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Investigation on the Prominence of Abrupt Expansion on the Base Pressure of an Axi-Symmetric Body

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Abstract: **This investigation presents the outcome of the tests conducted to control the base flows at supersonic Mach numbers. Also the efficiency of the flow controllers to govern the pressure in the base region in a rapidly expanded duct has been exercised. Four tiny jets of 1mm diameter are positioned at 90° intervals at a distance of 6.5 mm from the central axis of the main jet. The inertia levels of the abruptly expanded flows are 1.25, 1.3, 1.48, 1.6, 1.8, 2.0, 2.5 and 3.0. These jets are connected by an axi-symmetric circular brass tube whose cross-sectional area was 2.56, 3.24, 4.84 and 6.25 respectively. The L/D ratio of the enlarged duct was varied from 10 to 1 and NPR was varied from 3 to 11. However, the results presented were for Low Length to Diameter ratio, equal to 4. It was found that when the flow was discharged to the ducts of the given area ratios, it remained attached with the duct wall for all the inertia levels and the NPRs tested in the present case. It was found that the expansion level plays a significant role to decide the pressure at the base and its control efficacy. Whenever, the flow is over expanded, an oblique shock is formed at the nozzle lip, which in turn leads to enhancement of the pressure in the base region. The formation of the shock waves, reflection and recombination continued till the pressure becomes atmospheric. It was observed that the flow remains attached even for low length-to-diameter ratio, equal to 4. No adverse effect of back pressure was observed during the test. It was found that the micro jets can serve as controllers for the base pressure.**

Keywords: Base pressure, Active Control, Abrupt Expansion, Nozzle Pressure ratio.

I. INTRODUCTION

With the demand to acquire the advanced launchers, rockets and scramjets to meet the future economic requirements, the design aspects have to be researched further. In the development of advanced future nozzle designs for propulsion systems, the performance increases along with the reduction of cost, which is of course the most encouraging issue. Therefore, in base flow aerodynamics, a lot of concentration is being given to the base flow of the aerodynamic vehicles. The scope ranges from the nozzle design, flow field interactions, shock wave-boundary layer interactions, base drag and advanced concepts for these investigations. For example, in Europe, high area ratio concept is gaining strength for future engines, therefore is investigated to par with the requirements. The performance is highly dependent on the aerodynamic design of the expansion nozzle, the main parameters being the relief available to the flow at the exit of the nozzle and L/D ratio. The literature supports the dependence of the parameters to control the base drag of the flow. As the separation phenomenon is dominant at higher Mach numbers, various types of loads under dynamic conditions and phenomenon occur when the flow is separation. One such phenomenon is wall pressure effect on the flow analysis, which in turn affects the performance of the flow. Due to the enhanced need for large performance in guided/unguided rocket nozzles which allows the design & development of nozzles with the aim to have better performance and finally the larger area ratio, where the problem of flow separation and wall pressure effects come into action. Flow separation can be mitigated using both active and passive methods. Passive methods include increasing the nozzle length, or use of splitter plates or ribs. However passive methods are useful only up to a limited range of conditions and add undesirable effects after that range. Active control methods are another grade of explication to control the base drag. It includes use of micro jets, or actuator controlled algorithms to control the phenomenon of flow separation. And also, active methods are effective over a large range of operating conditions. Determination of wall pressure changes and area ratio changes in a nozzle flow have been used to analyze the flow structure and shock wave formation that contributes to the factor of base pressure change of the flow field.

The interaction of pressure distribution in the base corner along with the thickness of the boundary layer upstream of the flow was studied by Wick(Wick 2012). As per his understanding and the outcome of his studies the boundary layer is a cause of fluid flow for the base region and it was found that air expands abruptly after passing through a convergent nozzle. The under expanded gas jets from the blunt bodies was seen to produce a shock structure by applying numerical studies by Menon and Skews(Menon and Skews 2005). This shock structure was affected by the corners of the nozzle and barrel shocks were observed in the nozzle exit by changing nozzle orientation. Also Muller examined the effect of initial flow direction on the base pressure of nozzle(HALL, Mueller et al. 1970). The effect of base cavities on the base pressure at various angles was studied by Tanner(Tanner 1988). He found an increase in base pressure by applying cavities, and hence reduction in base drags. The experimental study to find the efficacy of control management when the jets at the exit of the nozzle are over/under or ideally expanded to control the base drag was studied by Rathakrishnan(Rathakrishnan 1999). The result was very effective in terms of percentage, as micro jets reduced the base drag without affecting the wall pressure distribution. It is found that many techniques can be used to reduce or even suppress the flow separation. These techniques include puffing or imbibition of air flow through channels(Wassen and Thiele 2007; Muminovic, Henning et al. 2008; Lehugeur, Gilliéron et al. 2010) or holes(Favier, Cordier et al. 2007; Rouméas, Gilliéron et al. 2008), sequential arrangement of pulsed jets, actuators(Boucinha, Magnier et al. 2008; Leclerc 2008; Aubrun, McNally et al. 2011) and others. Khan and Rathakrishnan (Khan and Rathakrishnan 2002; Khan and Rathakrishnan 2003; Khan and Rathakrishnan 2004; Khan and Rathakrishnan 2006) 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. All of these techniques come with pros and cons, as the steady puffing or suction through orifices normal to free stream flow and located close down stream of the separation line has been revealed to be effective in reattaching the flow, but such devices need a continuous supply of mass flow which is difficult to attain. In the case of channels, the mass flow rate has been shown to be very high in order to affect the requisite control. On the other hand, range of steady micro jets has proven much efficient in comparison to single set arrangement in terms of the flow rate needed, while being very effective in controlling separation. The reason behind this phenomenon is high ratio channels. Micro jets play their role as three dimensional arrangements which produce different flow structure and offer many advantages in reattaching the flow. Also, micro jets have been used to control the flow separation in conventional fields such as backward facing ramp(Kumar and Alvi 2006; Moreau 2007), and for two-dimensional airfoils(Favier, Cordier et al. 2007; Kumar and Alvi 2009; Kreth, Alvi et al. 2010).

II. EXPERIMENTAL SETUP

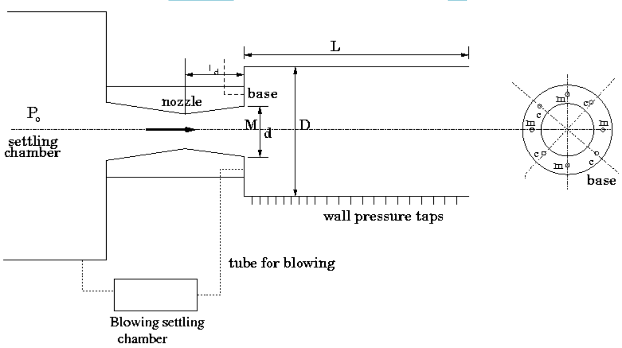


Figure 1. Experimental setup

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.

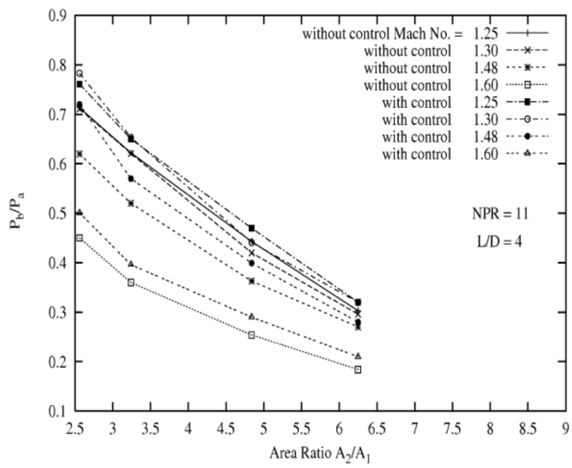
In the outlet boundary of the nozzle, eight holes of 1mm diameter each are drafted. Control of base pressure is achieved by gasping the air through control holes. Wall pressure tapes are also present to scale the wall pressure distribution in the duct.

Figure 2. Experimental Apparatus

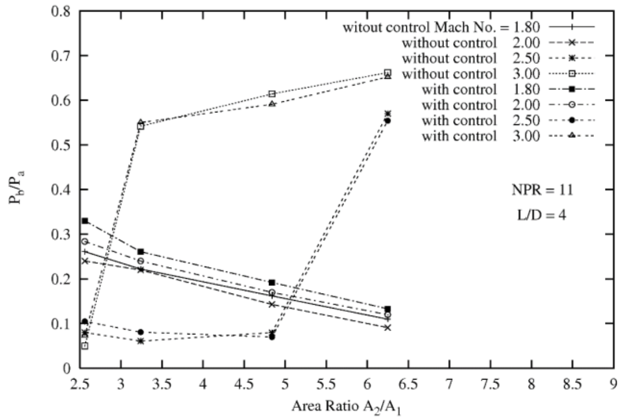
III. RESULTS AND DISCUSSION

The obtained values consist of the pressure value in the base corner (P_b); static pressure (P_w) in the abruptly expanded duct and expansion level NPR i.e. stagnation pressure (P_0) to ambient pressure (P_{atm}) ratio. The obtained pressures were transformed to non-dimensional data by multiplying them with the inverse of the back pressure. The effect of area ratio with the inertia level and NPR were obtained as shown in Figs. 3. It was evident that increase in relief of the flow simply indicates that relaxation space existing for the flow had increased

This sort of relief will make the shock/expansion waves at the nozzle lip to spread relatively more freely with increase of relief at the lip of nozzle/area ratio (Fig. 3 (a) - (b)). It was observed that for NPR 11 for Mach 1.25 to 1.6 all these jets were under expanded and hence the free shear layer from the nozzle exit passes through an expansion fan.



(a)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without control 2.50
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with control 1.80
with control 2.00
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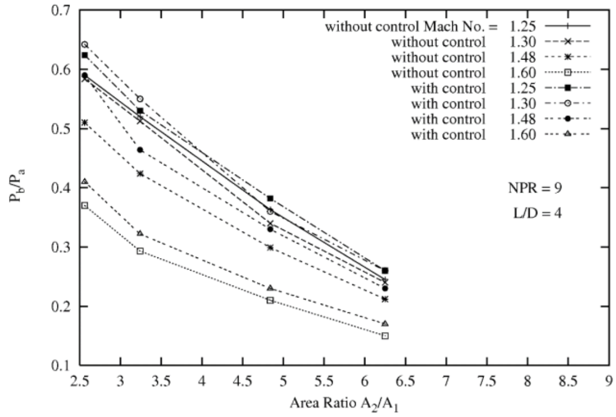
L/D = 4
P_b/P_a
Area Ratio A_2/A_1

(b)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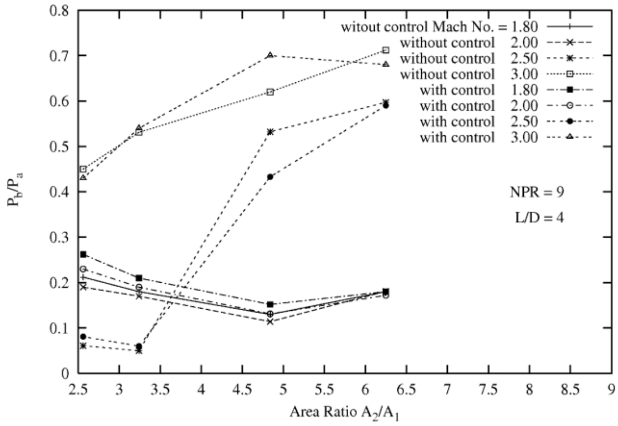
L/D = 4
P_b/P_a
Area Ratio A_2/A_1

(c)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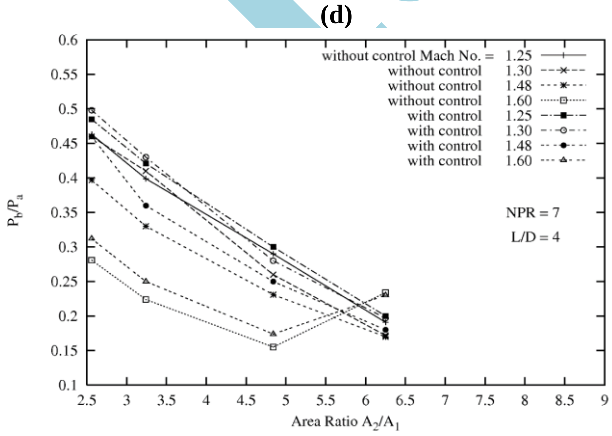
L/D = 4
P_b/P_a
Area Ratio A_2/A_1

(d)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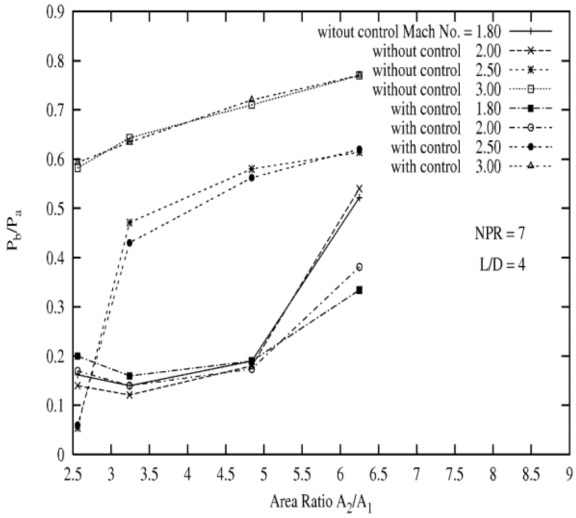
L/D = 4
P_b/P_a
Area Ratio A_2/A_1

(e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with control 1.80
with control 2.00
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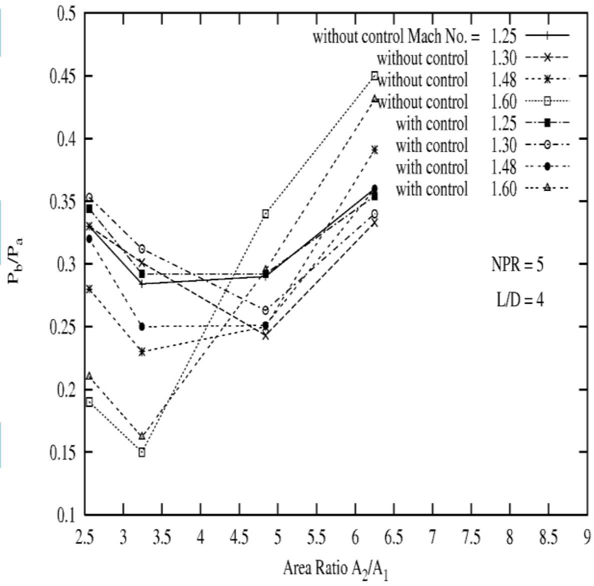
with control 3.00
NPR = 7
L/D = 4
P_b/P_a
Area Ratio A_2/A_1

(f)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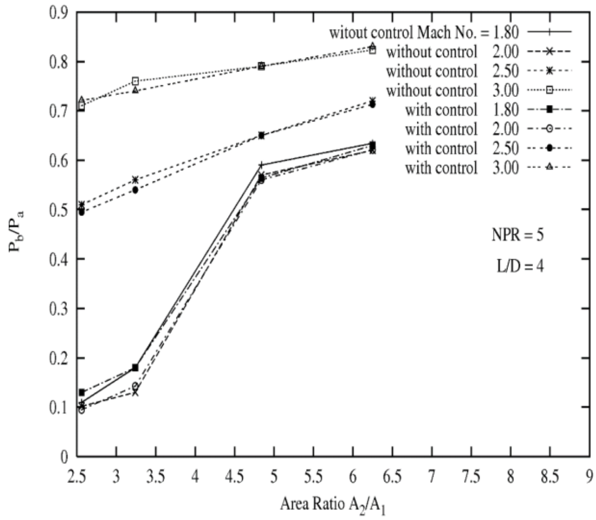
without control 1.60
with control 1.25
with control 1.30
with control 1.48
with control 1.60
NPR = 5
L/D = 4
P_b/P_a
Area Ratio A_2/A_1

(g)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with control 1.80
with control 2.00
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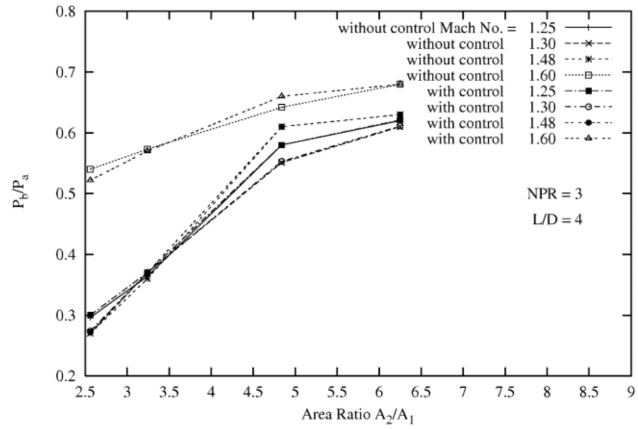
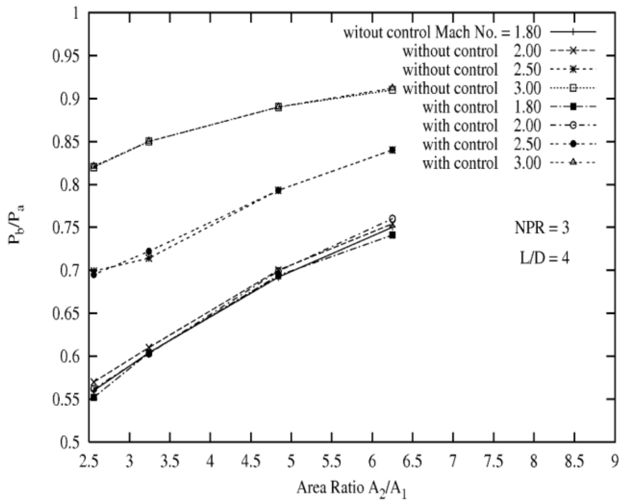
with control 3.00
NPR = 5
L/D = 4
P_b/P_a
Area Ratio A_2/A_1

(h)



(i)



(j)

Figure 3. Base pressure variation with area ratio A_2/A_1

In such conditions the increase in reattachment length due to the enhancement in the relief available to the flow at the exit of the nozzle has a tendency to results in fall of the pressure in the base area with further gain in area ratio. Furthermore, the control had been efficient for the Mach numbers, causing the base pressure to be higher in value as compared to the corresponding case without control. In Fig. 3(b) Mach number 2.5 and 3.0 were over expanded where the base pressure increases with increase in area ratio.

Similar results for NPR 9 were obtained as given in the Fig. 3(c)-(d). Here also the base pressure trend with area ratio similar to that for NPR 11, excluding the amount of base pressure at various conditions was slightly different from NPR 11.

Base pressure results for NPR 7 were also exhibited in Figs. 3(e)-(f) for Mach numbers between1.25 to 3. Here Mach number 1.25 to 1.6 was under expanded whereas Mach 1.8 being a little under expanded and Mach number 2 to 3 were over expanded. The result due to the change had been observed from these outcomes.

Similar results for NPR 5 were also observed as shown in the Figs. 3(g)-(h). Here Mach number 1.25 to 1.48 was under expanded, whereas Mach 1.6 is slightly under expanded and Mach 1.8 being slightly over expanded. The obvious effect of area ratio when the jets were almost correctly expanded was observed from these results exhibiting a mixed trend reflecting both under and over expanded situation. This was when jets were correctly expanded, the expansion fan at the nozzle exit due to increase in area ratio. This expansion fan had a control over the base pressure depending on the relaxation it enjoys due to area ratio effect.

4. Conclusion

From the above results, control with the help of tiny jets of 1 mm diameter to control the flow in the base region has been established. The flow field in the wall duct is dominated by the presence of both strong as well as the weak waves. The reflection of the waves from the wall, recompression and recombination's are taking place in the base region of the duct wall, thereby making the flow oscillatory.

The micro jets were showed as efficient active controllers, increasing the suction at the base region to appreciable level for few set of variables. The NPR plays a significant role in deciding the magnitude of the pressure in the base area for the case of in the presence and absence of the regulation mechanism at supersonic jet Mach number regime too.

All the non-dimensional wall pressure values exhibited in this paper are within an uncertainty range of 2.6% on the either side. All the investigation values are reproducible range of 3 per cent on both the sides.

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