Journal of Scientific Research and Development 3 (5): 1-6, 2016
Available online at www.jsrad.org
ISSN 1115-7569

An investigation of base flow control by wall pressure analysis in a suddenly expansion nozzle

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Abstract: This paper presents the results of an experimental investigation conducted at supersonic Mach number of 1.25 through a converging–diverging nozzle for diameter-ratio of 1.6. The experiments were conducted at different level of expansion viz. for correctly expanded and under expanded cases and, for length-to-diameter ratio of 10 to 1. From the results it is found that the flow remains attached with the suddenly expanded duct even for L/D = 1 for both with and without control cases. For some combination of the NPR and L/D ratio the flow field in the duct becomes oscillatory which; indicates that the flow in the duct is dominated by the waves however, it remained same even when the control in the form of micro jets are activated. Hence, the control does influence the flow in the duct wall. It is also seen that when the jets are under expanded the control becomes effective; however, with further increase in the level of under expansion they do not give the desired result. Hence, there seems to be a limiting value of level of expansion which will give desired result and at Mach 1.25, this value is $P_e/P_a = 1.5$.

Key words: Wall pressure; Base pressure; Flow separation; Active control; Abrupt expansion; Nozzle pressure ratio

1. 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 area ratio and length to diameter 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, different kinds of dynamic loads 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. The increasing demand for higher performance in rocket nozzles promotes the development of nozzles with higher performance and hence large 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 analyse 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 expansion corner with the boundary layer and thickness of upstream flow was studied by Wick (Wick, 2012). Boundary layer is a cause of fluid for the corner flow 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

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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 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 investigation to study the effects of micro jets under the influence of over, under and correct expansion 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 et al., 2008; Lehugeur et al., 2010) or holes (Favier et al., 2007; Rouméas et al., 2008), sequential arrangement of pulsed jets, actuators (Boucinha et al., 2008; Gilliéron and Kourta, 2008; Leclerc, 2008) and others. 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 aerofoils (Favier et al., 2007; Kumar and Alvi, 2009; Kreth et al., 2010).

2. 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. Fig. 1 depicts the experimental setup.

In the outlet boundary of the nozzle, 8 holes of 1mm diameter each are drafted. In the present arrangement the regulation of the pressure the separated region was accomplished by injecting the air through control chamber (Fig. 2).

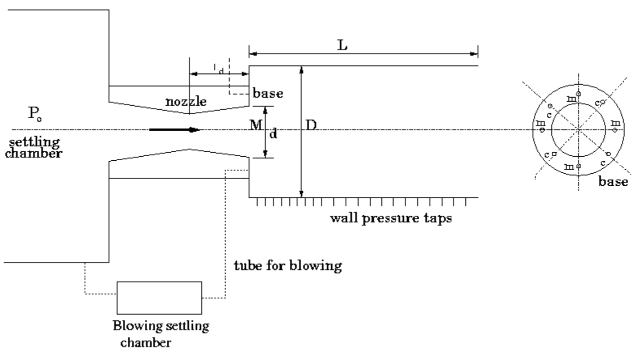

Fig. 1: Experimental setup

Fig. 2: Experimental apparatus

3. Results and discussion

The proficiency of the micro jets at supersonic Mach number of 1.25 for various nozzle pressure ratio and the different L/D and also, with correct expansion is investigated. As it has been found that even the correctly expanded flow has oscillations in view of the weak waves present at the lip of the nozzle which make the flow oscillatory for the nozzle, and stating this conformity, we need to study these results for further investigation. This problem of flow becoming oscillatory is encountered in both the active and passive control methods of base pressure, and our study will be to investigate the effect of control on wall pressure distribution for both the actions, viz. with and without control. The

Mach number 1.25 studied with area ratio of 2.56 as shown in Fig. 3 ((a) to (r)). In Fig. 3 ((a) to (b)) the results are for L/D = 1 and NPR = 7 and 9. Since the flow is highly under expanded, when micro jets are employed there is marginal increase in the wall pressure values and fluctuations indicated in the results are because of waves presents in the duct and also due to the effect of the back pressure. Similar results are seen in Fig. 3c and Fig. 3d and Fig. 3e for L/D = 2, excepting that when control was activated at NPR 11, it results in decrease of base pressure, whereas, at NPR 9 the control results in marginal increase in the base pressure. It was also observed during the tests that for this case jets became quite and when the wall pressure has increased it leads to increased value of the sound level of the jets.

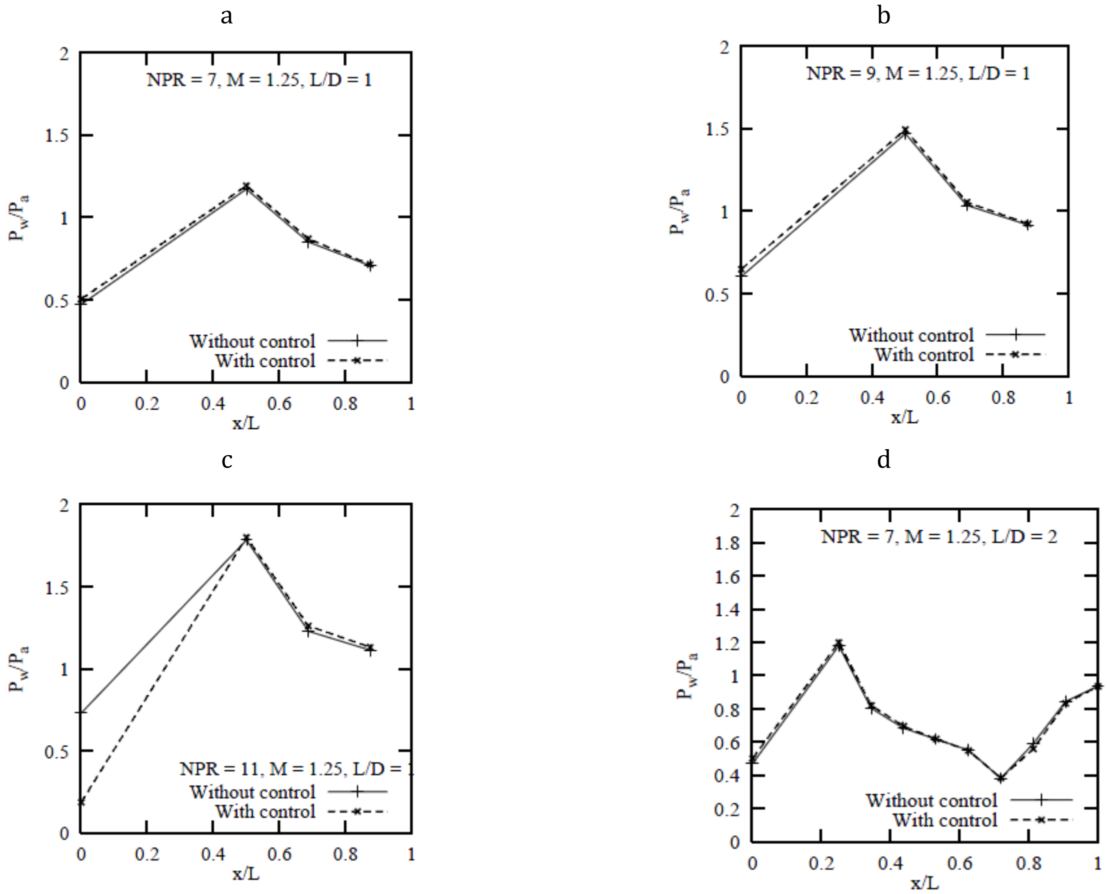

Fig. 3: The Mach number 1.25 studied with area ratio of 2.56

Results for L/D = 3 are shown in Fig. 4 ((f) to (g)), these results show oscillatory trends in the flow field due to the jets being under expanded, flows with and without control remains same. Fig. 5 ((h) and (i)) show wall pressure results for NPRs 7 and 11 at L/D =4. From the results it is seen that due to the presence of powerful shock non-dimensional wall pressure ratio has become 2 and 1.2 respectively for NPRs 11 and 7. In the presence of the shock waves the wall pressure is fluctuating, however, wall pressure with and without control remains the same. Similar results are seen at L/D = 5 for NPRs 7 and 11. Results for L/D = 6 at NPRs 9 and 11 are seen in Fig. 6 ((j) to (m)) they too show the similar trend as discussed above for lower L/Ds. At NPR 11 the magnitude is reduced and increase is 80 percent and 40 percent at NPRs 9 and 11, this is could be due to the combined effect of inertia level, level of expansion, length-to-diameter ratio, and the effect of the ambient atmospheric pressure.

Results for L/D = 10 for NPRs 7, 9, 11, and 2.59 are shown in Fig. 7 ((n) to (r)). It seen that the at lower L/Ds the maximum jump in the wall pressure was taking place within the reattachment length, which indicates that there is very strong shock at the nozzle exit and in the downstream the shock is becoming weaker during the process interaction, reflection and recombination of the waves, whereas, for this case there is 50 to 60 percent increase in the wall pressure for the initial taps but this progressive increase continues till the end of the duct. When we analyze the wall pressure results for correctly expanded case, it is found that there are few shocks within the reattachment length and in the downstream the flow is very smooth. This figure proves that the jets with correct expansion do have waves. Further, it is found that the wall pressure trends with and without control are nearly same, hence the control in the form of micro jets do not disturb the flow field.

e f g

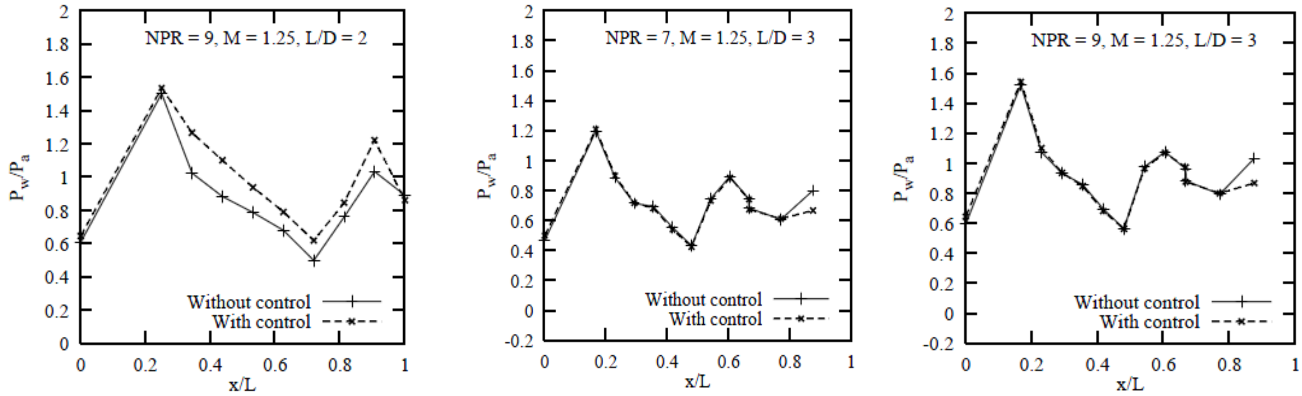

Fig. 4: Results for L/D = 3

h i

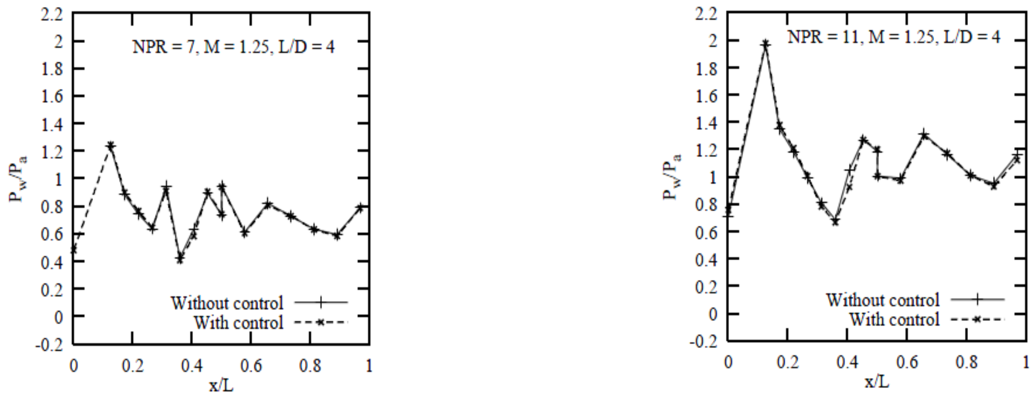

Fig. 5: Percentage change in wall pressure with x/L ratio (wall pressure results for NPRs 7 and 11 at L/D =4)

j k

l m

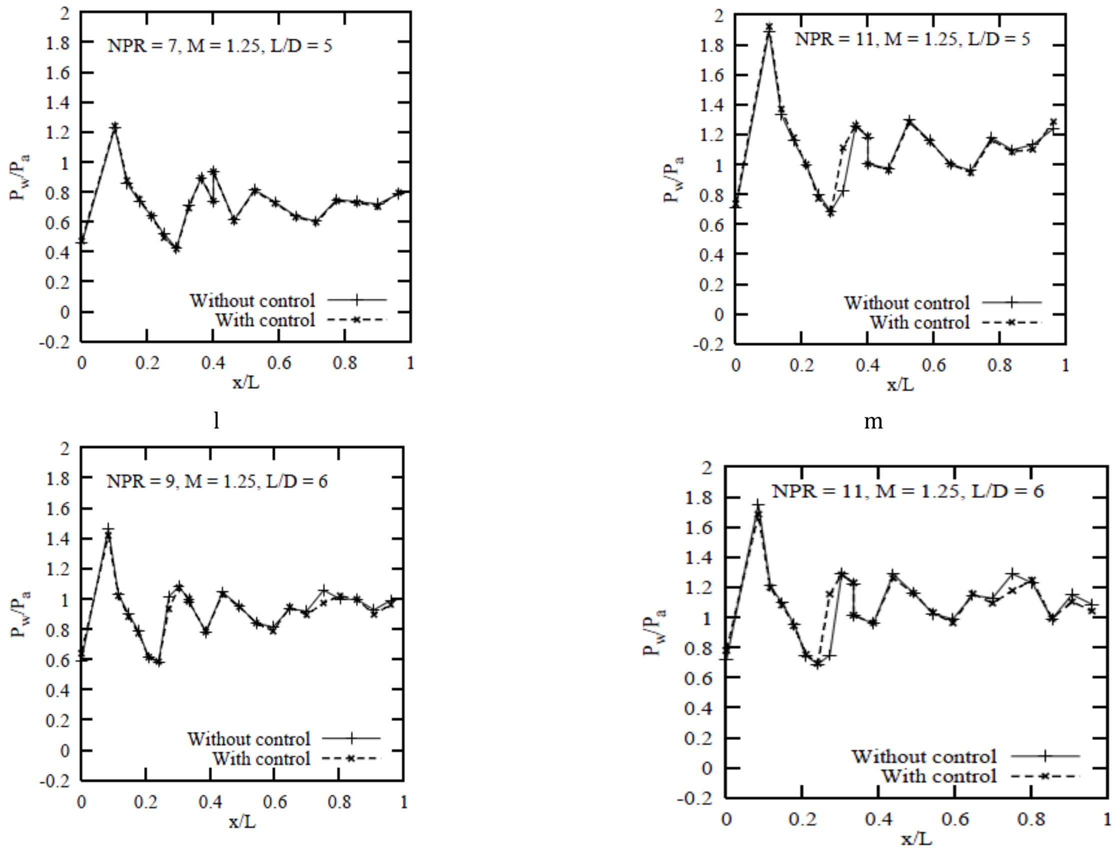

Fig. 6: Percentage change in wall pressure with x/L ratio (results for L/D = 6 at NPRs 9 and 11)

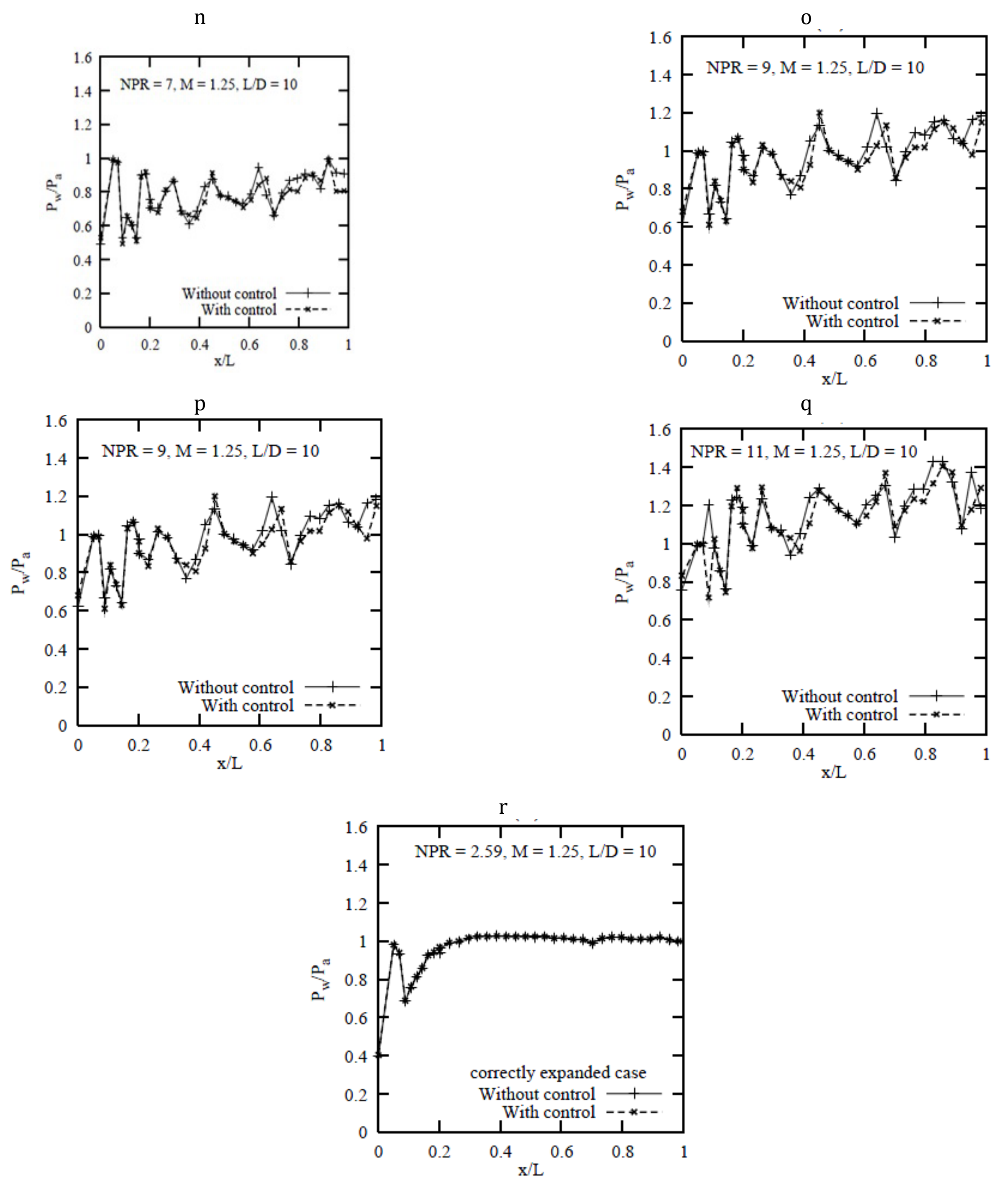

Fig. 7: Percentage change in wall pressure with x/L ratio (Results for L/D = 10 for NPRs 7, 9, 11, and 2.59)

4. Conclusion

In this investigation, the fundamental flow fields that appear in the correctly, and under expanded flows in supersonic Mach numbers are determined. The information regarding the effects of flow control on the wall pressure distribution is unaltered. Micro jet control mechanism is designed to study the problem of base pressure and its control effectiveness mechanism and as it influence on the flow quality in the enlarged. From the results as discussed above it is found that nozzle flux in the wall is surmounted by the wave occupancy. Also, the wave reproduction, reflection and interaction phenomenon is observed, in which the waves are constrained near the wall duct. Continuing, it is verified that the correctly expanded flows are not unconfined from the waves, as the oscillations can be clearly seen in the wall pressure of the augmented area. For lower L/D's there is initial high jump in the wall pressure due to the presence of strong at the nozzle lip and later the waves get weaken within few diameter length. For L/D = 10 the initial jump in the wall pressure is with the reduced magnitude, but in the downstream there is further increase in the wall pressure value due to the combined effect of Mach number, NPR, and L/D ratio. Wall pressure in the duct remains unchanged with and without control and hence the active control does not influence the wall pressure in the enlarged duct adversely.

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