EXPERIMENTAL STUDY OF SUDDENLY EXPANDED FLOW FROM CORRECTLY EXPANDED NOZZLES

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ABSTRACT
This paper presents the results of the experimental investigation conducted at supersonic Mach numbers through converging-diverging nozzles. The experiments were conducted for correctly expanded cases and, for length-to-diameter ratio of 10 to 1. The area ratios were 2.56, 3.24, 4.84, and 6.25. The results presented are only for correctly expanded jets. From the results it is found that at lower Mach numbers and area ratios the efficacy of the control in the form of micro jets is only marginal and the control results in increase of base pressure for all the Mach number. For the first two lower area ratios namely 2.56 and 3.24, it is also observed that the magnitude is getting enhanced considerably from Mach 1.6 and beyond, but for the larger area ratios namely 4.84 and 6.25 of the present study the control results in decrease of base pressure for Mach numbers in the range 1.6, 1.8, and 2.0. When we analyzed and plotted the wall pressure distribution in the enlarged duct the flow remains unperturbed and attached with the suddenly expanded duct for both with and without control cases. For Mach 1.48 the flow field in the duct becomes oscillatory which, indicates that the flow in the duct is dominated by the waves and when the active control is employed suppresses the noise, and this peculiar phenomenon happens only for this Mach number. However, for Mach 1.8 and 2.0 the flow structure in the duct remained oscillatory for the entire region of the duct, and for rest of the Mach numbers it remained same even when the control in the form of micro jets are activated. Hence, it can be stated that the control with the micro jets does influence the flow in the duct wall adversely except at Mach 1.48.

Keywords: base pressure, mach number, micro jets, sudden expansion, wall pressure.

INTRODUCTION
The discipline of “Base Flow Aerodynamics” is capturing a lot of attention in the past few years. The examination of base flow behind aerodynamic vehicles such as missiles, rockets, aircraft bodies and projectiles as well as re-entry vehicles is essential to understand the flow separation phenomenon, which leads to the formation of a low-pressure circulation region near the base. The interaction between the rocket exhaust and the transonic/supersonic separation external flow deteriorates the performance of launchers and projectiles, and base flow is the trigger. Talking about the advanced future nozzle mechanics, such as the plug nozzle, the performance becomes more relative 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, the pressure in this region is usually substantially lower than the free stream atmospheric pressure. This notable difference in pressures can be up to two-thirds of the total drag on the body of revolution at Transonic Mach numbers. Nevertheless, the base drag at supersonic speeds is around one-third of the total drag and has decreased in this stream. Whereas, the base drag is 10 per cent of the skin-friction drag in the sub-sonic flow as the wave drag will not be there. 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. The experimental study of an internal flow apparatus has a number of distinct advantages 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. The most important advantage of an internal flow apparatus is that complete static pressure and surface temperature measurements can be made not only along the entrance section to the expansion(analogous to a body of the projectile) but also in the wake region These measurements are particularly valuable if one wants to test theoretical prediction adequately. As stated numerous techniques have been analyzed to control the flow separation, hence base drag either by preventing it or by reducing its effects. Many researchers have adopted the passive methods like splitter plate, ribs at the base region of the enlarged duct, acoustic excitation, step body, locked vortex, but very few efforts have been made on active control strategies. Therefore, in the present work an effort is made to examine the base pressure manipulation with active control in with the help of micro jets under the effect of favorable, unfavorable pressure gradient and for ideally expanded cases; at high supersonic Mach numbers with micro jets.

LITERATURE REVIEW
In base flow aerodynamics, the aerodynamic forces are mainly loaded by separation over the rear slant, a torus on the base and two longitudinal vortices created
on the side edges (Ahmed et al. 1984; Spohn and Gillie’ron 2002; Roume’as et al. 2008) [1-3]. The abrupt expansion of air in a duct results in the base pressure and noise was studied by Anderson and Williams. When the flow remains attached, the base pressure showed minimum value, which depends mainly on the duct to nozzle area ratio and on the geometry of the nozzle. Various jet flow models for fuel injection into a combustion chamber and dispersion of effluents into rivers through a diffuser were studied by Green 1995[4]. A specific configuration of jet flow had found applications as a combustion burner in many industries (Nathan et al. 2006) [5]. Rathakrishnan and Sreekanth [6] studied flows in pipe with sudden enlargement. They concluded that the non-dimensional base pressure was 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 was possible to identify an optimal length-to-diameter ratio of the enlargement that will result in the 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 duct area ratio, the duct length must exceed a definite minimum value for minimum base pressure. The effectiveness of passive devices for axi-symmetric base drag reduction at Mach 2 was studied by Vishwanath and Patil [7]. The devices examined included primarily base cavities and ventilated cavities. Their results indicated that the ventilated cavities offered significant base drag reduction. They found a 50 per cent increase in base pressure and 3 to 5 per cent net drag reduction at supersonic Mach numbers for body of revolution.

The effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts was studied experimentally by Khan et al. [8]-[15]. From the experimental results, it was found that the micro jets can serve as active controllers for the base pressure. From the wall pressure distribution in the duct it was found that the micro jets do not disturb the flow field in the enlarged duct. Syed Ashfaq et al. [16]-[27] studied the effect of area ratio, nozzle pressure ratio, length to diameter ratio and control effectiveness for various area ratios for correctly and under expanded jets. From their result they found that the control in the form of the micro jets was very effective. One of the reason for this behaviour could be due the lowest area ratio, the space available for the flow to create the suction was the lowest and the vortex sitting at the base whose strength was constant was able to influence the base region very effectively leading to very low level of base pressure and also the wall pressure was found to be low and oscillatory in nature. This trend of the wall pressure having waviness was observed for all the NPRs and Length to Diameter ratio and it was also observed that this waviness nature was very strong at the higher NPRs as compared to the lower NPRs. They 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 were 2.56, 3.24, 4.84 and 6.25. Zakir et al [28], Jaimon et al [29], and Vigneshvaran et al [30] studies suddenly expanded flow at supersonic and sonic flow with active and passive control also; they applied CFD at supersonic Mach numbers.

It was found that many techniques can be used to reduce or even suppress two or three dimensional separation. In this study, we examine the use of micro jet based control in a suddenly expanded axi-symmetric duct, especially, the aim is to control the base pressure in the transonic/supersonic regime, which appears to be very promising. We will evaluate the micro jet efficiency to reduce the base drag and to gain some insight in the mechanism behind this approach.

**RESULTS AND DISCUSSIONS**

To substantiate the increase in base pressure achieved in the present investigation with active control in the form of micro jets, the cross plots of base pressure
values in the form of percentage increase in base pressure, which is defined as Percentage change in base pressure = \((\frac{P_b \text{ with control} - P_b \text{ without control}}{P_b \text{ without control}}) \times 100\) are used for presenting the results.

**Figure-2.** Quantifying the control effectiveness at different inertia level, L/D ratio, and area ratio conditions

**Figure-3.** At the lower L/D ratio the back pressure has got definite role to play in the control of base pressure.

To highlight the control effectiveness at different Mach numbers for a given area ratio and L/D ratio are shown in Figures 2 to 7. These plots are meant for quantifying the control effectiveness at different inertia level, L/D ratio, and area ratio conditions. The percentage increase or decrease of base pressure presented in these figures. The influence of area ratio is clearly seen from these results. For example, at Mach 2.0, for area ratio 4.84 results in about thirty percent increase of base pressure when control is employed, whereas, for area ratio 6.25 the control results in sixty percent decrease in the base pressure for a fix L/D of 3. Results for L/D = 4 are presented in Figure-4, here once again it is seen that at up to Mach 1.6 the control efficacy is insignificant for all the area ratio but at Mach 1.8 and 2.0 there is significant increase in the base pressure value but control results in decrease of base pressure for area ratios 4.84 and 6.25 and for the lower area ratio the control results in increase of base pressure.

**Figure-4.** Magnitude of the percentage in base.

**Figure-5.** Magnitude of the percentage in base has come down.

**Figure-6.** Lower mach numbers.
The influence of the L/D ratio is clearly seen in Figures 2 and 3, how at the lower L/D ratio the back pressure has got definite role to play in the control of base pressure. At the higher L/D ratio the trends are on the similar lines but the influence of the high L/D ratio is clearly seen in Figures 4 and 5 where it is seen that the magnitude of the percentage in base has come down, however, the trend remain on the similar lines and for L/D ratios 5 and 6 the magnitude has come down to twenty percent. Similar results are seen in Figures 6 and 7. It is also seen that at lower Mach numbers as well as the area ratio the control is effectiveness is marginal. Likewise, the other magnitude of control effectiveness at different Mach numbers for different area ratios are clearly seen from these results.

These results in reveal that the effect of area ratio on control effectiveness is negligible for correctly expanded jets for Mach numbers 1.25 and 1.3. For higher Mach numbers, area ratio 2.56 shows continuous increase of base pressure with control, whereas area ratio 3.24 shows an increase in base pressure only after Mach 1.6. But area ratios 4.84 and 6.25 behave differently exhibiting a decrease of base pressure with control for Mach number 2.0. Area ratio 6.25 responds to the control only at Mach 2.0 taking the base pressure to 17 per cent lower than what it was without control. For L/D = 8 for also control effectiveness with Mach number and area ratio exhibits almost identical behavior as in L/D = 10, for area ratios 2.56 and 3.24 show increase of base pressure over the entire range of Mach number, but area ratio 4.84 gives increase of base pressure up to Mach 1.6 and then results in drastic decrease in base pressure up to Mach 2.0. Area ratio 6.25 shows continuous decrease in base pressure up to Mach 1.8, but at Mach 2.0 there is steep decrease in base pressure. The results for L/D 4 and 3 are shown in Figures. also exhibit that the area ratios for Mach number range from 1.6 to 2.0 influences the base pressure strongly compared to the lower values of Mach numbers

The wall pressure distribution for all the Mach numbers are shown in Figures 8 to 13. The aim of the wall pressure was to insure that the flow field in the suddenly expanded duct is not made oscillatory due to the active control in the form of micro jets. From Figures-8-9 at Mach 1.25 and 1.3, it is evident that within the reattachment length there are fluctuations in the wall pressure due to presence of base vortex, interaction between the flow of dividing stream lines and the flow at the base region and further downstream the flow is very smooth as well as flow field with and without control remains identical.

Wall pressure results for Mach 1.48 and 1.6 are shown in Figures-10 and 11. In Figure-10 the wall pressure pattern is totally different from all the Mach numbers. It is seen that when controls are employed the wall pressure values have come down considerably as compared to beyond control case once the flow has just
crossed the reattachment length. Even though the sound measurements were not made but it was observed that the sound level has minimized considerably as compared to without control case. This observation conforms with the observation of Anderson and Williams (1968). Figure-11 shows the results for Mach 1.6, it is found that the flow field remains oscillatory due to the presence of the waves near the dividing stream line, short reattachment length, and base vortex in the base region and later there is progressive increase in the wall pressure value and here again the wall pressure tend to decrease when the micro jets were employed.

Similar results of wall pressure of Mach 1 and 2.0 are depicted in Figures 12 and 13. For Mach 2.0 the entire flow field in the enlarged duct has become oscillatory in view of the high Mach number and low area ratio, whereas for Mach 1.8 seventy percent of the flow field is oscillatory and in the far end there is smooth recovery of the flow in the enlarged duct.

**Figure-10.** The wall pressure pattern is totally different from all the Mach numbers.

**Figure-11.** The flow field remains oscillatory due to the presence of the waves.

**Figure-12.** Wall pressure of Mach 1.
**CONCLUSIONS**

From the above discussions we can draw the following:

a) It is found that at lower Mach numbers and area ratios the efficacy of the control in the form of micro jets is only marginal and the control results in increase of base pressure for all the Mach number for the first the lower area ratios namely 2.56 and 3.24.

b) It is also observed that the magnitude of the base pressure is getting enhanced considerably from Mach 1.6 and beyond, but for the larger area ratios like at 4.84 and 6.25 of the present study the control results in decrease of base pressure for the higher Mach numbers in the range 1.6, 1.8, and 2.0. At lower Mach numbers the trend is on the similar lines as discussed above.

c) When we analyzed and plotted the wall pressure distribution in the enlarged duct the flow remains unperturbed and attached with the suddenly expanded duct for both with and without control cases.

d) It is observed for Mach 1.48 the flow field in the duct becomes oscillatory which; indicates that the flow in the enlarged duct is dominated by the waves and when the active control is employed it suppresses the jets noise, and this peculiar phenomena happens only for this Mach number.

It is found that for Mach 1.8 and 2.0 the flow structure in the duct remained oscillatory for the entire region of the duct, and for rest of the Mach numbers it remained same even when the control in the form of micro jets are activated. Hence, it can be stated that the control with the micro jets does influence the flow in the duct wall adversely except at Mach 1.48.

**REFERENCES**


