Counter Clockwise Rotation of Cylinder with Variable Position to Control Base Flows

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Abstract. Experimental study of supersonic base flow at Mach 2 has been carried out to see the effect of cylinder when rotated counter clockwise inside the dead zone at variable locations near its base to control base pressure for different level of expansion for area ratio 9. Active cylinder of 2 mm diameter rotating counter clockwise when seen from top, is mounted as a controller. Three locations are chosen from the side wall of square duct namely at 2, 4, 6 mm respectively and 8 mm from square nozzle exit in the base region to mount the controller. Base pressure in recirculation zone and wall pressure along the square duct length has been measured with and without control. The experiments were carried out for NPR 2, 3, 6, 7.8 and 8.5. Cylinder when rotated counter clockwise as an active controller were found to reduce the base drag as high as 62 percent at NPR 8.5 when located near to duct wall and 50 percent when located away from duct wall for the same NPR. For perfectly expanded flows at NPR 7.8 the reduction in base drag was 53 percent near duct wall and 44 percent near duct wall. The active controller was up to 19 percentage effective for over expanded flows near to duct wall and up to 12 percent when located away from duct wall. Also, the control did not adversely affect the flow field. **Key words**: Wall pressure - base pressure - nozzle pressure ratio - active control

Abbreviation

A2/A1	Area ratio
M	Mach number
NPR	Nozzle pressure ratio
L/W	Length to width ratio
X/W	Duct axial distance to width 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	Width of nozzle exit [mm]
W	Duct width [mm]
X	Axial distance along x-axis [mm]

1. Introduction

Abrupt expansion leads to is a complex structure of flow field consisting of separation, recirculation and reattachment [1]. Further flow separation causes low pressure zone at the base, lift reduction and noise generation [2]. In high speed vehicles, such as ballistic missiles, projectiles and rockets the depression at base in jet off condition amounts to base drag as high as 50 percent of the total drag [3]. The base pressure acting at the base of bluff body moving at supersonic speeds is vital in prediction of its base drag [4]. Thus, managing the base pressure with an active controller will be focus of our study. Past researchers have developed tools such as periodic suction and injection [5], micro jets [6], plasma actuator [7] etc. to actively control flow field [8]. Active control techniques require the input energy, making it bit expensive but very effective [9]. Researchers have worked on control of flows for a very long era and a large amount of data is available in literature. So only relevant data to the present study is explored here. To manage base pressure in a desired manner a robust control devise is needed. We proposed a rotating cylinder in counter clockwise direction when viewed from top to modify the base field.

2. Literature Review

An active device for controlling the base pressure in high speed compressible flow regimes, near ambient shock waves, by modifying flow pattern inside the dead zone to authors knowledge is being studied for the first time. The inherent instability problem due to vortex shedding behind the cylinder viewed as bluff body [10] is being studied by ample number of researchers. The problem of flow past a rotating cylinder at low Reynolds number was studied extensively by [11] but he only concentrated on lift due to magnus effect and boundary layer control on an aerofoil. An experimental study of vortex-induced vibration in the crossflow direction of a rotating circular cylinder was carried out by [12]. Suppressing vortex shedding of a cylinder at low Reynolds numbers was achieved by using a smaller cylinder outside the recirculation area in the wake of the main cylinder for incompressible flows [13]. [14] studied the stability analysis of flow past a circular cylinder and concluded rotation helps stability but there is a critical rotation when instability is unavoidable. [15] studied effect of high rotation rates on the laminar flow around a circular cylinder, for higher Reynolds number in the steady flow regime. He concluded that the inherent drag force of cylinder decreases with increasing rotational velocities. [16] investigated on turbulent flow past a rotating cylinder at high Reynolds number. His results revealed stabilization of the acting forces at high spin rates, thus indicating a flow field with suppressed vortex-shedding activity [17]. studied uniform shear flow past a rotating cylinder. [18] investigated vortex shedding for a slow rotating cylinder at different speeds using a stepper motor. [19] studied wake of rotating circular cylinder in an incompressible flow. Rapidly rotating circular cylinder and oscillations were investigated in detail by [20]. Physical mechanism of transition in bluff bodies like rotating cylinder having 3D wake was elaborated in detail by [21]. From review of cylinder study, the flow physics for a single rotating cylinder, and the effect of rotation on cylinder and its interaction with surrounding has been well recorded. Most of the study are done for incompressible low speed flows to reduce the vortex shedding behind the cylinder by various means. One of the ways to get rid of its vortex shedding leading to instability is by reducing its diameter and/or rotating it. Thus, physics of rotating cylinder as a bluff body is well supported by vast literature but there is not a single case to the authors knowledge where cylinder is used to control base drag in compressible high-speed flows. We propose to use cylinder as an active controller rotating in counter clockwise direction at different locations along the base line 'Y-Y' as shown in figure 4.

3. Experimental Setup and procedure

3.1. Supersonic speed facility

The experiments were conducted in B.I.T research centre at supersonic laboratory, Mangalore, Karnataka, India. The supersonic speed facility consists of a settling chamber, with a provision to mount the jet nozzle on its flange. Compressed dry air is stored at a pressure of 200 to a maximum of 300 psi in two high pressure vessels namely storage tank. Compressed air from the storage tank is supplied to the settling chamber at a high pressure of 150 psi through a pressure regulatory valve (PRV) as shown in the figure 1 and 2. Once the flow attains equilibrium in the settling chamber, it is expanded through the square nozzle to the suddenly expanded square duct. The desired stagnation pressure at the settling chamber is achieved by controlling the pressure regulatory valve (PRV).

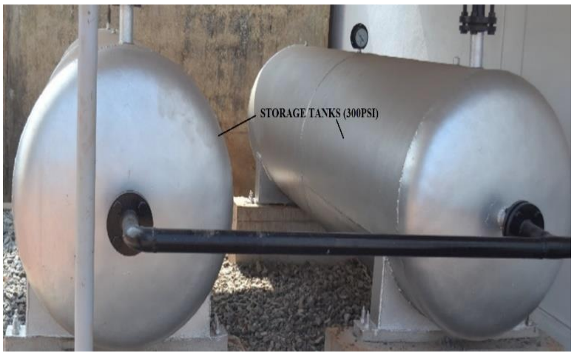


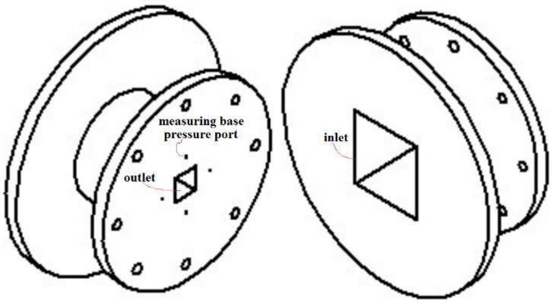
Figure 1. Photographic view of storage tanks

Pressure transducer 9205 is used for measuring base pressure behind exit of nozzle, wall pressure along the duct and stagnation pressure in the settling chamber. It has 16 channels and pressure range is approximately 0-150 psi. It averages 250 samples per seconds and displays the reading. The user-friendly menu driven LabVIEW software along with DAQ acquires data and displays the readings from all the channels simultaneously on the computer screen.

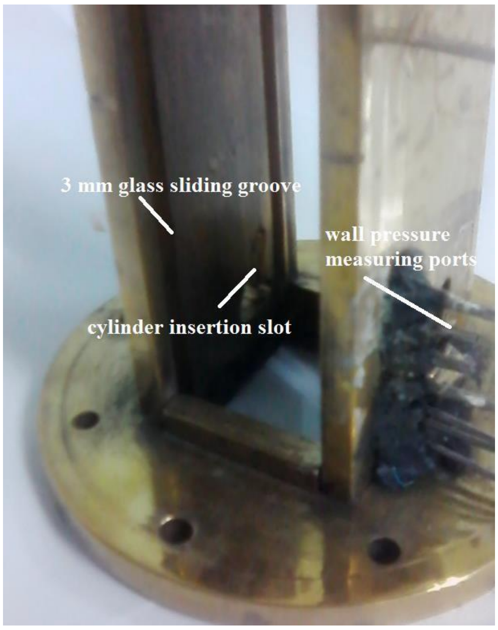
Figure 2. Photographic view of experimental setup

3.2. Fabrication process

The supersonic nozzle using analytical methods was designed for Mach 2 and then fabricated from brass for the same Mach number. Before starting an experiment, it is mandatory for people working in high speed flows to calibrate it. After calibration, the nozzle was attached with the flange of settling chamber at one end and expansion square duct at the other. The exit area of the square nozzle is 10*10 mm square. The Control cylinder of 2 mm diameter shown in figure 3 attached with the motor, positioned on 'YY' base line at 8 mm from nozzle exit was initially mounted at 2 mm from side wall through two roof adjustable table vertically in to the square duct. 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. Pressure taps along the duct wall of 1 mm ID steel tubes were used to record wall pressure.



(a) Square nozzle



(b) Square duct

Figure 3. Photographic view of fabricated square duct and square nozzle

Subsequently its position is varied along ‘YY’ at 4 mm and 6mm respectively as shown by green dots in figure 4. Base pressure was measured at 4 places by nozzle ports at 11.5 mm from centre. Taps begins at 7 mm from the nozzle exit and initially these were 3 mm apart and the distance between them in the axial direction progressively increased until maximum duct length of 300 mm as shown in Fig. 5. The NPR used for this study were 2, 3, 6, and 7.8. The area ratio A2/A1 and length width ratio L/W were 9 and 10 for all the NPRs.

Measurements were made for all NPRs with and without control. The settling chamber was provided with wire meshes to attain the stagnation state. When the flow becomes steady, the settling chamber pressure was recorded. At steady flow conditions the base pressure and the wall pressure in the duct were recorded by pressure transducers. Measurements for all NPRs for no control and control were completed for the square duct of 30*30 square mm cross-sectional area. The base pressure and wall pressure were made non-dimensional with atmospheric pressure and were presented as Pb/Pa and Pw/Pa after converting all reading from gauge pressure to absolute pressure.

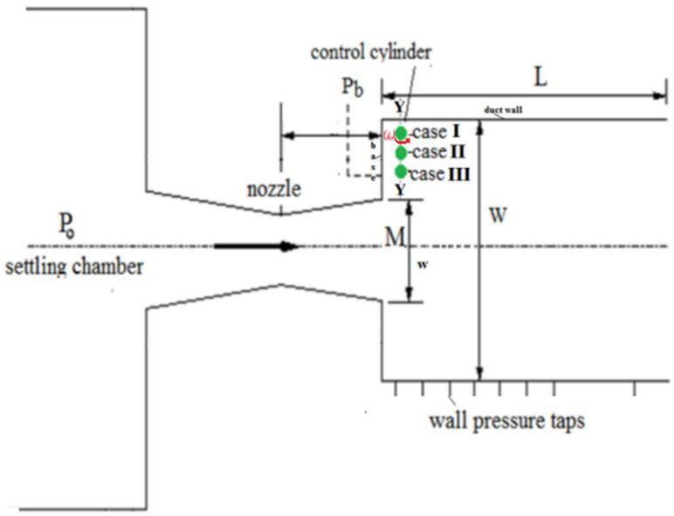


Figure 4. Schematic drawing of the nozzle and duct with different position of control cylinder shown in green dots

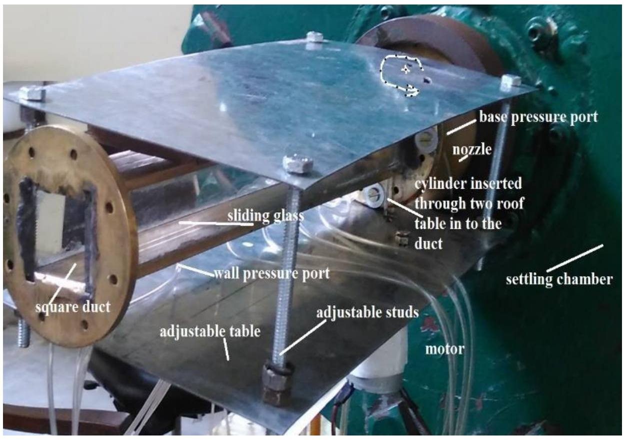


Figure 5. Photographic view of control cylinder, adjustable table and square duct

4. Results and discussions

The main aim of this investigation is to study the effect of the active control as well as the position of the cylinder placed normal to the flow and its influence on the base pressure when it is rotated in the counter clockwise direction along the base. The dynamic cylinder is located at 2 mm, 4 mm, and 6 mm from the base line sequentially and the base pressure as well as the wall pressure were recoded with and without control. The percentage change in base pressure is given by,

% Pb = [(Pb control-Pb no control)/Pb no control] × 100

Fig. 5 presents the percentage change in base pressure for various NPRs. From results, it is evident that as long as flow remains over expanded the control effectiveness is marginal and this trend continues till the NPR approaches close to the nozzle pressure ratio required for perfectly expanded case. At NPR

2 the flow is highly over expanded for Mach 2 and hence there is no change the base pressure even when the location of the cylinder was varied from 2 mm to 6 mm from the base line 3and was rotating clockwise as well. However, at NPR 3 the gain is 8 % when active cylinder was at 2 mm from the base

as compared to the other two locations where gain is 5 %. This difference seems to be due to its location in base corner. Further, it is found that control reversal takes place at NPR = 4 and 6.5. For the NPRs in the range 2 to 5 there is increase in the base pressure, and there is decrease in the base pressure for NPRs in the range 5 to 6.5, then for higher NPRs there is considerable increase in the base pressure which is more than sixty percent. The physics behind this phenomenon seems to be the strength of the oblique shock waves as long as the jets are over expanded, location of the rotating cylinder and the strength of the base vortex. From the results, it is evident that when the cylinder is located at 2mm from the base will give maximum increase in the base pressure. When this cylinder was shifted towards main jet there is progressive increase in the base pressure in the range 45 to 48 %.

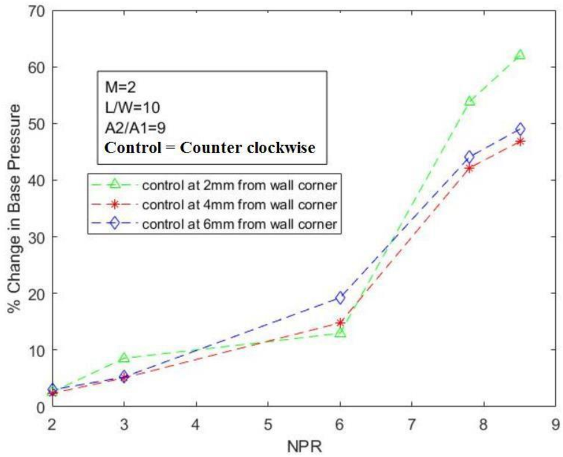


Figure 6. Percentage Change in Base Pressure with NPR

Non-dimensional base pressure variation with NPR for three different locations of the rotating cylinder. As discussed earlier when the dynamic control was located at 2 mm from the base line was most effective, here also we observe the similar results. It is seen that right from NPR 2 till 8.5 there is continuous decrease in the base pressure values for without control case. When the control was placed at 2 mm from the base as the rotating cylinder, it shows mixed trend, control results in increase of pressure for all the NPRs tested, but when compare the control effectiveness with reference to the other two locations of the control namely 4 mm and 6mm from the base, this location of the control results in maximum gain at NPR 3, lowest at NPR 6 and then increase for the NPRs 7.8 and 8.5. The control cylinder located at 4mm results lowest gain in comparison with 6 mm location. When control is located at 6 mm from the base it will be closed to the main jet and as well as the shear layer. Hence due to the combined effect of the interaction of the main jet, boundary layer, dividing stream line, base vortex and the rotating cylinder has resulted in this phenomenon.

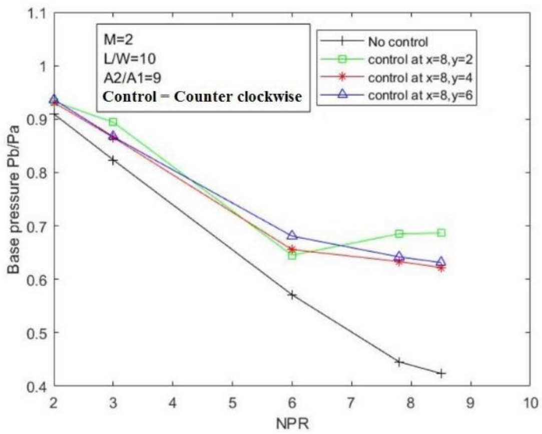


Figure 7. Base pressure variation with NPR

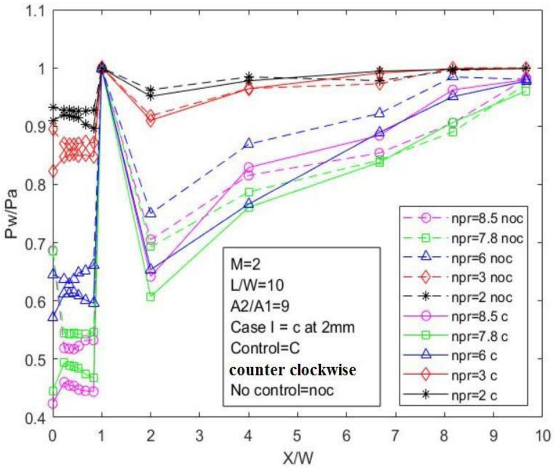


Figure 8. Flow development in the duct at different NPR for Case I

Wall Pressure flow pattern is shown in Fig. 8 for all the NPRs tested with and without control. At NPRs 2 and 3 flows with and without control are identical. Here at NPR 2 and 3 the control results in increase and decrease of the wall pressure. The same is the trend for NPR 6 is seen except the magnitude of control effectiveness has increased considerably due to the reduction in the level of over expansion but at x/w = 8 this increase is negligible due to the back-pressure effect. At NPR 7.8 the control shows mixed trend, due to the presence of weak wave at the nozzle exit, interaction with the dividing stream line, and active control and its location in the base corner.

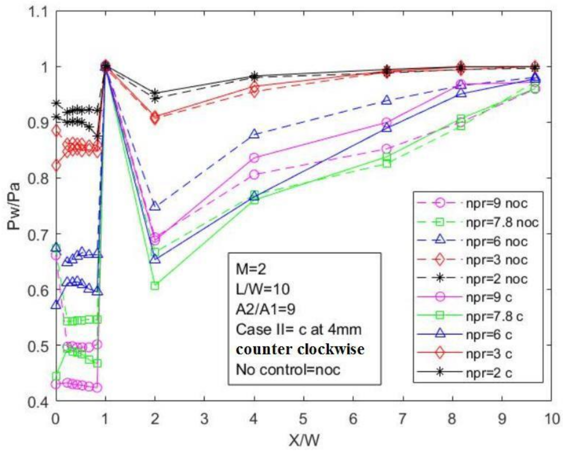


Figure 9. Flow development in the duct at different NPR for Case II

Figure 9 shows wall pressure results for the case II when control cylinder was at 4 mm from the base line. It is seen that wall pressure distribution in the duct with and without control are identical for NPRs 2 and 3, control results in decrease of wall pressure NPR 2 and increase for NPR 3 and this change is marginal and this trend is due to the level of over expansion at the exit of the nozzle. When we look wall pressure results for NPR 6, the initial values have reduced considerably due to the reduction in the level of over exapnsion and control results in appreciable decrease of wall pressure, but the magnitude of decrease in the down stream has reduced considerably due to the back pressure effect. At NPR 7.8 which is required for correct expansion, the results in decrease of wall pressure, at x/w = 1 there is strong wave in form resulting in sudden jump in pressure which is equal to the ambient pressure, then again flow expands to value around 0.65 and 0.6 without and with control and the control reversal takes place at x/w = 6.5 and 9. We see this fluctuating trend due to the jet being correctly expanded at NPR = 7.8, where Mach waves will be present, rotating cylinder is entraining some mass towards the base corner.

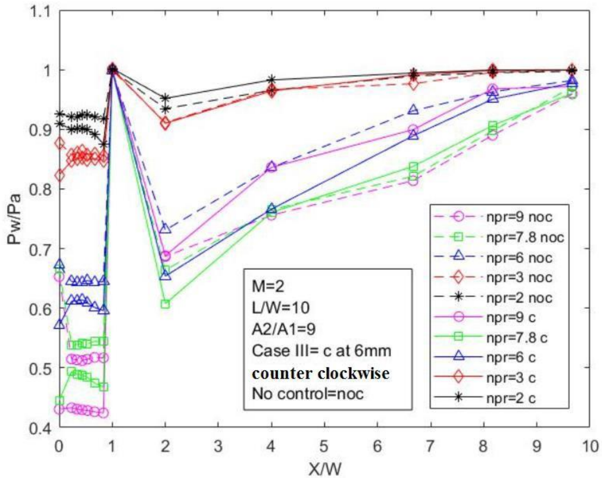


Figure 10. Flow development in the duct at different NPR for Case III

Figure 10 shows the results for case III where rotating cylinder is placed at 6 mm from the base line. This case also presents similar results as discussed earlier with the exception that control mechanism has been placed at 6 mm from the base line. We see a different trend for NPR 7.8 where the effectiveness is marginal as compare to the previous cases. This modification in the wall pressure flow field is due to the shock wave and boundary layer interaction, effect of the location of control mechanism near the main jet as well as the dividing stream line, which is not the case for the other two cases I and II. Hence, we can conclude that overall trend remains the same with minor variations in the values.

5. Conclusions

Base on the above discussions we can draw the following conclusions:

1. The case I when the control was placed at 2 mm from the base is most effective for controlling the base pressure resulting in maximum gain in the base pressure then comes the case III when the control was placed 6 mm from the base line. However, the control results in increasing the base pressure for all the three locations with minor changes in the control effectiveness.
2. The Case II seems to give average results due to its proximity from the base as well as the main jet.
3. When jets are perfectly expanded, they give mixed trend and control reversal takes placed along the enlarged duct wall many times due to the presence of weak wave.
4. Over all the flow field and the trend in the duct remains the same for all the cases. Hence, the control does not adversely affect the wall pressure flow field in the duct.

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