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Passive control of base pressure with static cylinder at supersonic flow

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Abstract. An experimental investigation for over expanded, perfectly expanded and under expanded supersonic jets is presented to study the effectiveness of a static cylinder to reduce base drag at Mach 2 through a converging diverging nozzle for a cross-sectional duct nozzle area ratio of 9. A static cylinder of 2 mm diameter at 2 mm from the side wall of a square duct and 8 mm from the square nozzle exit in the base region is installed as a passive control device. Base pressures in the wake flow after sudden expansion of jets in to a square nozzle have been measured. The length width ratio of the duct is 10. The jets were operated at different nozzle pressure ratios in the range from 2 to 9. The flow field in the square duct was also observed for all cases. Static cylinder as a passive controller was found to reduce the base drag as high as 59 percent at NPR = 9 and 14 percent at NPR = 6. The base pressure depends on Mach number, area ratio, length to width ratio, and nozzle pressure ratio (NPR). When flow from the nozzle is over expanded, the static control is ineffective till NPR is 6. The level of expansion plays a vital role. The flow flux in the square duct remains almost identical with and without control for most of the cases. However, at higher NPRs namely 6, 7.8, and 9 the control results in an increase as well as a decrease in the wall pressure along the duct. Passive control of the base flow is effective for higher NPRs. The flow field for perfectly expanded nozzle is dominated by the shock waves.

Key words: Wall pressure - base pressure - nozzle pressure ratio - passive control

Nomenclature

Abbreviation

M	Mach number
NPR	Nozzle pressure ratio

Roman Symbols

A_1	Exit area of nozzle [mm^2]
A_2	Cross-sectional area of duct [mm^2]
L	Duct length [mm]
P_a	Atmospheric pressure [cm of Hg]
P_b	Base pressure [cm of Hg]
P_w	Wall pressure [cm of Hg]
P_0	Settling chamber pressure [cm of Hg]
W_n	Width of nozzle exit [mm]

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W Duct width [mm]
X Axial distance along x-axis [mm]

1. Introduction

The major augmentation to the aerodynamic drag of a bluff body, or an abrupt change in cross-section is due to the low pressure in the base area, inside the recirculation zone. Decreasing the depression on the base would then be of considerable importance in many engineering applications. The physical mechanism influencing the drag at the base is still not well understood [1]. Passive flow control due to its simplicity has been largely reported by several researchers in the literature. A cylinder is a bluff body, which becomes an effective controller as its diameter is reduced. A stationary cylinder placed normal to a flow produces a repeating pattern of swirling vortices caused by separation of flow behind the cylinder. As the diameter of the cylinder is reduced the shedding behind the cylinder also reduces. Flow control of separation and/or the structure of shear layer(s) in the depression zone can be achieved by various methods like blowing, suction, surface roughness etc. These have been studied by researchers in the past such as [2]. Review articles by [3], [4], and [5] present a comprehensive bird's eye view of the diverse ways for subduing vortex shedding. According to [2] passive flow control is effectual for low Reynolds number only and is ineffective at high Reynolds number. So, it needs to be studied. In the studies reported so far, interaction of cylinders with each other, effect of different cylinder diameter on flow field have been studied for incompressible flows only.

2. Literature Review

2.1. The existing passive and active controls.

The base pressure in high speed flow has been divided in to passive and active control [6]. [7] studied flows sudden expansion for high speed compressible subsonic flows in circular pipes. They came to conclusion that the non- dimensional base pressure and hence the base drag is deeply affected by the geometric parameters. [8] studied active flow induced cavity oscillations of incidence. They observed that a base cavity acts as an effective control to decrease base drag by increasing the base pressure in axis-symmetric high speed compressible flows. [9] did experiments to study the effect of ribs on an abruptly enlarged flow field. He concluded that the ribs effect on the flow field and on base pressure was very significant. [10] reviewed different techniques for reduction of base, after body drag and turbulent base flows problems. He explored the developments that have taken place on the use of passive techniques to control the base drag by locked vortex after-bodies, ventilated cavities, simple cavities, multi-step after-bodies and simple after-bodies employing a non-axis-symmetric boat-tailing in different speed regimes. [11] studied subsonic flow near wake and the effect of base cavities on it. They studied the result of the base cavity on the wake behind thin 2D bluff body in the subsonic regime. Mach 2.5 flow is studied for base bleed control of near wake flow field by [12]. Their results across the base plate are comparatively uniform radial pressure gradients. [13] reviewed the theory of base pressure in incompressible steady base flow. [14] performed computational study of base drag reduction for a projectile in different flight phases. DNS of turbulent flow was studied over a backward facing step to get a better understanding of reattachment length, wall shear stress and oscillations [15]. An investigation of base flow control by wall pressure analysis was studied by [16]. The methods for the passive control of base pressure studied so far have been through grooves, cavities, ribs, tabs etc. Also, a lot of work using numerical simulation has been done to understand the theory of this complicated flow and obtain correlation between the physics of the boundary layer, recirculation zone and the wake behind reattachment, [1].

2.2. The proposed controller

Detailed investigation on the interaction of two circular cylinder in various arrangements in a flow field has been performed and its physics somewhat understood [17], but the cylinders were not placed in a recirculation zone nor to reduce the base drag. Suppressing vortex shedding of a cylinder at low

Reynolds numbers was achieved by using a smaller cylinder outside the recirculation area in the vicinity of the main cylinder [18]. From the review of flow control using a cylinder, it is evident that the passive cylinder itself being a bluff body should have small diameter so that its own vortex shedding is minimized. Detailed numerical study of the near wake area of a circular cylinder was done by [19]. Experimentally and numerically flow physics of incompressible flow about fixed cylinder pairs was performed for various cylinder arrangements. [20]. Thus, from the literature we see the urge to control base drag but there is not a single case to the best of authors knowledge where cylinder is used to control base pressure in compressible flows for different high-speed regimes. It is proposed to use a cylinder as a passive controller to reduce the base drag from a converging diverging nozzle flow at Mach 2.

3. Experimental Setup and procedure

3.1. High speed flow facility

The experiments were done in B.I.T research centre at supersonic research laboratory, Mangalore, Karnataka, India. The test facility consists of internal flow apparatus. Compressed dry air at a very high pressure from the storage tank is ducted to the settling chamber through a pressure regulatory valve. Once the flow attains equilibrium in the settling chamber it is abruptly expanded through the square nozzle into the suddenly expanded square duct as shown in figure 1. Pressure measurement is done by transducer 9205 (NI) and DAQ. Measurement were done by 16 channel DAQ ranging from approximately 0-150 psi. It takes 250 samples per seconds, takes average and writes on the hard disk. The LabVIEW software as virtual instrumentation along with DAQ acquires data and displays the pressure readings from all the 16 channels, concurrently in the computer screen.

3.2. Fabrication process

By using analytical approach, we calculated the design Mach number and then fabricated supersonic nozzle of Mach 2 having semi-divergence angle of 5 degree and nozzle exit area as 10*10 mm square, based on the design. The material used was brass. Once fabricated, the nozzle was calibrated for Mach 2. Square duct of area ratio 10 with taps for pressure measuring and sliding glasses for flow visualization were also fabricated as shown in figure 1 ,2 and 3. A 2- mm diameter steel control cylinder was used to

control the base pressure. It is located at 8 mm from the base and 2 mm from the wall. Base pressure was measured at 4 places at 11.5mm from centre. Flange of square nozzle has 8 holes to fasten it with the square duct. The sudden expansion square duct was also fabricated from brass with its length 10 times its width i.e. L/W= 10.

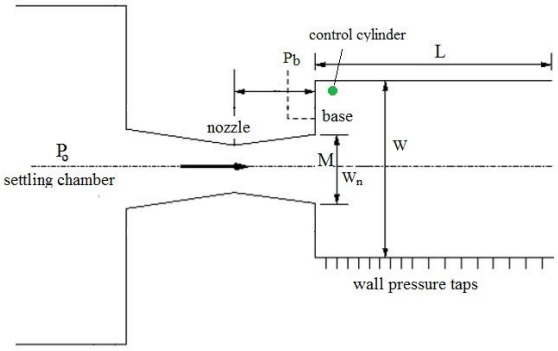


Figure 1. Experimental setup

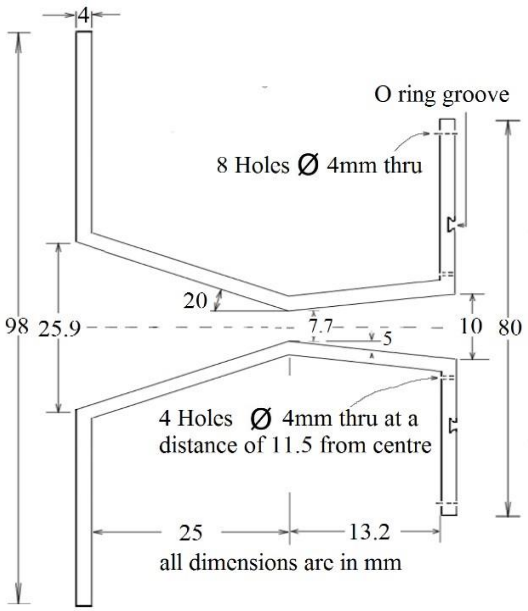
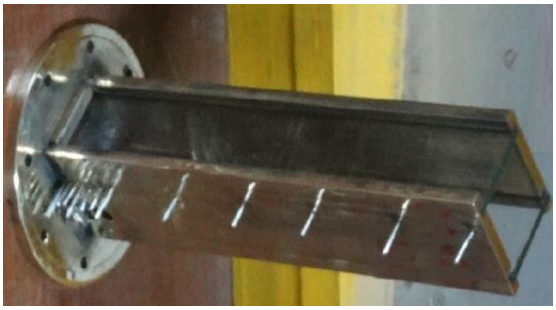
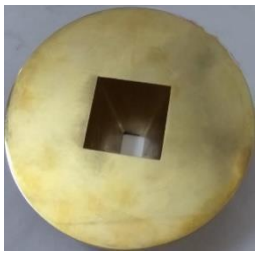


Figure 2. Schematic drawing of the Nozzle.

Duct wall pressure taps of 1 mm ID steel tubes were used. Wall pressure taps began at 7 mm from the nozzle exit. These were 3 mm apart initially and the distance between them in the axial direction progressively increased until maximum duct length of 300 mm as shown in figure 3(a). The NPR used for this study were 2, 3, 6, 7.8, and 9. The L/W ratio was 10, Area ratio (A2/A1) was 9 for all NPRs and the nozzle exit Mach number 2. The settling chamber pressure was recorded under steady state conditions. At steady flow conditions the pressure at the base and the on the wall in the square duct were recorded by pressure transducers.



(a) Square duct with two sliding glasses



(b) Nozzle inlet,

(c) Nozzle exit

(d) Cylinder

Figure 3. Photographic view of fabricated parts

Figure 4. Photographic view of nozzle, duct and cylinder attached to the settling chamber

Measurements for all NPRs with and without control were completed for L/W =10 for the square duct of 30*30 mm square cross- sectional area and length 300 mm. The main aim of this investigation is to study the workability of a static cylinder as a passive control device placed normal to the flow for controlling base pressure. To see the increase and its effectiveness in base pressure at different NPR with and with no control, the base pressure results are also presented in terms of percentage.

4. Results and discussions

4.1. Base pressure

The investigation done experimentally concentrates on the effectiveness of cylinder as passive control, located in the base region of an abrupt expanded square duct, to control the pressure at the base. The parameters
considered are the area ratio, L/W ratio, and the nozzle pressure ratio (NPR) at Mach 2. The percentage change in base pressure is given by,

$$P_b = [(P_{b\ control} - P_{b\ no\ control})/P_{b\ no\ control}] \times 100$$

The dependence of base pressure on the NPR for an area ratio of 9 at L/W = 10, for NPRs from 2 to 9 are presented in figures 5 and 6. It is well known from the literature that whenever the jets are over expanded the control either by active or passive means are not very effective. Similar trends are seen in figure 5. The percentage increase in the base pressure up to NPR 6 is less than 20 percent, whereas, when the jets are perfectly expanded or under expanded the control mechanism results in substantial increase in the base pressure value and as high as 59 % increase is recorded.

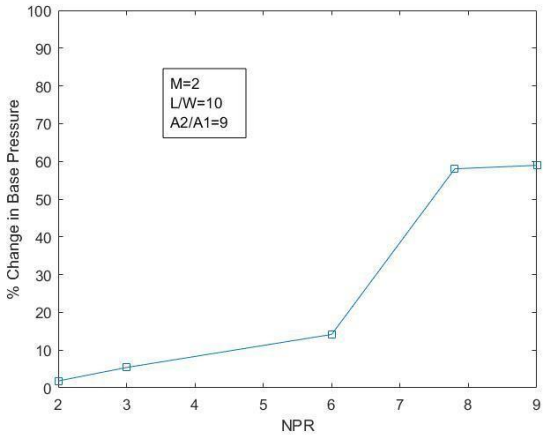


Figure 5. Percentage Change in Base Pressure with NPR

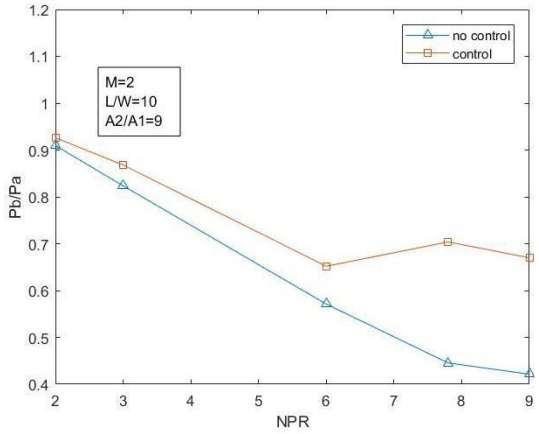


Figure 6. Base pressure variation with NPR

The practical reason for the enhancement of base pressure may be the impression of the shock at square nozzle exit which flushes the flow away out of the base region, thereby making the vortex positioned at the base weak. Further the weak vortex confronts with the presence of passive control in the form of static cylinder. This may be due to increase in NPR, leading to reduction in the level of over expansion; thus, at the nozzle exit weak oblique shock is present as compared at lower NPRs.

4.2. Wall pressure

The variation of base pressure with NPR is shown in figure 7. At low NPRs, the base pressure is very high with and without control mechanism. This trend is due to the level of expansion. With an increase in NPR the base pressure continues to decrease till the flow becomes perfectly expanded. It is also seen that as long as the flow from the nozzle is over expanded the control effectiveness is marginal. When the jet is perfectly expanded or under expanded the control mechanism is effective. This trend matches with the findings of earlier studies [21]. When a passive control mechanism is introduced to manage the base pressure, there is a possibility that it might adversely affect the nature of the flow field in the square duct. To observe this undesirable effect, the wall pressure along the square duct was measured. Wall pressure distribution along the length of the duct for NPR = 2 is shown in Figure 7. At NPR=1.89 the ideal critical condition is reached. Hence at NPR 2, flow at the exit of the nozzle will be over expanded. Accordingly, the wall pressure in the enlarged duct begins with a very high value Pw/Pa = 0.9, decreases up to X/W = 1, which seems to be the reattachment length, then further downstream due to the presence of the shock wave a jump in the wall pressure rendering it to be equal to atmospheric pressure is detected. Further, due to the presence of the expansion wave wall pressure marginally decreases and then further downstream it reaches atmospheric pressure. Results shown in Figure 8 are for NPR = 3 and they show similar trends as discussed for Fig. 6 with the exception the NPR has slightly increased and hence the level of over expansion has gone down marginally, and the

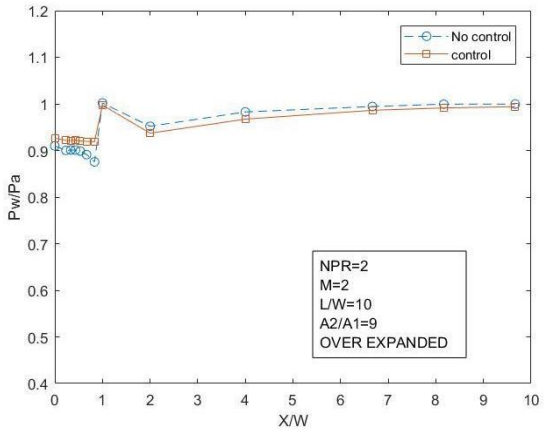


Figure 7. Flow development in the duct at NPR=2

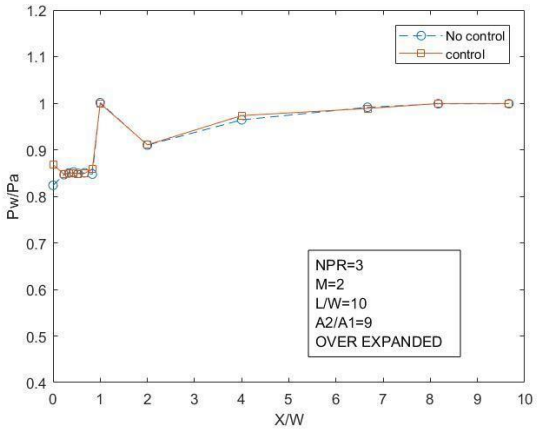


Figure 8. Flow development in the duct at NPR=3

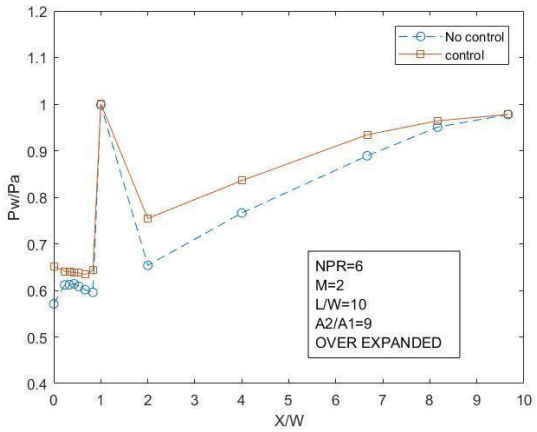


Figure 9. Flow development in the duct at NPR=6

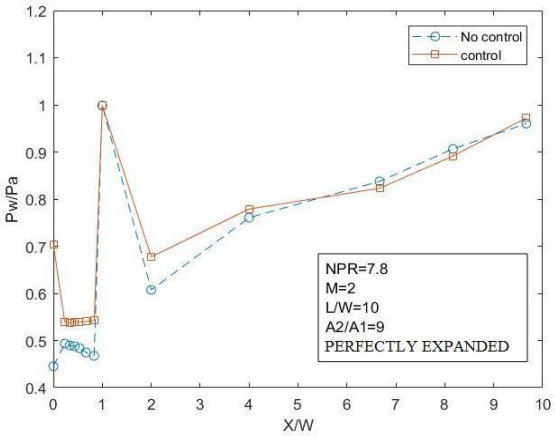


Figure 10. Flow development in the duct at NPR=7.8

Wall pressures for perfectly expanded nozzle flow is presented in figure 10. The difference in the results for NPR 6 and 7.8 is that for NPR 7.8 at X/W = 0, the pressure at the base region has further decreased and the control mechanism in the form of static cylinder in the wake region results in substantial increase in the base pressure and this increase is 59% which will be useful in reducing the base drag in the case of external flows in rocket and missile aerodynamics. In figure 10., at X/W =1, an

oblique shock is present which results in a sudden increase in wall pressure taking it to the level of atmospheric pressure. In the downstream at X/W = 5 onwards the control mechanism results in a marginal decrease of wall pressure. This figure also proves that the flow from perfectly expanded nozzles is not shock free instead it is dominated by shock waves. Figure 11. presents the results for the highest NPR tested. For this NPR = 9, the flow is under expanded (i. e. Pe/Pa = 1.15). For this case the results show similar trends as was seen when NPR was 7.8 with the exception that the magnitude of base pressure has marginally decreased for both cases of flow with and without the control mechanism. In this situation the flow is under expanded, here again when the control was employed results in decrease of wall pressure from x/w = 4 onwards. This trend could be due to presence of the shock train in the duct and its strength, reflection from the wall as well as the shock interactions.

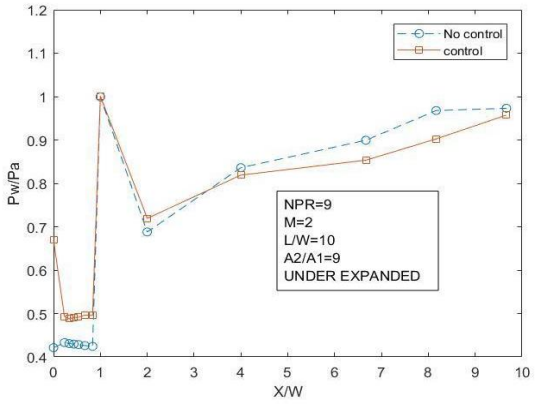


Figure 11 Flow development in the duct at NPR=9

5. Conclusions

Based on the above discussions we conclude that the base pressure is a function of Area ratio, L/W ratio, and NPR, for a particular Mach number. When flow from the nozzle is over expanded the passive control, mechanism is less effective till NPR is 6. This indicates that expansion level plays a vital role. Once the flow is perfectly expanded or under expanded the control mechanism becomes effective and base suction in the base area is reduced and 59 percent increase in the base pressure is achieved. The flow field in the duct remains almost identical with and without the control for most of the cases. However, at higher NPR namely, 6, 7.8, and 9 the control device results in an increase as well as decrease in the wall pressure along the duct. Passive control of the base flow seems to be effective for higher NPRs. The flow field for perfectly expanded nozzle is dominated by shock waves.

Acknowledgments

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