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Control of Nozzle Flow Using Microjets at Supersonic Mach Regime

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ABSTRACT

This article reports the active control of base flows using the experimental procedure. Active control of base pressure helps in reducing the base drag in aerodynamic devices having suddenly expanded flows. Active control in the form of microjets having 0.5 mm radius placed at forty-five degrees apart is employed to control the base pressure. The Mach numbers of the present analysis are 1.7, 2.3, and 2.7. The length to diameter (L/D) ratio is varied from 10 to 1 and the nozzle pressure ratio (NPR) being changed from 1 to 10 in steps of 1 for base pressure measurements. The area ratio for the entire analysis is fixed at 2.56. Wall pressure distribution along the enlarged duct is also recorded. No change in base pressure increase/decrease is thoroughly analysed as well. From the experimental investigation, it is found that control plays an important in modifying the base pressure without disturbing the wall pressure distribution. The base pressure variation is entirely different at L/D = 1 compared to a higher L/D ratio due to change in reattachment length and the requirement of the duct length at higher inertia levels. The quality of the flow in the duct in the presence and absence of control remained the same.

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1. INTRODUCTION

The occurrence of the problems due to the sudden expansion or the flow past backward-facing step is widespread which encounter in the automobile industry and the design of aerospace vehicle at all the range of Mach number from less than one, equal to one, and greater than one. The use of shroud and jet configuration in the form of a supersonic parallel diffuser can be considered as an application of sudden expansion problem. A similar application can be seen in systems employed for simulation of rocket and jet engines test cell under high altitude condition where a jet discharges into a shroud and hence produces a useful sub-atmospheric discharge pressure [1-8]. In an internal combustion engine, the exhaust port has a similar flow condition where the jet of hot exhaust gases flows out through the exhaust valve. The flow expansion is inward rather than outward in case of flow around the base of a missile in flight or blunt edged projectile, can be considered as another application of suddenly expanded flows [9-12].

Khan et al. performed a series of experiments to understand the role of microjets as an active control in various cases of base pressure control as well as the variation with Mach number, NPR, and L/D ratio, and wall pressure distribution. At the start, Khan et al. [1] analyzed the effect of microjets in order to manage the base pressure variations at the base of the nozzles which are symmetric about its axis. The results reveal that the microjets are helpful as an active controller in regulating the base pressure without any contrary impact on wall pressure distribution. Khan et al. [2] changed the NPR (nozzle pressure ratio) from 3 till 11 in the step of 1 for their next analysis. Up to 95% increase in base pressure is obtained for a particular L/D ratio, NPR, Mach number and the area ratio. Their experimental results show that there are some combinations of these parameters at which the base pressure increases to its maximum and decreases to its minimum in comparison to the without control cases [3]. Similar conclusions were made by Khan et al. when they investigated

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experimentally at various area ratios, Mach numbers, and L/D ratios in this study as well and in [4,5].

For correct, under and over-expansion, the microjets influence was estimated which were of orifice diameter = 1mm for Mach from 1.25 to 3.0. The jets aided in improving the base suction to zero levels without any effect on flow distribution [8]. Another observation made by Khan et al. [6] was that at Mach above two, the control efficacy results in a decrement of the pressure at the base region for NPR 5 to 9. Rehman and Khan [13] studied for fixed area ratio at 4.84 for Mach numbers at low supersonic, medium, supersonic and high supersonic Mach numbers at various NPR for L/D variation from 10 to 1. They also obtained an improvement in the base pressure values which was forty percent. Khan et al. [14] carried another experimental work adopting a passive control technique using many cavities in a square duct. The comparison is made between passive control and no control of base pressure. These cavities helped in increasing the base pressure leading to reduced base suction and drag without any reverse impact on flow in the enlarged duct.

When active control for Mach number 1.1 to 2.8 and 2.56 of area ratio was adopted to regulate the base suction at the nozzle exit, the Jets helped in reduction of drag. The results showed that an increase in the base pressure by 65% is achieved without any side effect on the flow field of the duct [15]. One more new technique adopted by Khan et al. [16] to decrease the base pressure in a backward facing step was by providing two dimples on the base of expansion. 1.27 to 1.69 NPR was applied. The backward step with a 150-degree angle of incidence expanded into the duct of 25 mm square cross-section computational analysis used the SST (shear stress transport) model with Reynolds number greater than twelve thousand. The passive dimples helped in providing reduced base suction effectively. In [17] Another method of providing passive control is by using a static cylinder at the base of the nozzle exit of 2 mm diameter is proposed. The square duct was attached at the nozzle exit and the passive control lead to a 59% increase in base pressure with the static cylinder at NPR 9. However, for overexpansion, the cylinder was found to be inefficient.

In the following study, using an active cylinder, the analysis was performed by rotating the cylinder inside the recirculation zone by Asadullah et al. [18]. Fifty-six percent and seventeen percent enhancement in the base pressure for under and over expansion cases without any harm to the wall pressure. Alrobaian et al. [19] demonstrated low-cost open type wind tunnel to analyze flow over an object from a square nozzle at subsonic speed. Reattachment point was visualized using transparent glass and found that attaching the test bodies to the traverse is easy. Vikramaditya et al. [20] studied the fluctuation in pressure at the base of the missile at Mach 0.7 in the absence and presence of a cavity. Experiments were conducted for different azimuthal positions, and the presence of cavities provided increased base pressure and reduction in pressure fluctuations. Based on Strouhal number the cavity showed narrow band tones of three types as observed from the spectra.

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 2.56 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 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 (Pb). 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. In this experimental investigation, active control has been used. Hence, it is mandatory to investigate the nature of the flow the of the duct having sudden enlargement and to ensure that the nature of the

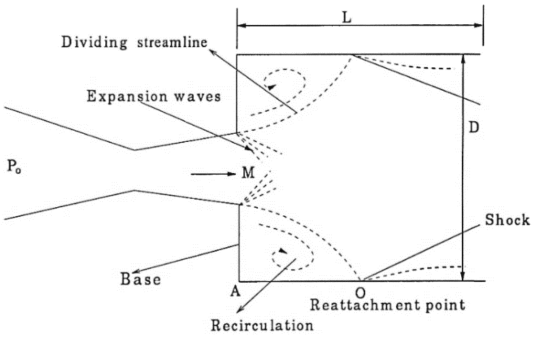


Figure 1. A view of the flow field with the sudden expansion

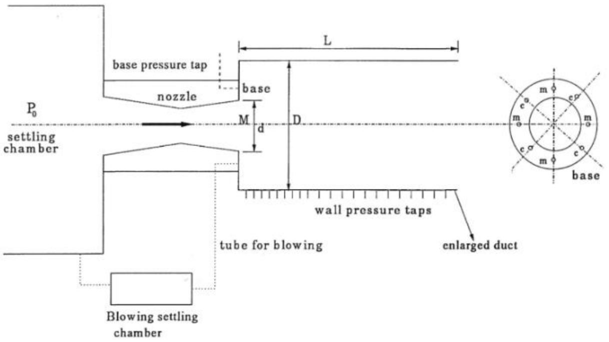


Figure 2. The setup used for active control

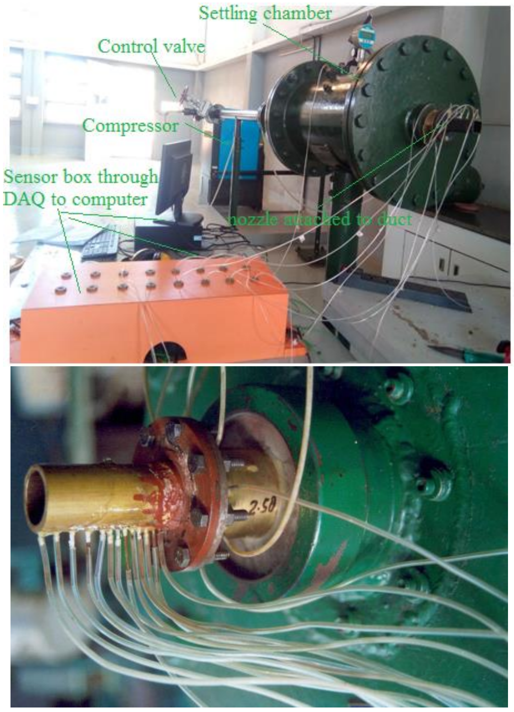


Figure 3. Photo view of the setup and microjet orifice

flow in the duct remains identical for the condition of control is present or not. In this study, in order to accomplish the requirement, the static wall pressure was the pressure taps which are used on the wall at a distance of 8 mm each, nine holes are made and the remaining holes are at a distance of 10 mm each. The Length to diameter ratio (L/D) used in this study is varied from 1 to 10, and the readings were recorded for different L/D ratios. The experiments are done for Mach numbers like 1.7, 2.3, and 2.7 for a given L/D for NPR in the range 2 to 10. In literature, usually, L/D ratio employed is 3 to 5 for without control for sub-sonic and sonic cases. With control, this ratio can be varied from 1 to 10. For each value of L/D ratio, with and without control, the NPR is varied from 1 to 10 in an increment of 2; initially, two lengths each, and later for the short length, 1 L/D each and the readings are noted in every single time. PSI System 2000 is used as a pressure transducer to record the change in base pressure variation. The range of the pressure which can be tested is from 0-300 psi of the transducer employed, and it has 16 channels. The sampling rate of the pressure transducer are two hundred and fifty in one second, and then the observed data will be displayed on the monitor and recorded on the hard disk of the computer. The wall pressure was recorded using mercury multi-tube manometer.

Few errors/uncertainties occur during the estimation of quantities using the measured data. Generally, the uncertainties are associated with wall and base pressure. The error involved while measuring a quantity affects the dependent variables that can be calculated using the analogy of the derivative of a function. An error of up to ±1.8% is involved in the data measurement and estimation of quantities.

3. RESULTS AND DISCUSSION

The flow parameters like base pressure (P_b) at the nozzle exit, distribution of static wall pressure (P_w) along the duct wall length, the level of expansion (NPR), level of inertia of the flow (i.e., Mach M) of the jet were considered. The geometrical parameters like area ratio and L/D ratio are considered during the experimentation of the present study. Here, NPR is the ratio of P_o/P_a, the area ratio (i.e., A_2/A_1), and L/D ratio of the duct as depicted in Figure 2. Figure 3 shows the arrangement of setup and orifice used at the nozzle base. The pressure in the base corner, as well as the end to wall pressure along the enlarged duct, 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 2.56 throughout. Before discussing the results, let us discuss the physics of the flow and the flow development once the jet has exited from the nozzle.

When the flow is passing through the converging nozzle, the flow at the exit will always be correctly expanded. Whereas, in the case of the converging-diverging nozzle the flow can be over expanded, correctly expanded, and under-expanded. When the flow is exhausted in the suddenly expanded duct, at the exit of the nozzle, the shear layer will be separated and will get reattached with the duct. Where the flow gets reattached with the duct, it is called the reattachment point. The distance from the exit of the nozzle to the reattachment point is called the reattachment length. The location of the reattachment point mainly depends on the parameters like area ratio (A_2/A_1) or the diameter ratio (D_2/D_1). However, it will depend on the level of inertia of the flow, NPR, and the duct length as well. In this investigation, the location of the microjets is fixed at the pitch circle diameter of 13 mm (i.e., pcd = 13 mm). Hence, for an area ratio of 2.56 in the case when the duct diameter is more than 16 mm, the radius of the duct is 8 mm, which implies that the control mechanism is located at the center of the base area and not closed to the main jet,. Due to the flow separation, the area between the nozzle exit and the reattachment point is called the dead zone or recirculation zone. From the reattachment point again there will be the growth of the boundary layer. The main aim of the control mechanism is to break the powerful vortex located in the dead air zone. By doing so, the strength of the vortex will get reduced, and hence the base pressure will increase.

Figure 3 shows the variation of dimensionless base pressure with NPR from 1.6 to 10 at Mach numbers 1.7, 2.3, and 2.7 for a flow having active control and no control. The L/D ratio, in this case, is equal to 10 (fixed). The NPR at correct expansion for Mach 1.7, 2.3, and 2.7 are 4.94, 12.5, and 23.3, respectively. When we look at the NPR needed for correct expansion, at these NPRs and the NPRs tested, we found that the nozzle at Mach 1.7 undergoes through over-expansion, correct expansion and under-expansion as well. The level of under-expansion at the highest NPR tested is 2.03. For the remaining inertia levels namely 2.3 and 2.7, the nozzles remained over-expanded. It is also found that with an upward movement for defined value of the NPR, the level of over-expansion has gone down. The level of over-expansion at the highest NPR for these Mach numbers is 0.8 and 0.43 (i.e., P_e/P_a = 0.8, and 0.43), respectively. From Figure 3, it is seen that in case of Mach 1.7 till NPR continuous decrement in the pressure in the dead zone and for NPR more than 4, this decrease in the base pressure is arrested, and the base pressure in the absence of control also results in enhancement of the base pressure. The dependence of control in the form of microjets on the pressure at the base with the change in NPR is observed. However, the control has affected the magnitude of the pressure in the recirculation region at all NPRs. The control efficacy is visible at higher NPRs.

Interestingly, the control effectiveness is found to be comparable even at NPR = 1. This implies that at lowest NPR the control is active as well. It is also seen that up to a specific value of NPR, the impact of the control in the form of decrement of the pressure at the base area when is compared with the case of no control. After this NPR, the base pressure with control remains above the base pressure with no control. This effect of control on base pressure can be related to the nature of the wave formation, and hence, the level of expansion when the jet is exiting the nozzle and the duct ratio L/D while the relief for the flow is fixed. During the flow with under-expansion and over-expansion, usually, expansion waves and likely the oblique shock at nozzle exit is found. Hence, a widespread impact on the pressure in the recirculation zone is caused by the wave. This may be the reason that the base pressure decreases initially up to a level of NPR. Once the NPR is equal to the NPR needed for correct expansion, the nature of the flow in the dead zone and hence the pressure at the base will continue to change as long as these waves are formed and getting changed due to the dynamic conditions of the flow. The nature of the flow will be wavy. Due to these jets passing through the oblique shock waves, across which there will be sudden increase in the pressure behind the oblique shock and hence; the base pressure attains a high value. Once the operating NPR is equal, the NPR needed for correct expansion the presence of the oblique shock will get replaced by the Mach waves across which the flow will be isentropic and followed by the expansion waves when the jet becomes under-expanded.

From the results, it is found that when the nozzles are ideally expanded, they are not free from the waves. When the operating NPR of the test is more than the required NPR for correct expansion of the nozzle when the nozzles are under the influence of the favorable pressure gradient. From the literature survey, it is found that whenever, the jets are under-expanded, and under these circumstances, when active or passive controls are activated they are beneficial, and control becomes effective. The level of expansion leads to a significant effect of control on the level of base pressure at large NPR and high Mach, in comparison to the situation at smaller Mach numbers. In Figure 4, the results for the pressure at the base and its variation at L/D ratio marginally lower than the previous one (i.e., L/D = 8) for the different inertia levels from M = 1.7, 2.3, and 2.7 for a flow having active control and no control is represented. The trend of base pressure variation for both the cases (i.e., when the control is employed of as well as in the absence of the control) is similar to that of the previous case of L/D = 10. One new observation at NPR = 1.6 can be made that in this case, where control is not useful. The effectiveness of control changes at NPR 3.5 for Mach 1.7 and NPR 4.5 for Mach 2.3. However, the efficacy of the control at Mach 2.7 at all NPR remains negligible. The reasons for this behavior may be due to the decrement in the duct length. There will be some change in the flow field due to the L/D effect. Microjets are found to be effective at lower Mach numbers, and this control effect becomes much higher at higher NPR. Nevertheless, the control effectiveness at higher NPR with control is less in comparison to the control efficiency at higher NPR during L/D = 10.

The base pressure variation at L/D = 6 for different Mach numbers along with NPR = 1.6 to 10 is depicted in Figure 5. Comparison between the presence of

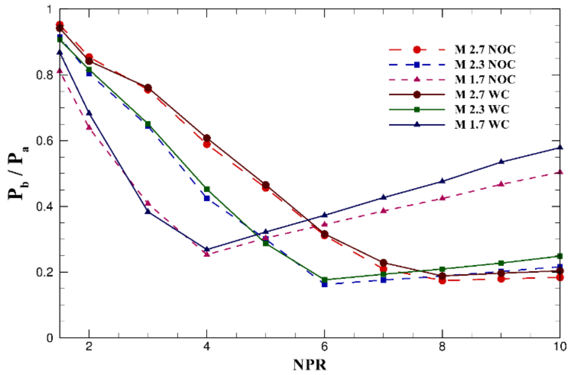


Figure 4. Variation of base pressure at L/D = 10

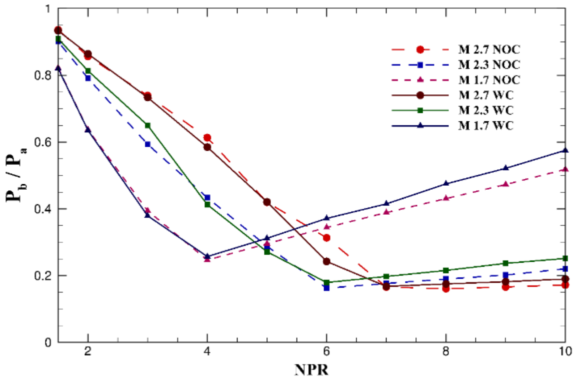


Figure 5. Variation of base pressure at L/D = 8

control of flow jet and its absence is shown in Figure 5. Like in the previous case, here too the base pressure effectively gets increases for lower Mach numbers and at higher NPR. Here, unlike the previous L/D = 8 cases, the control effectiveness at Mach 2.7 is found to increase the base pressure. The control effect changes at NPR 4 for Mach 1.7, at NPR 6 for Mach 2.3, and at NPR 7 for inertia level M = 2.7. After the reversal at these respective NPRs, the base pressure increases irrespective of Mach number and for flow in the presence and absence of control. Figure 6 shows at L/D = 5 the base pressure values with the change in the expansion levels of the jets at different Mach numbers of 1.7, 2.3, and 2.7. The control effectiveness is found to more at L/D = 5 compared to L/D = 6 at higher NPR. Even at Mach 2.7, the effectiveness is more profound after NPR value of 7. The effectiveness is reversing similar to the previous case as shown in Figure 6. However, for inertial level M = 1.7 at NPR = 4, the control effect reversal is more progressive than the previous case. The phenomena occur due to the jets are correctly expanded at Mach number 1.7, and for the remaining Mach numbers, the nozzles are of over-expanded for Mach 2.3, and 2.7.

Figure 7 shows the base pressure variation at L/D = 4 and Mach values of 1.7, 2.3, and 2.7 for with and without control. The control effect is found to be negligible for Mach 1.7 and 2.3 at all NPRs. The effectiveness reverses at NPR = 6.2 for Mach 2.7 and is found to improve the base pressure till NPR = 9 and then at NPR=10 the effectiveness remains nearly the same for this Mach. In Figure 8, the base pressure variations are shown which reveal that the control effect is observable at all NPR and Mach numbers. For Mach 1.7 the control effect does not reverse while for Mach 2.3 and 2.7 at NPR = 6 the control reverses. At Mach 1.7 the base pressure is found to be affected by the control at all NPR. At NPR = 7 and Mach 2.7, the effect is found to be highest compared to all other cases considered in this study. Figure 9 depicts the pressure at the base for the low duct length (i.e., at L/D = 2). As in the case of L/D = 3, the control effect does not reverse for Mach 1.7. For Mach 2.3 and at NPR = 5 the effectiveness reverses whereas for the Mach 2.7 it is found that the control reduces base pressure effectively at all NPR. For without control at Mach 2.7, the length of the duct (enlarged) seems to be insufficient such that the shear layer does not attach to the duct wall. At L/D = 1 and for Mach 2.3 and 2.7 (Figure 10), the expanded flow does not re-attach due to insufficient duct length. Mach 1.7 seems to be satisfied with L/D = 1 as seen from Figure 10. The behaviors are entirely different for higher L/D ratios.

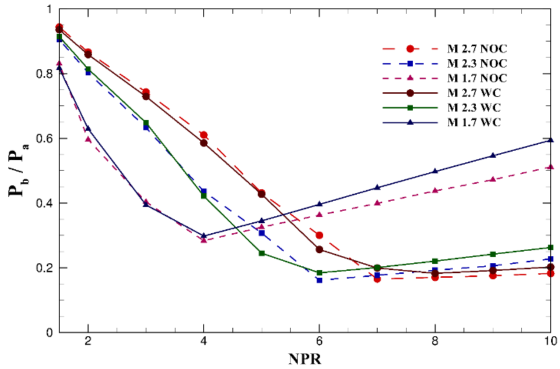


Figure 6. Variation of base pressure at L/D = 6

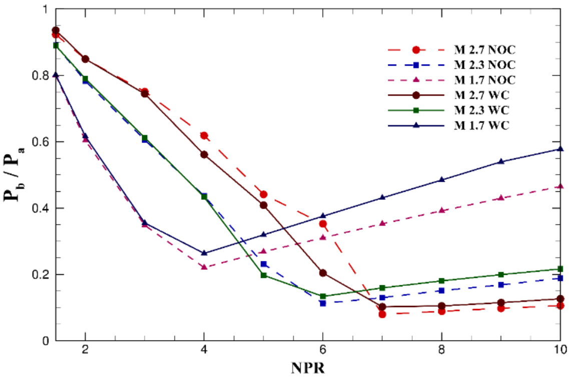


Figure 7. Variation of base pressure at L/D = 5

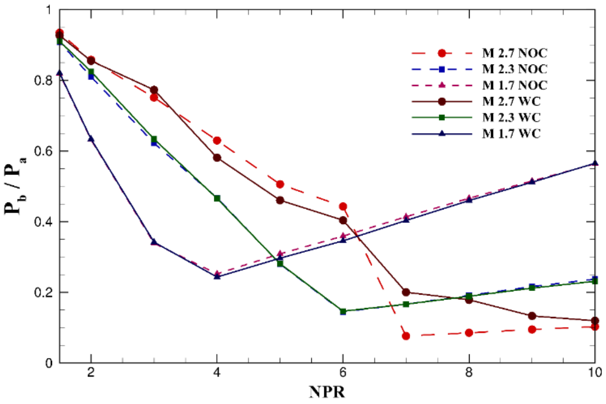


Figure 8. Variation of base pressure at L/D = 4

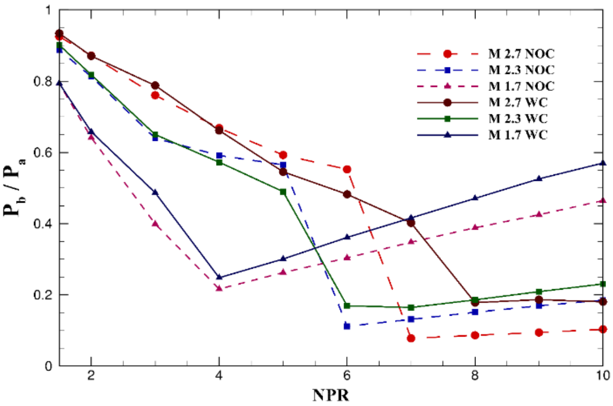


Figure 9. Variation of base pressure at L/D = 3

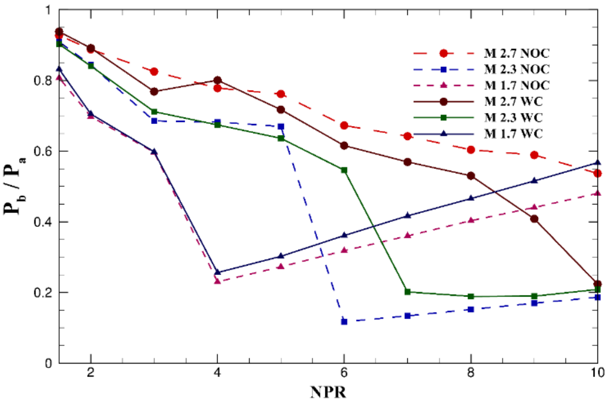


Figure 10. Variation of base pressure at L/D = 2

The distribution of static wall pressure for Mach 1.7, 2.2 and 2.7 are shown in Figure 12 for L/D = 10 for different NPRs. The pressure field seems to behave identically with control and without control. Hence, the wall pressure does not get influenced adversely leading further to oscillate violently due to active control. The essential advantage of using active control in increasing the base pressure as the primary issue associated with the control of base flow in augmenting the oscillatory nature of the wall pressure field should be avoided. At all these L/D ratios, surprisingly the lowest and highest improvement obtained is at NPR of 6. From Figures 4-11 it is seen that when the L/D ratio is large, at lower Mach number provides a substantial increase in base pressure than at the higher Mach numbers at lower L/D ratios. Similarly, at the NPR of 6, almost for all L/D values the percentage increase in base pressure is least for different Mach numbers. However, at the least L/D ratio, the percentage increase in the base pressure obtained by the control is highest at the lower NPR which is more interesting. Nearly 370% increase in the base can be noted as shown in Figure 10.

The main reason behind the variation concerning NPR equal to 6, is due to over-expansion below NPR 6, and later due to correct and under-expansion, the effect of microjets leads to substantial increase in base pressure. At L/D ratio of 4 and 2, the percentage change in base pressure remains smooth for most of the NPR range except at NPR six, and seven whereas at other values of L/D ratio the percentage increase is different. Hence, it can be stated that due to changes in the shock wave structure with the magnitude of NPR changes.

4. CONCLUSION

From the analysis conducted at different NPR, L/D ratio, and a fixed area ratio were investigated. Mach number and comparison between control and no control few critical observations and the conclusions are drawn which are as follows. The base pressure is an active function of NPR and L/D ratio. For higher L/D ratios and higher NPR, the control effectiveness is significant whereas at lower L/D ratio the behavior is entirely different. For a particular value of NPR and at L/D ratio the control tends to reverse the control effect where the base pressure increases for the presence and absence of

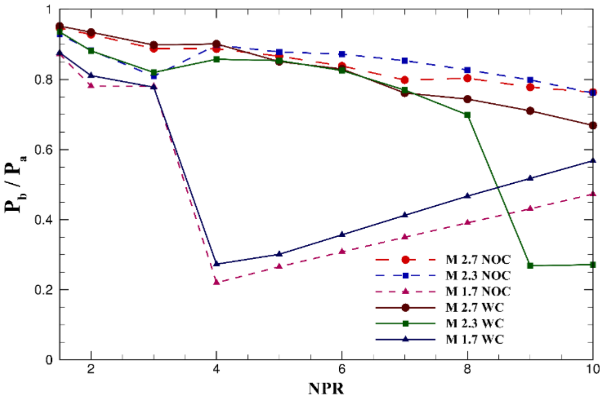
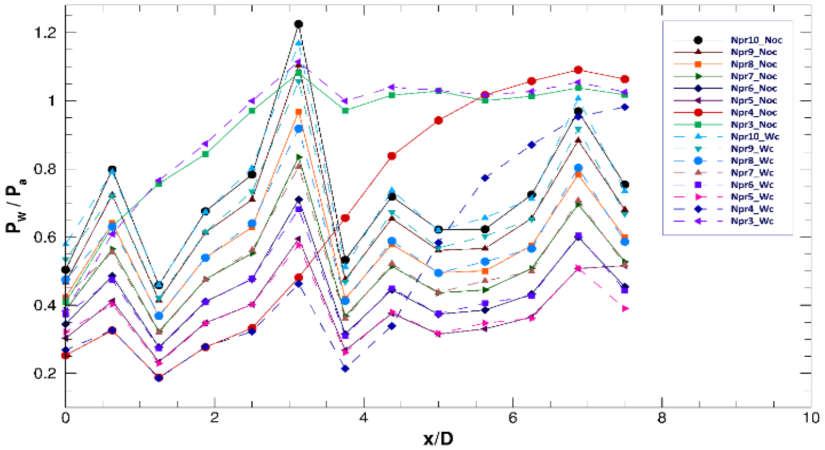
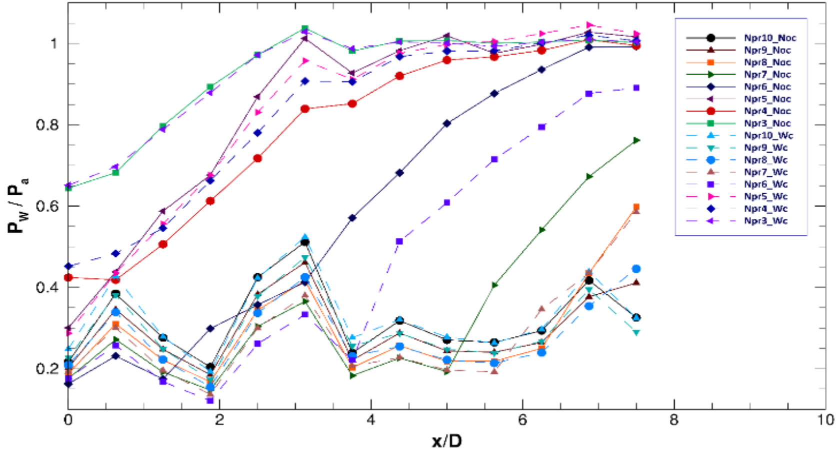


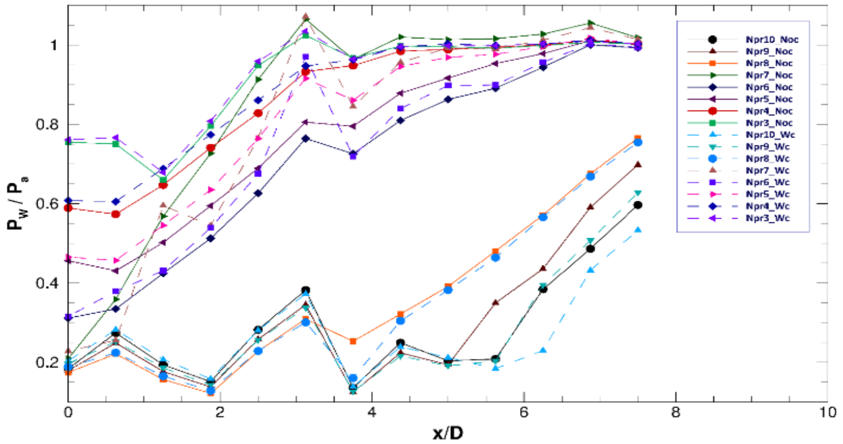
Figure 11. Variation of base pressure at L/D = 1



(a) Mach 1.7



(b) Mach 2.3



(c) Mach 2.7

Figure 12. Distribution of wall pressure for L/D = 10

the control. The flow when exiting from the nozzles at inertia level of M = 1.7, the flow seems to be attached with the duct even at L/D = 1. Whereas, for the remaining inertia levels, the minimum duct length required seems to be L/D = 2. At lower L/D the nature of the flow inside the duct is affected by the ambient pressure, affecting the efficacy of the control by the small sonic jets. While scanning the flow field inside the duct wall, the nature of the flow remains the same in the presence and the absence of the control mechanism, which is one of the significant advantages.

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Control of Nozzle Flow Using Microjets at Supersonic Mach Regime

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چکیده

این مقاله کنترل فعال جریان‌های پایه را با استفاده از روش تجربی گزارش می‌دهد. کنترل فعال فشار پایه به کاهش کشش (drag) پایه در دستگاه‌های آیرودینامیک با جریان گسترش ناگهانی کمک می‌کند. کنترل فعال در قالب میکروجت با شعاع ۰,۵ میلی‌متر و زاویه‌ی ٤۵ درجه نسبت به هم، برای کنترل فشار پایه به کار می‌رود. اعداد ماخ تحلیل حاضر ۱,۷، ۲,۳ و ۲,۷ است. نسبت طول به قطر (L / D) از ۱۰ به ۱ متغیر است و نسبت فشار نازل (NPR) از ۱ تا ۱۰ در پله‌های ۱ برای اندازه‌گیری فشار پایه تغییر می‌کند. نسبت مساحت کل تحلیل در ۲,۵٦ ثابت است. توزیع فشار دیواره در امتداد کانال بزرگ نیز ثبت شده است. عدم تغییر افزایش یا کاهش فشار پایه نیز به‌طور کامل بررسی شده است. از تحقیقات تجربی مشخص شده است که کنترل بدون ایجاد اختلال در توزیع فشار دیوار نقش مهمی در اصلاح فشار پایه دارد. تغییر فشار پایه در $L / D = 1$ ، در مقایسه با نسبت L / D بیشتر به دلیل تغییر در طول اتصال مجدد و نیاز به طول مجرای در سطوح بالای اینرسی، کاملا متفاوت است. کیفیت جریان در کانال در شرایط کنترل و عدم کنترل ثابت باقی مانده است.

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