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Experimental Investigation of the Base Flow and Base Pressure of Sudden Expansion Nozzle

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Abstract. This paper presents an experimental investigation of an airflow from convergent-divergent axisymmetric nozzles expanded suddenly into circular duct of larger cross-sectional area than that of nozzle exit area, focusing attention on the base pressure and the flow development in the duct. To investigate the influence of area ratios and nozzle pressure ratios on the flow field developed in the duct, the micro jets of 1 mm orifice diameter located at 900 interval along a pitch circle diameter 1.3 times the nozzle exit diameter were employed as the controller of the base pressure. The Mach number investigated in the present study was 1.87, 2.2 and 2.58. The area ratios of the present study are 2.56, 3.24, 4.84 and 6.25. The nozzle pressure ratio (NPR) used were 3 and 5. The length-to-diameter ratio of the enlarged duct was varied from 10 to 1. The level of expansion at the nozzle exit (i.e. before sudden expansion) influences the wall pressure very strongly. From the results it is observed that for NPRs 3 there is no appreciable gain in the base pressure, and hence control employed in the form of micro jets is not effective for this NPR, however, at NPR 5, there is significant change in the base pressure values for all the area ratios. This clearly indicates that the level of expansion plays an important role to dictate the value of the base pressure and ultimately the control effectiveness by the micro jets.

1. Introduction

The flow field generated by the infringement of high-speed flows usually results in a very unsteady flow field. When such flows are generated at the rear end of aerospace vehicles, this flow can lead to a host of adverse effects that can diminish aircraft performance. One of the important related issues is the occurrence of base flow aerodynamic side loads due to vortex shedding and asymmetric flow separation inside a rocket nozzle. This problem has been well studied through experiments as well as computations. The unsteady separation phenomenon inside the nozzle can lead to steady/unsteady forcing of the thrusting nozzle, as well as associated mechanisms due to fluid–structure interactions [1-5]. The presence of such unsteady side loads can also result in adverse control systems of the vehicle in pitch, roll, and yaw [6]. Since the nozzle is located in the wake of the main body, response of the nozzle and the associated mechanical systems to the oscillating outer flow in the presence of asymmetric loading due to internal flow has been studied [4, 7, 8]. The investigations have demonstrated the origin of these unsteady phenomena at the base of the nozzle are 1) asymmetric separation line, 2) pressure pulsations at the separation and reattachment locations, 3) aeroelastic coupling, 4) transition of separation pattern between restricted shock separation (RSS) and full shock.
separation (FSS), and 5) external flow instabilities such as buffeting [9]. A computational approach to model the fluid-structure interactions of the one such nozzle using detached-eddy simulations coupled with second-order structural computations for different nozzle configurations has been studied [10].

In fluid dynamics research community, the efficient and effective control of turbulent flow has turned an upcoming goal. Innumerable applications of turbulence flow control include viscous drag reduction in numerous aerodynamic and hydrodynamic applications, regulation of heat transfer, reduction of wall pressure fluctuations and flow-generated noise, reduced oscillation and unsteadiness in resonance-dominated flows, and so on. These control techniques are also used to delay the transition to turbulence, and prevention/delay of boundary-layer separation in various internal and external flows leading to performance loss. The interaction of pressure distribution in the expansion corner with the boundary layer and thickness of upstream flow was studied by Wick [11]. 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 [12]. 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 [13]. The effect of base cavities on the base pressure at various angles was studied by Tanner [14]. 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 and others [15-22]. 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. 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 Khan and others [20-27]. 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.

Therefore in this study, we have employed micro jets as active control devices in our examination, the correlation of base pressure change with flow Mach number has been demonstrated at different L/D ratios.

2. Experimental Procedure
The fringed nozzle-enlarged duct is fixed at the end of the settling chamber by a slot holder arrangement. The base pressure taps and wall pressure taps are measured matching the channels of pressure sensors connected on bread board to a data logger at a time in each run for different Mach numbers and expansion levels, as shown in figure 1. Pressure sensors used for this experiment are Honeywell TruStability® Board Mount Pressure Sensors, HSC Series - High Accuracy, Low Pressure Sensors - HSCDANN015PAAA5 (Absolute) and HSCDANN010BGAA5 (Gauge). Data acquisition is done with the help of Graphtec MIDI LOGGER GL820, with a 20-channel input. The model area ratio (D2/d2) is varied in the range from 1.5 to 4. The L/D ratio is another variable parameter 4, 5, 6 for pipe diameters 19 mm, 16 mm, and 13 mm respectively. NPR can be calculated accurately, while Mach number can be estimated from isentropic relationships. The measurements include the stagnation pressure of the settling chamber, the base pressure, and the wall pressure distribution along the length of the duct. All of the pressures are measured using absolute pressure sensors, except for the settling chamber pressure, which is measured using gauge pressure sensor. A data logger is used for data acquisition. Tests done using pressure sensors and data logger for a particular case with repeated testing for the same, showed that it was repeatable within ±2~3% accuracy with the previous results of the same case.
3. Results and Discussion
The obtained values consist of base pressure ($P_b$); along the length of the duct and the NPR i.e. stagnation pressure ($P_0$) to back pressure ($P_{atm}$) ratio. The obtained pressures were made non-dimensional by dividing them with the atmospheric pressure/back pressure. This investigation focuses attention on the effectiveness of active control in the form of micro jets, located at the base region of suddenly expanded axi-symmetric ducts, to modify the base pressure at supersonic Mach number, which is more prone to screech. The parameters considered in the present study are the area ratio of the enlarged duct, L/D ratio of the suddenly expanded duct, the jet Mach number and the level of expansion (NPR).

The dependence of base pressure on Mach number, four area ratios namely 2.56, 3.24, 4.84, and 6.25 for NPRs from 3 and 5, and L/D ranging from 1 to 10, are given in Figure 3 and Figure 4 respectively. Results of the base pressure with and without control are compared. It is seen from these results that in supersonic regime the Mach number has got very strong influence on the base pressure. For a given Mach number the nozzle pressure ratio (NPR) which dictates the level of expansion has a strong role to play on the control effectiveness of the micro jets. Also, it is seen that with increase of NPR the control becomes more effective in increasing the base pressure for Mach numbers in the range from 1.87 to 2.58. The physical reason for this may be the influence of the shock at nozzle exit which turns the flow away from the base region, thereby weakening the vortex positioned at the base. This results in increase of base pressure since the weakened vortex at the base encounters the mass flow injected by the micro-jets. Therefore, the turning away tendency of incoming flow comes down leaving the vortex almost intact. At this situation when the micro jets are introduced they may propagate without any deflecting tendency, thereby entraining some mass from the standing vortex and convecting it away from the base causing the base pressure to assume higher values than those for without control. It is well known from literature that passive controls perform better in the presence of favourable pressure gradient. In the present study the combined effect of favourable pressure gradient and the relief due to area ratio on the active control effectiveness is investigated. The percentage change in base pressure as function of length to diameter ratio and area ratio are presented for NPR = 3 and 5.

Figure 3 (d) represent the results of base pressure dependence on area ratio for L/D= 4. For NPR = 3 results do not show any change from the previous L/D. Later, results for NPR = 5 are shown in figure 4 (d), it is seen that for Mach 1.87 the results are similar to that of for L/D = 5. But for other Mach numbers namely 2.2 and 2.58 the values of base pressure are on the higher side. The physical reasons for this behavior may be the strength of the oblique shock and the reattachment length at these Mach numbers. Figure 3 (e) represent the change in base pressure with respect to Area ratio for L/D = 5. Results for NPR = 3 are shown in Figure 3 (e). As this NPR belongs to the over expanded case for the Mach number tested and $P_b$ assumes very high value. The control effectiveness is only marginal for all the area ratio and Mach number tested except for Mach 2.58 for area ratio 6.25, Mach 1.87 for area ratio 2.56. Results for NPR = 5 are shown in Figure 4 (e), and they exhibit similar trend as

![Figure 1. Experimental setup](image-url)
discussed earlier except the magnitude of the base pressure as the level of over expansion has come down.
Results are shown in Figure 3 (a) to (h) represents the plots of dependence of % change in base pressure on A2/A1 for NPR 5. In the case of NPR = 5, it can be seen that the behaviour is the same as that of at L/D = 4 excepting that the magnitude of base pressure has slightly increased. The reasons for this increase may be due the decrease in the duct length and the base pressure is influenced by the back pressure. Further, it is seen that the minimum Pb is at L/D = 6 which is in agreement with the results of Rathakrishnan and Sreekanth [28], for subsonic and transonic flow. The control is only of marginal influence on the base pressure for all values of L/D for highest level of area ratio. Further, it is seen that when the area ratio decreases the trend is different, microjets tend to reduce Pb for all the area ratios. It becomes independent from L/D > 6 onwards. However, for area ratio 4.84 it is found that at L/D = 10 there is a drastic change in the behaviour. The base pressure decreases drastically with and without control. The physical reason for this behaviour may be that for this area ratio the relief enjoyed by the suddenly expanded flow is much more than what it was for other area ratios. Hence, the level of expansion causing the formation of shock or expansion fan at the nozzle lip will have a strong effect on Pb as well as its control ability. It happens when the free shear layer expanding into the suddenly expanded passage finds sufficient relief, it re-attaches downstream of the reattachment point for lower area ratios. This increase in reattachment length helps the formation of a powerful vortex at the base causing low base pressure. But for Mach number 1.87 and above even lower NPRs are unable to dictate the reattachment as they do at lower Mach numbers since the shock wave at the nozzle lip becomes stronger with the increase of overexpansion level causing the flow to deflect towards the shock. This causes hindrance to the formation of a strong vortex at the base. Because of
this the base pressure shoots up with increase of Mach number. Also, the control becomes ineffective since the shock strength dominates the flow process. These results imply that the flow field becomes sensitive to the relief effect at the expanded plane. However, it should be realized that increase of area ratio beyond some limiting value will not ensure the effects mentioned above for suddenly expanded flows both in subsonic and supersonic flows.

A physical explanation for this interesting phenomenon calls for a deeper investigation around these parameters. In regards of this, in the present investigations even the measurement of sound for Mach number 1.87, L/D = 10. Further, this is well known from the literature that there is a possibility of screech tone in the Mach number range 1.6 - 1.9. This may be the reason for oscillatory behaviour of the wall pressure and drastic reductions in the overall sound pressure level and hence very low noise.
NPR=5, L/D=3

Area Ratio

%change in Base Pressure

- NPR Change in Base Pressure 1.87
- % Change in Base Pressure 2.2
- % Change in Base Pressure 2.58

(c)

NPR=5, L/D=4

Area Ratio

%change in Base Pressure

(d)

NPR=5, L/D=5

Area Ratio

(f)
Figure 3: Base pressure variation with Area ratio for different Mach numbers at NPR 5.
4. Conclusions
From the above results Control with the help of micro jets to control base pressure has been established. The flow field in the duct remains unaltered when jets are highly over expanded. With the increase in NPR the control in the form of micro jets becomes for effective for all NPR 5 as compared to NPR 3. The flow field is dominated by the presence of the waves both strong as well as the weak waves or acoustic waves. The reflection of the waves from the wall, recompression and recombination’s are taking place in the base region as well as partially in the duct wall, thereby making the flow oscillatory. The micro jets can be used as effective controllers, increasing the base suction to appreciable level for some combination of parameters. The nozzle pressure ratio plays a key role in deciding the magnitude of base pressure with and without control, in the high supersonic jet Mach number regime too.

All the non-dimensional wall pressure values exhibited in this paper are within an uncertainty band of ± 2.6%. All the investigation results are within the range of ± 3 per cent.

References
[1] Lefrancois E, Dhatt G, Vandromme D. Fluid–structural interaction with application to rocket engines. International journal for numerical methods in fluids. 1999;30(7):865-95.
[2] Blades EL, Luke EA, Ruf J. Fully Coupled Fluid-Structure Interaction Simulations of Rocket Engine Side Loads. AIAA paper. 2012;3969.
[3] Brown AM, Ruf J, Reed D, D’Agostino M, Keanini R, editors. Characterization of side load phenomena using measurement of fluid/structure interaction. 38th Joint Propulsion Conference and Exhibit, AIAA Paper, 2002.
[4] Ostlund J, Muhammad-Klingmann B. Supersonic flow separation with application to rocket engine nozzles. Applied Mechanics Reviews. 2005;58(3):143-77.
[5] Dumnov G, editor. Unsteady side-loads acting on the nozzle with developed separation zone. 32nd Joint Propulsion Conference and Exhibit, AIAA Paper, 1996.
[6] Srivastava N, Tkacik PT, Keanini RG. Influence of nozzle random side loads on launch vehicle dynamics. Journal of Applied Physics. 2010;108(4):044911.
[7] Frey M, Hagemann G, editors. Flow separation and side-loads in rocket nozzles. 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit; 1999.
[8] Damgaard T, Østlund J, Frey M. Side-load phenomena in highly overexpanded rocket nozzles. Journal of Propulsion and Power. 2004;20(4):695-704.
[9] Verma SB, Stark R, Haidn O. Relation between shock unsteadiness and the origin of side-loads inside a thrust optimized parabolic rocket nozzle. Aerospace Science and Technology. 2006;10(6):474-83.
[10] Lüdeke H, Calvo J. A Fluid Structure Coupling of the Ariane-5 During Start Phase by DES. 2008.
[11] Wick RS. The effect of boundary layer on sonic flow through an abrupt cross-sectional area change. Journal of the Aeronautical Sciences. 2012.
[12] Menon N, Skews B. 3-D shock structure in underexpanded supersonic jets from elliptical and rectangular exits. Shock Waves: Springer; 2005. p. 529-34.
[13] HALL J, CR, Mueller T, Roache PJ. Influence of initial flow direction on the turbulent base pressure in supersonic axisymmetric flow. Journal of Spacecraft and Rockets. 1970;7(12):1484-8.
[14] Tanner M. Base cavity at angles of incidence. AIAA Journal. 1988;26(3):376-7.
[15] Khan SA, Rathakrishnan E. Active control of suddenly expanded flows from overexpanded nozzles. International Journal of Turbo and Jet Engines. 2002;19(1-2):119-26.
[16] Khan SA, Rathakrishnan E. Control of suddenly expanded flows with micro-jets. International Journal of Turbo and Jet Engines. 2003;20(1):63-82.
[17] Khan S, Rathakrishnan E. Control of suddenly expanded flow. Aircraft Engineering and Aerospace Technology. 2006;78(4):293-309.
[18] Khan SA, Rathakrishnan E. Active Control of Suddenly Expanded Flows from Underexpanded Nozzles. *International Journal of Turbo and Jet Engines*. 2004;21(4):233-54.

[19] Ashfaq S, Khan SA, Rathakrishnan E. Active Control of Flow through the Nozzles at Sonic Mach Number. *International Journal of Emerging trends in Engineering and Development*. 2013;2(3):73-82.

[20] Chaudhary ZI, Shinde VB, Bashir M, Khan SA. Experimental Investigation on the Effectiveness of Active Control Mechanism on Base Pressure at Low Supersonic Mach Numbers. *Innovative Design and Development Practices in Aerospace and Automotive Engineering: Springer*; 2017. p. 197-209.

[21] Baig MAA, Al-Mufadi F, Khan SA, Rathakrishnan E. Control of base flows with micro jets. *International Journal of Turbo and Jet Engines*. 2011;28(1):59-69.

[22] Baig MAA, Khan SA, Rathakrishnan E. Active Control Of Base Pressure In Suddenly Expanded Flow For Area Ratio 4.84. *International Journal of Engineering Science and Technology*. 2012;4(5):1892-902.

[23] Khan S, Bashir M, Ullah MA. An investigation of base flow control by wall pressure analysis in a suddenly expansion nozzle. 2016.

[24] Chaudhary Z, Shinde VB, Bashir M, Khan S. Experimental investigation of the base flow from the nozzles with sudden expansion. International Journal of Applied Engineering Research.10(92):2015.

[25] Baig MAA, Khan SA, Rathakrishnan E. Effect of Mach number In a Suddenly Expanded Flow for Area Ratio.

[26] Baig MAA, Khan SA, Rathakrishnan E. Control of Nozzle Flow in Suddenly Expanded Duct with Micro Jets. *International Journal of Engineering Science & Advanced Technology [IJESAT]*.2:789-95.

[27] Ashfaq S, Khan S, Rathakrishnan E. Control of suddenly expanded flow for area ratio 3.61. *International Journal of Advanced Scientific and Technical Research*. 2013(3):798-807.