Effect of Area Ratio on Base Pressure in a Suddenly Expanded Duct for Under Expanded Flow ft Mach 1.87

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Abstract - The results of an experimental investigation carried out to control the base pressure in a suddenly expanded axi-symmetric passage is presented in this paper. An active control in the form of micro jets is employed to control the base pressure. Air injection at four locations at the base, symmetric to the nozzle axis is used as the active control. The jet Mach number studied and the area ratios are 1.87, and 2.56, 3.24, 4.84, and 6.25. The L/D ratio is varied from 10 to 1. The experiments are conducted at a fixed level of under expansion (i.e. Pe/Pa = 1.5). In addition to base pressure, wall pressure field along the duct was also measured. As high as 80 percent increase in base pressure was achieved for certain combination of parameters of the present study. The minimum Length-to-diameter ratio of the duct required is L/D = 2 for area ratios 6.25 and 4.84. Whereas, this requirement is L/D = 1 for area ratios 2.56 and 3.24.

Keywords - *Microjets, Wall pressure, L/D Ratio, Area ratio.*

I. INTRODUCTION

Researchers in the field of ballistics have long been concerned with the problem of sudden expansion of external compressible flow over the rear of projectiles and its relationship with the base pressure, since the base drag, which is a considerable portion of the total drag is dictated by the base pressure. Fig. 1 shows the sudden expansion flow field.

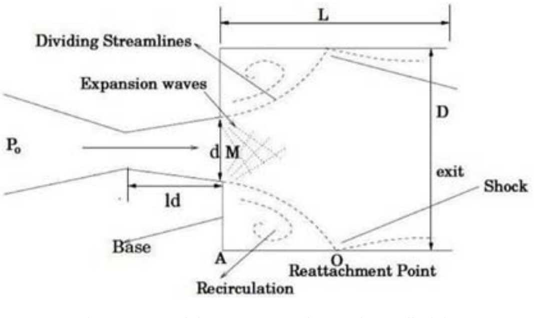

Fig. 1 : Sudden Expansion Flow field

The experimental study of an internal flow apparatus has a number of distinct ad-vantages over usual ballistics test procedures. Huge volume of air supply is required for tunnels with test-section large enough so that wall interference, etc., will not disturb flow over the model. 'Stings' and other support mechanism required for external flow tests are also eliminated in the internal flows.

II. LITERATURE REVIEW

The effect of boundary layer on sonic flow through an abrupt cross-sectional area was studied by Wick [1]. He observed experimentally that the pressure in the corner of expansion was related to the boundary layer type and thickness upstream of the expansion. He considered boundary layer as a source of fluid for the corner flow. He concluded that the mechanism of internal and external flow was principally the same and base pressure phenomenon in external flow could be studied relatively easily by experiments with internal flow. Korst [2] investigated the problem of base pressure in transonic and supersonic flow for cases in which the flow approaching the base is sonic or supersonic after the wake. He devised a physical flow model based on the concepts of interaction between the dissipative shear flow and the adjacent free stream and the conservation of mass in the wake.

Anderson and Williams [3] worked on base pressure and noise produced by the abrupt expansion of air in a cylindrical duct. With an attached flow the base pressure was having minimum value which depends mainly on the duct to nozzle area ratio and on the geometry of the nozzle. The plot of overall noise showed a minimum at a jet pressure approximately equal to that required to produce minimum base pressure. Rathakrishnan and Sreekanth [4] studied flows in pipe with sudden enlargement. They concluded that the non-dimensionalized base pressure is a strong function of the expansion area ratios, the overall pressure ratios and the duct length-to-diameter ratios. They showed that for a given overall pressure ratio and a given area ratio, it is possible to identify an optimal length-to-diameter ratio of the duct that will result in maximum exit plane total pressure at the nozzle exit on the symmetry axis (i.e. minimum pressure loss in the nozzle) and in a minimum base pressure at the sudden enlargement plane. The separation and reattachment seemed to be strongly dependent on the area ratio of the inlet to enlargement. For a given nozzle and enlargement area ratio, the duct length must exceed a definite minimum value for minimum base pressure. Tanner [5] studied base cavity at angles of incidence. He concluded that a base cavity could increase the base pressure and thus decrease the base drag in axi-symmetric flow. He varied the angle of incidence from 0 to 25^0. At $\alpha= 2^0$, he found the maximum drag decrease. Kruiswyk and Dutton [6] studied effects of base cavity on subsonic near-wake flow. They experimentally investigated the effects of the base cavity on the near-wake flow field of a slender two dimensional body in the subsonic speed range. Three basic configurations were investigated and compared; they are a blunt base, a shallow rectangular cavity base of depth equal to one half of the base height and a deep rectangular cavity base of depth equal to the base height. Schlieren photographs revealed that the base qualitative structure of the vortex street was unmodified by the presence of the base cavity. The weaker vortex street yielded higher pressures in the near-wake for the cavity bases, and increases in the base pressure coefficients of the order of 10-14 per cent, and increases in the shedding frequencies of the order of 4-6 per cent relative to the blunt-based configuration.

Pandey and Kumar [13] studied the flow through nozzle in sudden expansion for area ratio 2.89 at Mach 2.4 using fuzzy set theory. From their analysis it was observed that L/D = 4 is sufficient for smooth development of flow keeping in view all the three parameters like base pressure, wall static pressure and total pressure loss. The above review reveals that even though there is a large quantum of literature available on the problem of sudden expansion, vast majority of them are studies without control.

Suddenly expanded flow with control seems to be of interest with many applications. This will help in minimizing the base pressure in the case of combustion chamber to maximize the mixing, and maximize the base pressure in case of rockets, projectiles, aircraft bombs and missiles to result in base drag reduction. Therefore, an attempt has been made to investigate the control of base pressure field with micro jets.

III. EXPERIMENTAL SETUP

Figure 2 shows the experimental setup used for the present study. At the exit periphery of the nozzle there are eight holes as shown in the figure, four of which (marked c) are used for blowing and the remaining four (marked m) are used for base pressure (P_b) measurement. Control of the base pressure is done, by blowing through the control holes(c), using the pressure from the blowing chamber by employing a tube connecting the chamber and the control holes (c). Pressure taps are provided on the duct wall to measure wall pressure distribution in the duct. First nine holes are made at an interval of 4 mm each and remaining are made at an interval of 8 mm each. Experiment is conducted for Mach number 1.87. Since active control is employed in the present study, L/D ratios upto 10 had been tested. The L/D ratios tested are 10, 8, 6, 5, 4, 3, 2 and 1 and for each value of L/D ratio NPR employed were 3, 5, 7, 9, and 11. However, the results are presented for under expanded case only and the level of under expansion considered was 1.5 (i.e. $P_e/P_a= 1.5$). In the present study, the area ratios used are 2.56,3.24, 4.84, and 6.25 and the blow pressure ratio is nearly same as the respective NPRs.PSI model 9010 pressure transducer (interfaced with a PC) was used for measuring pressure at the base and the stagnation pressure in the settling chamber.

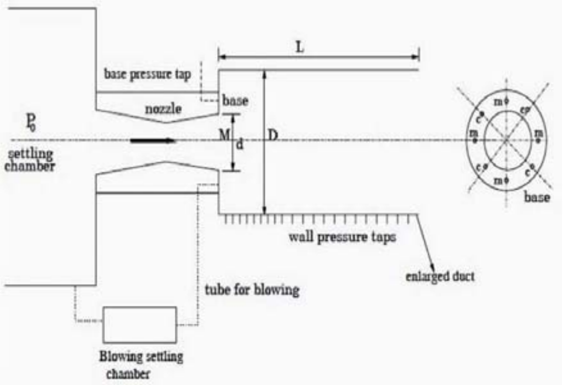

Fig. 2 : Experimental Setup

IV. RESULTS AND DISCUSSION

The measured data consists of the base pressure (P_b), wall static pressure (P_w) distribution along the length of 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 atmospheric pressure (i.e. the back pressure). In addition to the above pressures, the other parameters of the present study are the jet Mach number (M), the area ratio (duct cross sectional area/nozzle exit area), length to diameter ratio of the duct (L/D) and the blow pressure ratio. To quantify the increase in base pressure achieved with active control, cross plots of base pressure in the form of percentage increase in base pressure.

The percentage change in base pressure as a function of L/D ratio has been shown in Fig. 3 for area ratios 2.56, 3.24, 4.84, and 6.25 at Mach 1.87 under the influence of favorable pressure gradient. It is seen that the maximum gain achieved for the present parameters are 20 per cent, 30 per cent, 60 per cent, and 80 per cent for area ratios 2.56, 3.24, 4.84, and 6.25.The physical reason for this behaviour may be since the base pressure level is dictated by the level of expansion at the nozzle exit and the duct L/D ratio for a given area ratio. There will be an expansion fan at nozzle lip for under expanded flow. 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 Mach number 1.87, under the influence favorable pressure gradient. The above discussed behavior of base pressure with L/D ratio for the cases of with and without control is clearly seen in Fig. 3.

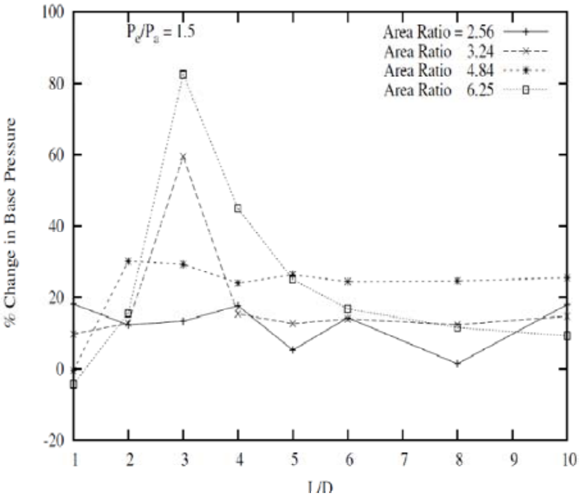

Fig. 3 : Percentage Change in base pressure with L/D

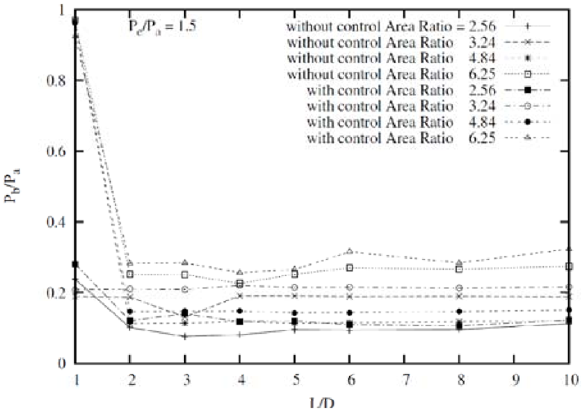

Fig. 4 : Base pressure variation with L/D

Non-dimensionalized base pressure variations with L/D ratio at Mach 1.87 for the cases with and without control are compared in Fig. 4. It is clearly seen that the functional dependence of base pressure with L/D is unaltered and the control results in increasing the base pressure throughout for the lower area ratio namely 2.56 and 3.24. Further, the minimum duct length required for these area ratios is L/D = 1. However, the control tends to modify the base pressure level at all L/Ds. Further, for higher area ratios 4.84 and 6.25the base pressure becomes independent of L/D for L/D = 2 and above and control results in increasing the base pressure for all the L/Ds. The minimum duct length required for the flow to be attached with the duct wall appears to be L/D = 2.Further, the higher values of base pressure for higher area ratios (Fig. 3 and 4) is due to the relief enjoyed by the flow and the vortex at the base is not able to create suction which otherwise is able to do so for lower area ratios. It is evident from this result that, the L/D ratio and area ratio has a defined role in the control of base pressure with micro-jets. Again, it can be stated that, the base pressure due to the recirculating flow at the base is dictated by the reattachment length, which is the distance from the beginning of the enlargement 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 [4] that this minimum length is L/D = 3, for subsonic and sonic flows.

It is in disagreement of the above findings. This may be because the experiments by Rathakrishnan and Sreekanth [4] were upto sonic Mach number and at a maximum NPR of 3. In the present study even L/D = 1 is sufficient for the flow to be attached with the duct and when micro jets were activated the control results in increase of base pressure for Mach 1.87 for all the L/Ds of the present study. One of the major problems associated with base flows is the oscillatory nature of pressure field in the enlarged duct just downstream of the base region. This can be understood by scanning the wall static pressure along the duct. In the present investigation also, attention was focused to study the effect of the active control on the enlarged duct wall pressure field. To study this wall pressure distribution for all the Mach numbers, tests were conducted with and without controls. In the figures 5 to 8 wall pressure distribution at L/D=10 for different area ratios is shown. It was found that the pressure field with control and without control behave almost identically. This ensures that the active control does not influence the wall pressure adversely rendering it to oscillate violently. This can be considered as one of the major advantages, since the major problem faced while using a control on base pressure is that the control will augment the oscillatory nature of the wall pressure field.

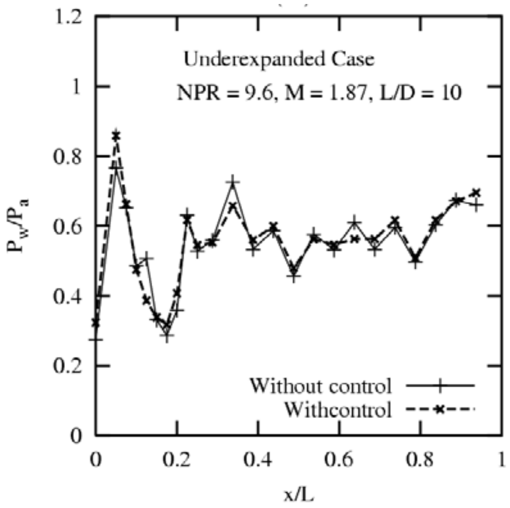

Fig. 5 : Wall pressure distribution at area ratio 2.56

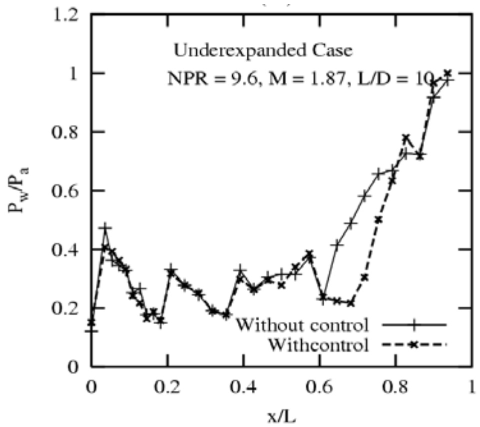

Fig. 6 : Wall pressure distribution at area ratio 4.84

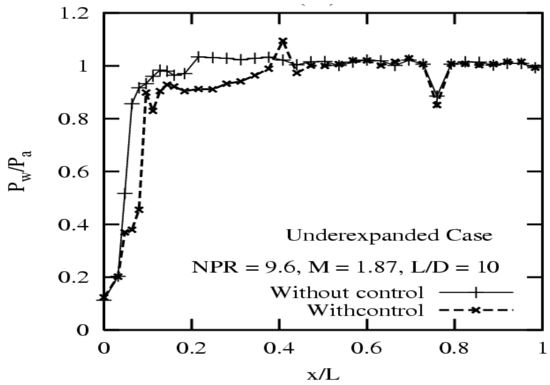

Fig. 7 : Wall pressure distribution at area ratio 6.25

V. CONCLUSIONS

Active control in the form of micro jets to control base pressure level has been demonstrated. The micro jets serve as an effective active control, raising the base suction to almost zero level for some combination of parameters. There is no adverse effect of the active control on the enlarged duct flow field. The nozzle pressure ratio has a definite role to play in fixing the level of base pressure with and without control, in the supersonic Mach number regime too It is seen that the maximum gain achieved for the present parameters are 20 per cent, 30 per cent, 60 per cent, and 80 per cent for area ratios 2.56, 3.24, 4.84, and 6.25.

All the non-dimensional base pressure presented in this paper are within an uncertainty band of ±2.6 per cent. Further, all the results are repeatable within ±3 per cent.

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