Base control using micro jets for Area Ratio of 5.06

Fharukh Ahmed G M, Sher Afghan Khan

Abstract: Experimental research work is carried in this article to analyze the effect of active control on base pressure variation. Investigations are performed at Mach number of 1.7, 2.3, and 2.7, NPR 1 to 10, and L/D ratio from 10 to 2 for change in base pressure variation. Active control in the form of four micro jets of 1 mm orifice diameter is employed for the investigation. At L/D = 10, the control affected the level of base pressure at higher NPR. At L/D = 6, 4, and 2 the base pressure variation obtained are different, and the control affects the level of base pressure at lower Mach number then at higher Mach number. However, the wall pressure remains unaffected due to the application of microjets in the enlarged duct.

Keywords: Base flow; active control; base pressure; micro jets; area ratio; base drag.

1. INTRODUCTION

In the area of ballistics, researchers have always been concerned about the issue related to external compressible flow in which the sudden expansion around the tail of projectiles and association of it with base pressure. Low base pressure at the tail decides base drag which is a substantial share of the total drag, defined by the base pressure. It is a commonly known fact that the base pressure is lower than its nearer atmospheric pressure in high-speed projectiles. Moreover, the test data of most ballistics presented over the years reveals that the flight Mach number is an essential factor affecting base pressure [1]–[3]. The use of internal flow apparatus for experimental investigation has several advantages over real ballistics trial processes. As a requirement, considerable supply of air is necessary for tunnels having test section, in order that wall interference will not disrupt the flow across the model. Extra support mechanisms like stings can be eliminated which are required in external flow during the experimental internal flow analysis. Another significant advantage of using internal flow apparatus being that complete surface temperature and static pressure calculations can be made along the wake region and entrance section at the expansion area. These tests are essential for proper theoretical prediction as they are of practical importance [4]–[11].

Many investigators have studied experimentally and numerically the phenomena of a sudden expansion in order to reduce the base drag related issue. Srikanth and Rathakrishnan [12] developed a correlation between base pressure and area ratio, NPR (nozzle pressure ratio), and ratio of duct length-to-diameter by studying the results obtained in their previous study reported in [1]. For Mach numbers of 1.87, 2.2 and 2.58 and area ratio 4.84 with NPR variation from 3 to 11, the study by Baig et al. [13] concluded that 45% increase in base pressure is obtained. Another similar study using area ratio of 6.25 with NPR from 3 to 11 and L/D ratio of 1 to 10 gave an increase of about 55% of base pressure using active control. A thorough analysis is also reported related to wall pressure distribution for an area ratio of 2.56 for the same L/D ratio and NPR. The results revealed that the wall pressure distribution does not have any adverse effect on the enlarged duct. One more study was carried out by the same authors to improvise the base pressure without hurting wall pressure distribution [14]. Khan et al. [15] operated control for Mach numbers 0.2, 0.4, 0.6, 0.8, and 0.9 and with area ratios of 2.56, 3.24, 4.84, and 6.25. Length to diameter (L/D) ratio was varied from 1 to 10 during the experimentation. Reduction in base pressure using microjets and no adverse effect on wall pressure was obtained. Baig et al. [16] carried similar study for an area ratio of 3.24 for NPR from 3 to 11 and obtained a 70% increase in base pressure.

Asadullah et al. [17] analyzed wall pressure distribution for low supersonic Mach number, i.e., at 1.3. The results showed that the expansion and compression waves reduced drastically at L/D =3 due to variation in back pressure. NPR of 2.77 and 4.16 was used in another experimental investigation for base pressure reduction analysis using active control for an area ratio of 2.56. The L/D=8 and 10 revealed a completely different base pressure variation compared to L/D ratios of higher values. Negligible increase in wall pressure for under expanded flows was obtained, and for the case of with and without control, the effectiveness remained same [18]. In yet another study of Baig et al. [19] performed another single study at Mach 1.87 while the area ratios were varied accordingly as 2.56, 3.24, 4.84, and 6.25. Under expansion study was performed choosing and length to diameter ratio was varied from 1 to 10. 80% increase in base pressure was obtained, an area ratio of 6.25 and 4.84 is found suitable for length to diameter ratio of 2, and for area ratios 2.56 and 3.24 the length to diameter ratio of 2 is found suitable. Ashfaq et al. [5] carried out a series of experiment considering sonic Mach numbers to control the base pressure by providing four microjets. Area ratios of 2.56, 3.24, 4.84, and 6.25, and L/D ratio of 1 to 10 was operated for the experimental analysis. The area ratio of 6.25 and NPR of 1.5, 2.0, and 3.0 was applied which lead to effective control of base pressure [20]. Another study is reported by them for under expanded flow for subsonic and sonic flows with nearly the same configuration [21].

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Quadros et al. [22] used the L9 orthogonal array for the planning of experiments and found that the lower area ratios are useful in control than the higher area ratios. Analysis of variance and multiple linear regression analysis were performed for the obtained experimental results. Fifteen random test results were used for the prediction of accuracy to test two linear regression models. Their analysis revealed that the linear regression model is enough to predict the base pressure accurately with and without control. Computational fluid dynamics analysis were performed for further in-depth analysis and validation was performed with the experimental results. For Mach number 1.25 and nozzle diameter ratio of 1.6 experiments were performed for under-expanded and correctly expanded cases by Khan et al. [23]. Surprisingly, the flow filed became oscillatory for a particular combination of NPR and L/D ratio. The said phenomenon was observed in the case of both controls and without control. Several other relevant research works carried out using active control include [24]–[33]. Baig et al. [34] carried experimental investigation using the control to reduce base pressure in sudden expansion flows with the axi-symmetric passage. Microjets at four different locations were used to control the base pressure. Mach numbers of 1.87, 2.2 and 2.58 were employed for the experimental investigation. The area ratio was fixed at 2.5, and the length to diameter ratio was varied from 1 to 10. Nozzle pressure ratio (NPR) of the operating nozzles were changed from 3 to 11. As high as a 65% increase in base pressure was obtained during their analysis, and it was found that the flow field was not disturbed in the enlarged duct using the microjets.

From this literature review of recent articles shows that many studies are conducted to reduce base pressure in sonic, transonic and supersonic flow using passive and active controls. However, for Mach number of 1.7, 2.3, and 2.7, area ratio of 5.06 the combination of NPR and L/D ratios the base pressure analysis is not reported. In this article use of active control technique to reduce base pressure with the aid of microjets is reported in detail.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the essential features of sudden expansion flow filed is illustrated showing the reattachment point, expansion waves, and recirculation zone. The same concept is used to perform the experimental investigation with the application of four micro jets at the base as shown in Figure 2. The experimental facility available at High-Speed Aerodynamics Laboratory (HSAL), IIT, Kanpur, is employed for the analysis. The experimental setup is schematically shown in Figure 2. The side view shown at the right side of Figure 2 shows the presence of eight holes along the circular position outer to the nozzle exit. The holes marked with ‘c’ are the microjets placed suitably for blowing and holes ‘m’ marked in the Figure are to measure the base pressure (P_b). By blowing air, active control is accomplished through the holes ‘c’ consuming the pressure from a tube connected through the blowing chamber as shown in Figure 2. The blowing chamber uses the same pressure from the settling chamber. To measure the wall pressure and the flow field nature in the duct (enlarged one), pressure taps were used on the wall. At a distance of 8 mm each, holes are made which are nine in number, and the remaining holes are prepared at a distance of 10 mm. The Length to diameter ratio (L/D) used in this study is varied from 10 to 1, and the readings for each ratio is conducted. The experiment is repeated for Mach numbers like 1.7, 2.3, and 2.7. In literature usually, L/D ratio employed is 3 to 5 for without control. With control, this ratio can be varied from 10 to 1. For each value of each number, L/D ratio, with and without control the NPR is varied from 1 to 10 in a step of 1 each, and the readings are noted every single time. PSI System 2000 is used as a pressure transducer to record the change in base pressure variation. The pressure range is 0-300 psi of the transducer employed, and it has 16 channels. The sampling rate of the pressure transducer is 250 samples per second, and then the reading is displayed on the monitor and recorded. The wall pressure were recorded using mercury manometer.

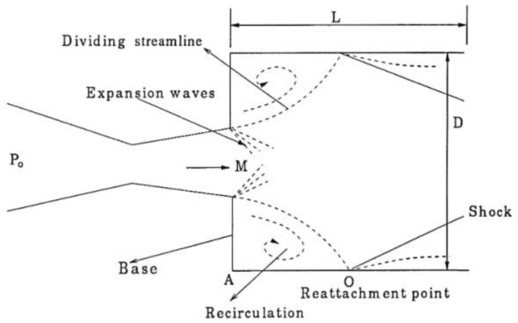

Figure 1. The sudden expansion flow field

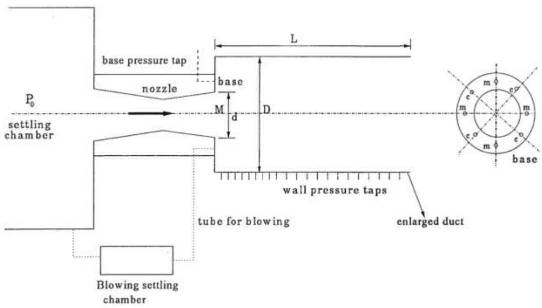

Figure 2. Experimental setup for active control

3. RESULTS AND DISCUSSIONS

Mach number (M), area ratio, L/D ratio, base pressure (P_b) at the nozzle exit, static wall pressure (P_w) distribution along the length of duct wall, and NPR (nozzle pressure ratio) are the data points recorded during the investigation. NPR is the ratio of stagnation pressure (P_o) to back pressure (P_a), i.e., Po/P_a, area ratio being the ratio of cross-sectional area of the duct to nozzle exit area, and L/D stands for length to diameter ratio of the duct (refer Figure 2). The base pressure and wall pressure are non-dimensionalized using back pressure (P_a). The Mach numbers for the analysis chosen are 1.7, 2.3, and 2.7. Detailed comparative analysis of base pressure with no control (NOC) and with control (WC) is provided in this section. The area ratio in the pressure investigation is fixed at 5.06 throughout. The L/D ratios selected for the base pressure variations are 10, 6, 4, and 2.

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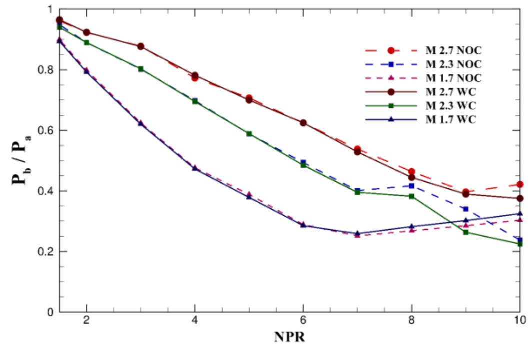

Figure 3. Variation of base pressure at L/D = 10

The variation of base pressure with NPR at Mach numbers 1.7, 2.3, and 2.7 for a flow having active control and no control is shown in Figure 3. The NPR is varied from 1 to 10 for each Mach number with L/D=10. No functional dependence of control on base pressure with change in NPR is observed. However, the control has affected the level of base pressure at higher NPR. The trend may be because as the NPR increases the level of overexpansion comes down; hence the oblique shock at the nozzle exit becomes weaker than those at lower NPRs. The control effectiveness is found to be comparable at NPR=10 for all Mach numbers. For Mach 2.3 and 2.7, the base pressure with control remains below the base pressure without control at all NPR. However, for Mach 1.7 the base pressure reverses at NPR 7 and remains above the base pressure without control. This effect of control on base pressure can be related to the nature of the base pressure expansion level at the exit of the nozzle and the duct ratio L/D while the area ratio is fixed. During the flow with under expansion and over-expansion, there will be an expansion fan and oblique shock at nozzle lip respectively. Hence, a widespread impact on the base pressure level is caused by the wave at the nozzle exit. Presence of these waves leads to a significant effect of control on the level of base pressure at higher NPR.

The results of base pressure variation at L/D=6 with NPR for Mach numbers 1.7, 2.3, and 2.7 for a flow having active control and no control is shown in Figure 4. The trend of base pressure variation with and without control is similar and remains functional at all NPR. However, the trend is not similar to the case of L/D=10. The effectiveness of control gets reversed around NPR 7 for Mach 1.7, and no specific effect of control on base pressure at Mach 2.3 and 2.7 are obtained. Microjets are found to be effective at lower Mach number of 1.7, and this control effect becomes much higher at higher NPR.

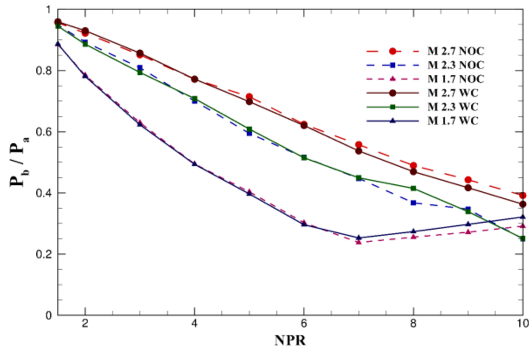

Figure 4. Variation of base pressure at L/D = 6

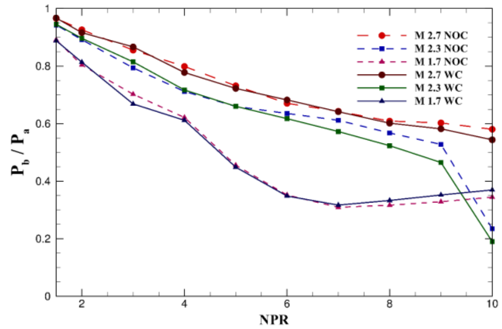

Figure 5. Variation of base pressure at L/D = 4

Figure 5 shows the base pressure variation at L/D=4 with NPR and Mach values of 1.7, 2.3, and 2.7 for with and no control. At Mach 1.7 the control results in a decrease of base pressure till NPR 7 and then the control effectiveness reverses. At higher values of NPR = 7 and Mach 1.7, high values of base pressure are obtained which is due to the structure of shock occurring at the nozzle exit, reattachment location length, the effect of back pressure, the impact of the shear layer and base vortex interaction. At Mach 2.3 and 2.7, the control reduces the base pressure at all NPRs. Specifically for Mach 2.3 and at NPR = 5, the control reduces the base pressure effectively. Whereas for Mach 2.7 the control effectiveness is marginal. The base pressure variations at L/D = 2 is shown in Figure 6. The trend followed by Mach 1.7 is similar to the previous case. The other Mach numbers behave entirely different from that at higher L/D ratios. For these Mach numbers, the flow seems not to be attached to the wall of the enlarged duct. For higher NPR and at Mach 2.3 and 2.7, the base pressure fluctuates above and below the mean value and control does not pay any significant role in either increase or decrease of base pressure.

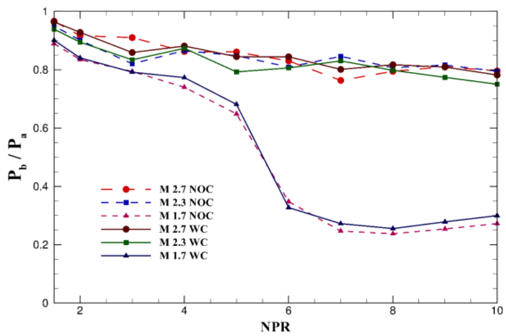

Figure 6. Variation of base pressure at L/D = 2

The distribution of static wall pressure for Mach 17, 2.2, and last 2.7 are shown in the below Figure 7 considering fixed L/D = 10 for different NPR. The pressure field seems to behave identically with control and no control. Hence the wall pressure does not get influenced adversely leading further to oscillate violently due to active control. Whenever we employ the control using either active or passive control in increasing the base pressure; the primary issue associated with control of base flow related to wall pressure in supplementing the oscillatory nature is completly evaded.

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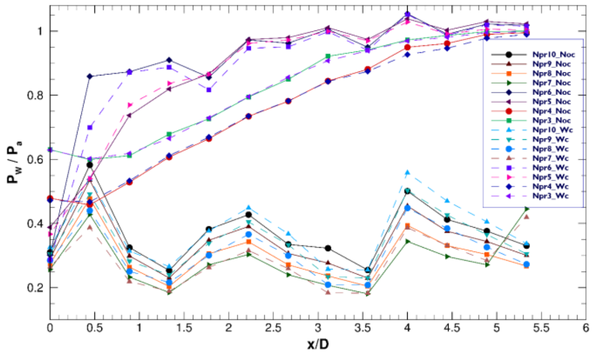
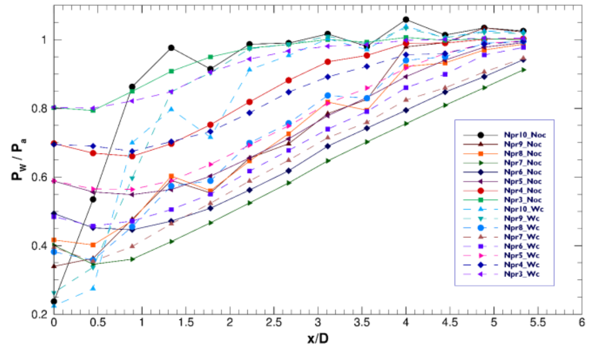
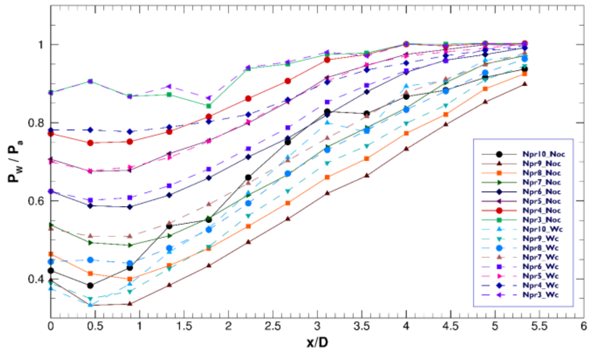


(a) Mach 1.7



(b) Mach 2.3



(c) Mach 2.7

Figure 7. Distribution of wall pressure for L/D=10

4. CONCLUSION

This article reports the experimental investigation of the effect of active control on base flow for Mach numbers 1.7, 2.3, and 2.7. NPR and L/D ratio were also varied to understand the base pressure changes. From the analysis, it is concluded that the control effectiveness is found to be comparable at NPR=10 and L/D=10 for all Mach numbers. For Mach 2.3 and 2.7, the base pressure with control remains below the base pressure without control at all NPR. However, the effectiveness of control gets reversed around NPR 7 for Mach 1.7, and no specific effect of control on base pressure at Mach 2.3 and 2.7 are obtained. The wall distribution, on the other hand, does not get affected due to the application of active control, which stands as the significant advantage of the present analysis.

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