-bodies can be design that provide significant total drag reduction (as high as 50 per cent) compared to (unmodified) blunt bases; however, compared to axi-symmetric boattailed after-bodies of a given base area, the multi-step after-bodies have relatively higher drag. Finally, the certain flow features involving separation and reattachment on multi-step after-bodies were discussed based on flow visualization studies. Singh and Rathakrishnan [5] studied the effect of tab geometry on flow characteristics of sonic jet. It is found that the tabs are very effective to control the jets. Khan and Rathakrishnan [6-10] 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. Jagannath et al. [11] studied the pressure loss in a suddenly expanded duct with the help of Fuzzy Logic. They observed that minimum pressure loss takes place when the length to diameter ratio is one. Further it was observed that the results given by fuzzy logic are very logical and can be used for qualitative analysis of fluid flow through nozzles in sudden expansion. An experimental study has been conducted by Lovaraju P. et al. [12] to investigate the effectiveness of passive controls in the form of small tabs and a cross-wire projecting normally into the flow at the nozzle exit, on the characteristics of an axi-symmetric sonic jet operated at three underexpansion levels. The present investigation on the effectiveness of cross-wire and tabs on the underexpanded sonic jets shows that, both the passive controls are effective in reducing the axial extent of supersonic core significantly. Also, both the controls render the symmetric shock-cell structures unsymmetrical and weaker, all along supersonic core. The cross-wire/tab controlled jets grow wider in the direction normal to the cross-wire/tab at all the operating conditions. However, the tabbed jets grow much wider compared to the cross-wire controlled jets. Pandey and Kumar [13] studied the base pressure in a suddenly expanded circular ducts using fuzzy set theory. From their analysis it was observed that L/D ratio is 6 for base pressure for Mach 1.58, 1.74, 2.06 and 2.23, which is in very close agreement with the experimental results. The effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts is studied experimentally by Ashfaq et al. [14]. From the experimental results, it was found that the micro jets can serve as active controllers for base pressure. From the wall pressure distribution in the duct it found that the micro jets do not disturb the flow field in the enlarged duct. Ashfaq andKhan [15] 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 activecontrol 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

EXPERIMENTAL METHOD

Fig. 1 shows the experimental setup used for the present study. At the exit periphery of the nozzle there are eight holes as shown in Fig. 1, four of which are (marked c) were used for blowing and the remaining four (marked m) were used for base pressure (P_b) measurement. Control of base pressure was achieved by blowing through the control holes (c), using pressure from a settling chamber by employing a tube connecting the settling chamber, and, the control holes (c). Wall pressure taps were provided on the duct to measure wall pressure distribution. First nine holes were made at an interval of 4 mm each and remaining was made at an interval 8 mm each. From literature it is found that, the typical L/D (as shown in Fig. 2) resulting in P_b maximum is usually from 3 to 5 without controls. Since active controls are used in the present study, L/D ratios up to 10 have been employed.

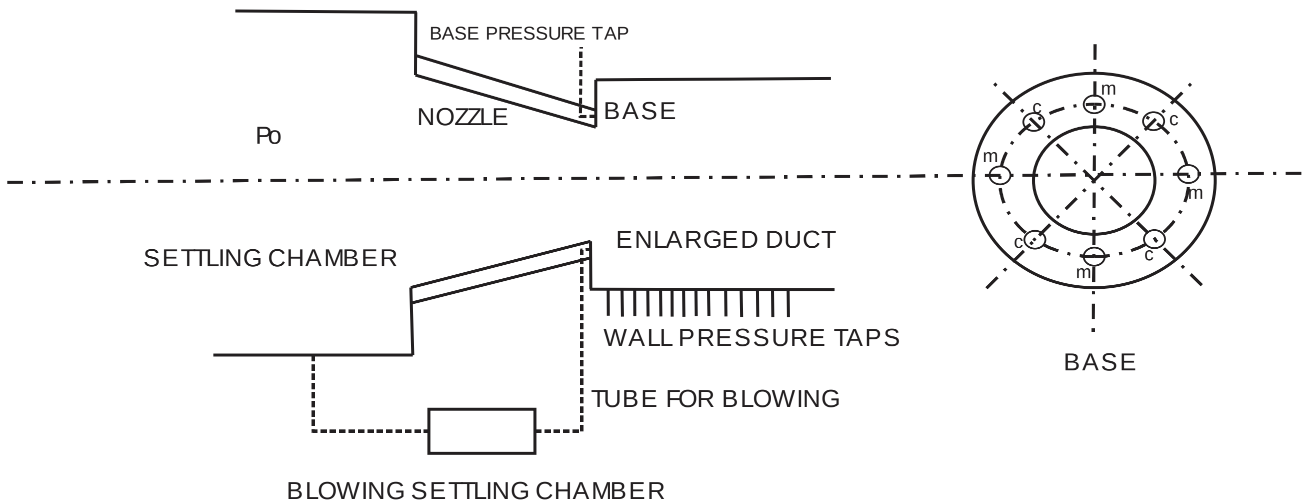

Fig.1: Experimental setup

The experimental setup of the present study consisted of an axi-symmetric nozzle followed by a concentric axi-symmetric duct of larger cross-sectional area. The exit diameter of the nozzle was kept constant (i.e. 10 mm) and the area ratio of the model was 3.61 defined, as the ratio of the cross-sectional area of the enlarged duct to that of the nozzle exit. The suddenly expanded ductswere fabricated out of brass pipe. Model length was ten times the inlet diameter so that the duct has a maximum L/D = 10. The lower L/Ds were achieved by cutting the length after testing a particular L/D.

PSI model 9010 pressure transducer was used for measuring pressure at the base and the stagnation pressure in the settling chamber. It has 16 channels and pressure range is 0-300 psi. It averages 250 samples per second and displays the reading. The software provided by the manufacturer was used to interface the transducer with the computer. The user-friendly menu driven software acquires data and shows the pressure readings from all the 16 channels simultaneously in a window type display on the computer screen. The software can be used to choose the units of pressure from a list of available units, perform a re-zero/full calibration, etc. The transducer also has a facility to choose the number of samples to be averaged, by means of dipswitch settings. It could be operated in temperatures ranging from -20° to +60° C and 95 per cent humidity.

RESULTS AND DISCUSSION

The measured data consists of base pressure (P_b); wall static pressure (P_w) along the duct and the nozzle pressure ratio (NPR) defined as the ratio of stagnation pressure (P_0) to the back pressure (P_{atm}). All the measured pressures are non-dimensionalized by dividing them with the ambient pressure (i.e. the back pressure). In the present study the control pressure in the control chamber will be the same as the NPR of the respective runs as the air is drawn from the main settling chamber. Hence, additional source of energy for micro jets is not needed.

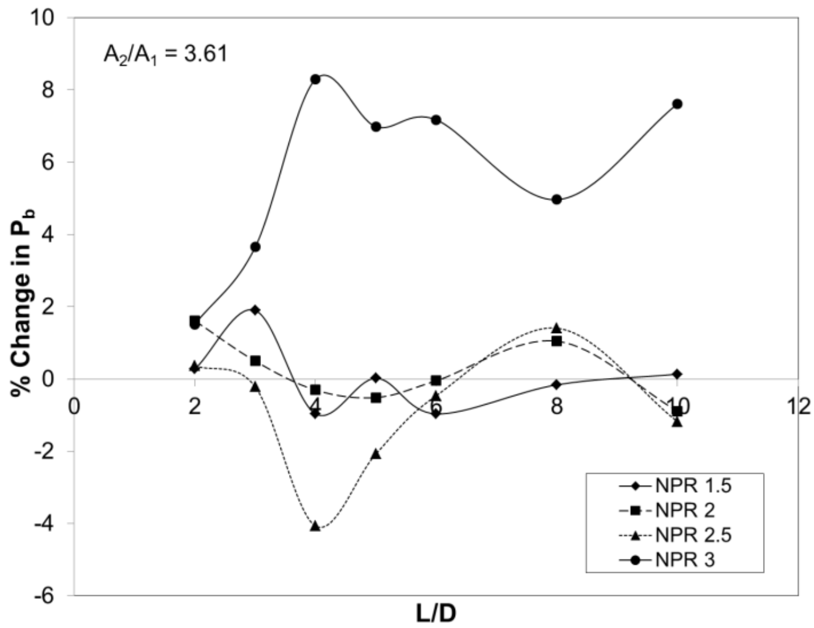

Fig.2: Percentage change in base pressure variation with L/D

Fig. 2 represents the percentage increase in base pressure as a function of L/D ratio and NPR. It is seen that the micro jets do influence the base pressure favourably (to increase) and adversely (to decrease). The favourable and adverse nature of influence is found to be governed by the NPR.

For L/D = 2 to 10, in the present study, for NPR 3.0 the micro jets favourably influence the base pressure, resulting in a maximum of 8 % increase in base pressure. This can be considered as a great advantage since the vehicles like missiles flying at supersonic Mach numbers the base drag (the base pressure [suction] x base area) can be as high as 60 % of the total drag. Therefore, even a small increase in base pressure will result in significant reduction of drag. For other NPRs the increase or decrease in base pressure is only marginal. This is in total agreement with minimum length requirement limit reported by Rathakrishnan and Sreekanth [16].

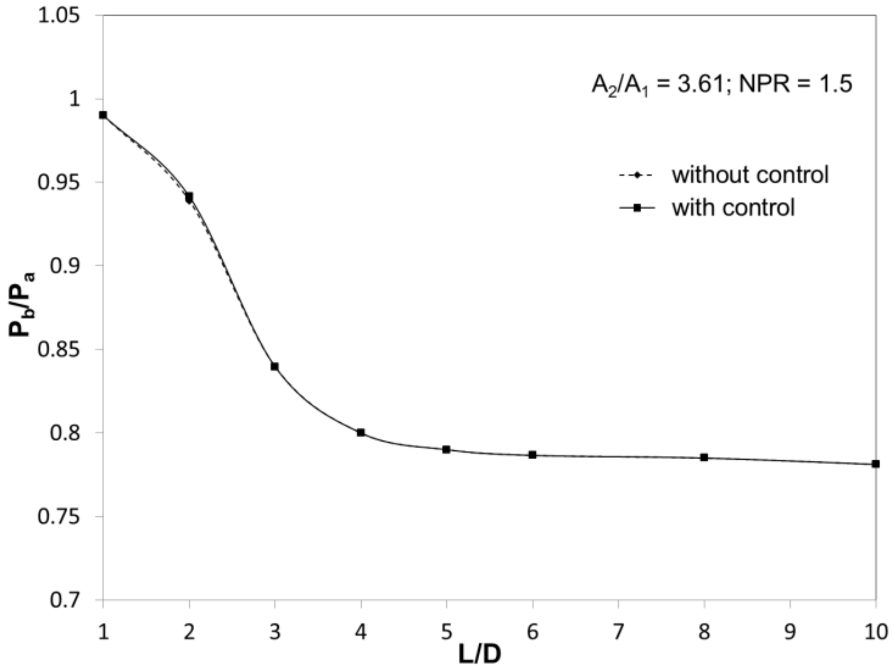

Fig.3: Base pressure variation with L/D

Non-dimansionalized base pressure variation with L/D ratio for NPR 1.5 and 2.0 for the cases of flow with and without control are compared in Figs. 3 & 4. It is clearly seen that the functional dependence of base pressure with NPR is unaltered by the control. However, the control tend to modify the base pressure level. Also, the control effectiveness in modifiying the level of base pressure gets enhanced with increase of NPR. This agrees well with the findings of Navin Kumar Singh and Rathakrishnan [5], who reported that the effectiveness of passive control in the form of tabs in enhancing the mixing increases with increase of favorable pressure gradient. For the NPRs establishing favorable pressure gradient the control becomes progressively more effective with increase of favorable pressure gradient. Furthermore, it is seen that the control results in decrease of base pressure compared to without control case, up to certain NPR and L/Ds and then increases the base pressure to stay above that for without control case.

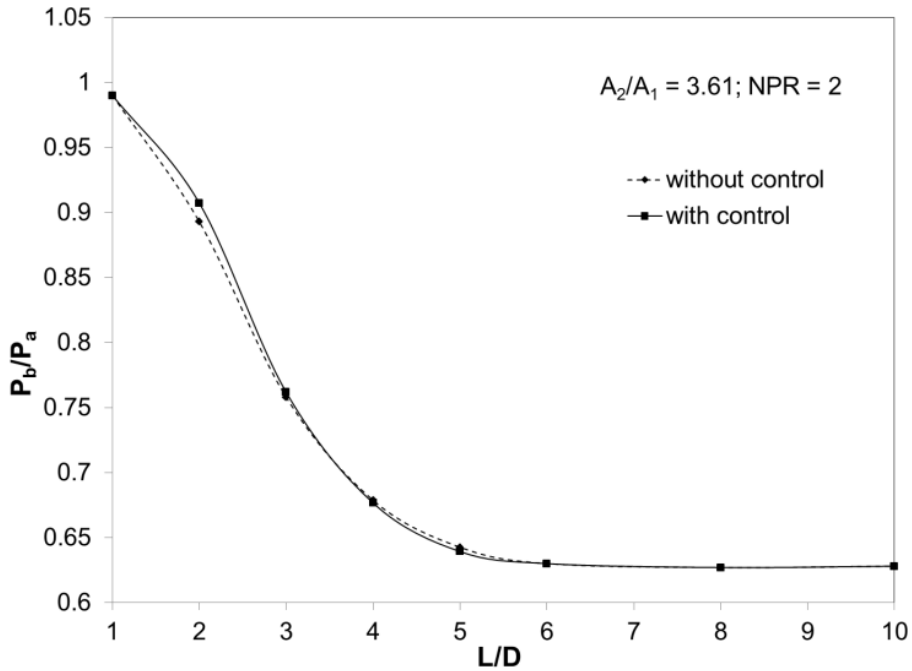

Fig.4: Base pressure variation with L/D

A closer look at the flow process at the base of the duct will explain the reason for this behavior. The base pressure level is dictated by the expansion level at the nozzle exit, the Mach number, strength of the vortex at the base and the duct L/D, for a given area ratio. There will be an expansion fan and Mach wave at nozzle lip, for under and correctly expanded flows, respectively. Thus, the wave at the nozzle lip has a dominant influence on the base pressure level. This causes the control to become more effective at higher NPR under the influence of the favourable pressure gradient. Further, in the present study the NPR tested they fall under the category of correct and under expanded case only as the flow is through a converging nozzle, hence, the Mach number at the nozzle exit will be unity and due to the level of expansion the flow will be either under expanded or ideally expanded. When we consider the NPRs in the range of 1.5 and 2, here the flow will be dominated by the waves and when the micro jets are activated under these conditions this will lead to lot of inter actions in terms of intersection of the wave, reflection of the wave from the duct and so on. Hence, it is difficult to predict a definite trend. Therefore, all the results are case sensitive and one has to take up case by case basis, as this study is a technology demonstration. However, when the flow from the nozzle is under expande the flow will have a tendency to deflect away from the base which will results in the reduction of the strength of the base vortex and hence relatively increased value of base pressure. When the nozzle flow is correctly expnded the flow will consist of Mach waves and when the flow is passing through these waves delecting away tendency will not be present and no loss of pressure as across the Mach the flow will remain isentropic locally. The above discussed behavior of base pressure with NPR for the cases of with and without control is clearly seen in Figs. 3 & 4. Further it is seen in this figures that the control effectiveness reversal is taking place at L/Ds 4, 5 and 8 for NPR 1.5. Whereas, for NPR 2.0 the control effectiveness reversal takes place at L/Ds 4 and 6.

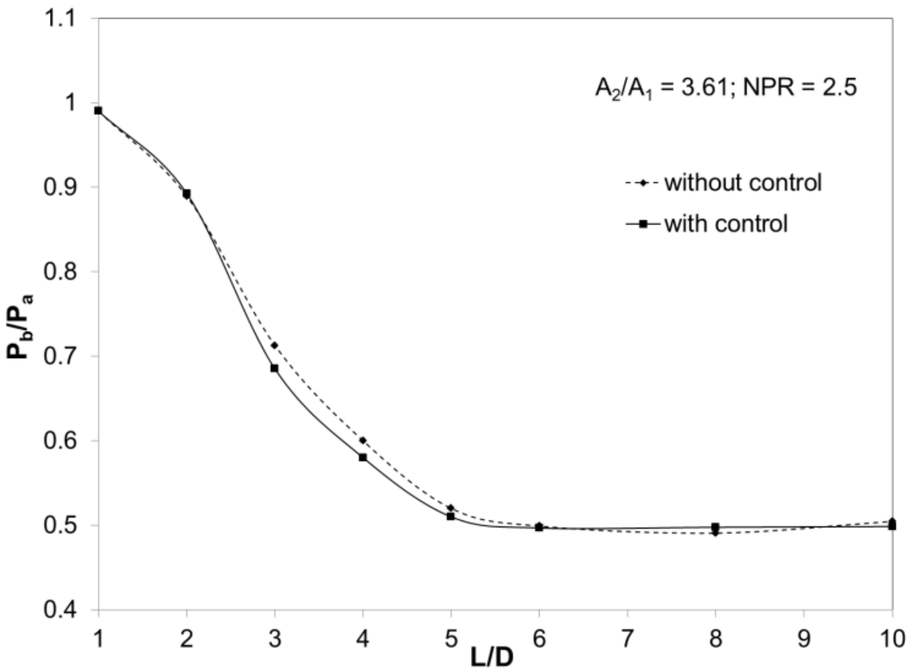

Fig.5: Base pressure variation with L/D

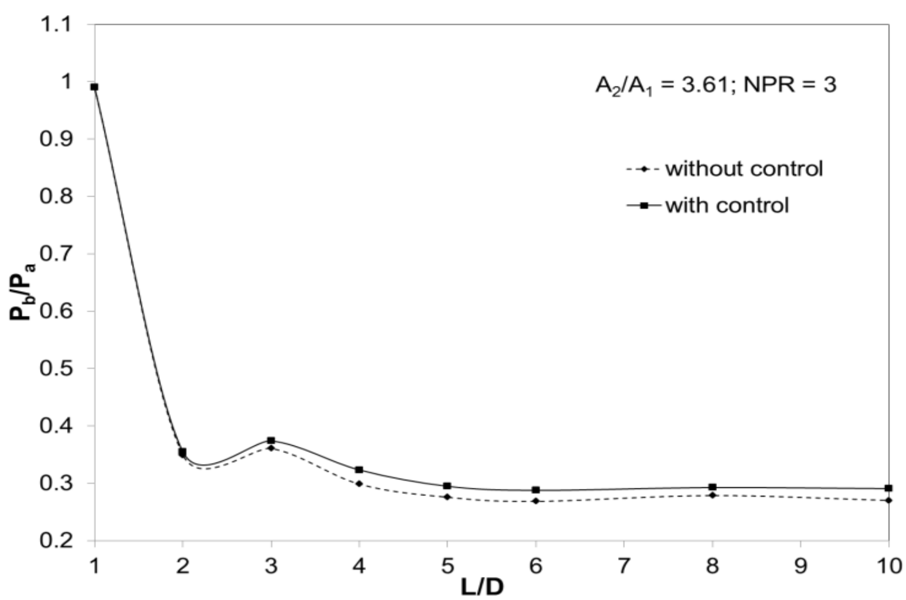

Fig.6: Base pressure variation with L/D

Base pressure results for NPRs 2.5 and 3.0 are shown in Figs. 5 & 6. For this L/D the behaviour at NPR 2.5 is same as that for NPRs 1.5 and 2.0. It is evident from these results that, the L/D has a defined role in the control of base pressure achieved with micro jets. It can be stated that, the base pressure due to the recirculation of the flow at the base is dictated by the re-attachment length, which is the distance from the beginning of the enlargement duct to the point where the free shear layer from the nozzle attaches with the duct wall. For this to take place the duct should have a definite length. It has been proved by Rathakrishnan and Sreekanth [16] that this minimum length is L/D = 5. As seen from the Fig. 6 that for NPR = 3, the control becomeseffective as long as the flow is attached with the enlarged duct wall. It is found that the control in the form of micro jets results in increase of the base pressure for L/D =2 and above. In general duct L/D = 5 appeared to be the limit for base vortex strength manipulation except for NPR = 3 where this limit comes down to L/D = 2 and L/D less than 5 proved to be insufficient for the flow to re-attach in most of the cases. Hence, it is evident from the above results that the rate of increase becomes a function of nozzle expansion level. Further, the micro jets become effective in enhancing the base pressure when the nozzle is under expanded.

CONCLUSION

From the results and discussions of the present experimental investigation presented, the following conclusions can be drawn. The base pressure is strongly influenced by the geometrical parameters *viz.* the area ratio of the passage, the length to diameter ratio of the enlarged duct. The level of expansion at the nozzle exit (i.e. before sudden expansion) influences the base pressure very strongly. When the micro jets are activated they were found to influence the base region, taking the base pressure to considerably higher values compared to that for without control, for most of the cases for area ratio 3.61. However there is certain combination of parameters for which the active control results in decrease of base pressure. From the present investigation it is evident that for a given nozzle pressure ratio one can identify the duct length to diameter ratio which will result in maximum increase/decrease of base pressure. In general duct L/D = 5 appeared to be the limit for base vortex strength manipulation except for NPR = 3 where this limit comes down to L/D = 2 and L/D less than 5 proved to be insufficient for the flow to re-attach in most of the cases.

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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