Base Pressure Control by Supersonic Micro Jets in a Suddenly Expanded Nozzle

S. A. Khan
Department of Mechanical Engineering, Faculty of Engineering, International Islamic University, Kuala Lumpur, Malaysia. E-mail: sakhan06@gmail.com

Zakir Ilahi Chaudhary
Department of Automobile Engineering, M H S S College of Engineering, Mumbai, India.e-mail: zakirilahi1@gmail.com

Vilas B. Shinde
Department of Mechanical Engineering, Datta Meghe College of Engineering, Airoli, Navi Mumbai, India.e-mail: vbs_life@rediffmail.com

Abstract—Experimental studies were conducted in sudden expansion axi-symmetric passage for controlling base pressure and their outputs were showcased in current paper. Micro jet active control techniques are used for controlling base pressure. These controls constitute four spaces around base and symmetric to nozzle axis. Mach numbers of the abruptly expanded flows studied for base pressure range from 1.1 to 2.8 and the obtained wall pressure distribution is depicted for Mach number 1.1, 1.5, 2.1, and 2.8 respectively. In this paper the area ratio of the study was 2.56 and the L/D ratios were up to 1 from 10 respectively. Nozzles working on the concerned inertia level were performed with NPR from 3 to 11. It is found that the active controls through the micro jets are capable of regulating the pressure in the recirculation zone. In the presence of favourable pressure gradient the control becomes effective. An appreciable 65% hike in the pressure at the base was accomplished for the above discussed parameters of the current research.

Index Term—Base Pressure; Wall Pressure; Flow Control; Nozzle Pressure Ratio, Micro jets.

I. INTRODUCTION

The pressure at the blunt base is substantially low as compared to the atmospheric pressure. The flow field at the base which is very complex is one of the significant and complex problems in fluid dynamics. It is well known that at subsonic speed for incompressible flow where the wave drag is absent, the base drag due to low-pressure recirculation will be 10% per cent of the skin-friction drag but base drag at high subsonic and transonic speed (0.8 < M < 1.2) for compressible flow could be approximately 60% of the total drag and at supersonic speed (1.2 < M < 5) could be approximately 30% of the total drag. Hence, a small increase in the base pressure could lead to substantial decrease in the drag and ultimately increase in the range of the projectiles and missiles. Triggered primarily by the requirements in technological developments, numerous research investigations have been reported in literature devoted to reducing the base drag penalty employing both active as well as passive control techniques. These techniques aim at manipulation/alteration of the near wake flow field for controlling the base pressure flow field. Abruptly expanded flow field is a complicated flow with the separation of flow, formation of a low pressure re-circulation region and gets attached again with the duct wall. The point where the bifurcating flow line hits the wall is known as the reattachment location. In such a case the shear layer divides such a flow into two distinct flow regions, the first is the primary flow area and the next is the low pressure region.

Fig. 1. Flow field with sudden Expansion

Badrinarayanan [1] explored tentatively the base streams at supersonic Mach numbers. Point by point estimations in the separated stream at the blunt base for 2-D and 3-D bodies of revolutions were made at Mach two. The outcomes were very significant on the conduct of isolated streams and show the significance of stream inversion. The impact of air infusion in the base region demonstrates that the pressure in the recirculation zone increments fundamentally with the air infusion. Anderson and Williams [2] undertook research of suddenly expanded air flowing through a cylindrical duct to assess base pressure characteristics. For a connected stream the base pressure clocks least which in turn relies on the conduit to
the area of the nozzle proportion and on the geometrical variable of the nozzle and plots also depict the same.

Bar-Haim and Weihls [3] investigation was more on the method of decreasing drag on completely submerged revolving bodies using boundary layer. His research led to conclusion that this is possible for axi-symmetric bodies, which transition is slowed down and can regulate the separation at the blunt base. He used the suction to delay the flow separation as well as the transition of the boundary layer from laminar to turbulent. Computations were incorporated to express the drag in terms of the Reynolds number based on the characteristics length in the range of $10^3$ to $10^6$, resulting in the reduction of the drag force up to 78%.

Rathakrishnan and Sreekanth [4] contemplated streams in the circular duct with sudden increment in the duct step height. They inferred that the pressure at the base is a more reliable of the development area proportions, the general pressure proportions and the channel L/D ratios. Their demonstrations depict that for a fixed general pressure proportion and a given area proportion, it is conceivable to recognize an ideal L/D value of the area of sudden increase that will bring about highest exit stagnation pressure (i.e. least loss in pressure energy of the nozzle) and the pressure at the base with abruptly expanded area of the plane. Srikant and Rathakrishnan [4] built up an observational connection for base pressure as a component of the pressure at the nozzle proportion, area proportion and L/D ratio of the amplified conduit, utilizing the test information.

Rathakrishnan, Ramanaraju and Padmanaban [5] considered the impact of cavities for a Mach equal to or less than 1 with sudden expansion. The trio reasoned that the cavity will impact by the smooth flow in the circular duct on the fundamental stream field in the conduit was all around articulated for huge channels and the cavity AR had noteworthy impact on the stream field and also on the base pressure. From their outcomes it is seen that increment in AR in the range 2 to 3 brings about reduction in base pressure yet for increment in AR from 3 to 4, the pressure at base shoots up. Similarly, Pandey and Rathakrishnan studied the passive control of the base flows. In their tests they used C-D nozzle operating at Mach 1.74 with cavities.

Vishwanath [6] reassessed the management of the flow for blunt base flows along with the attachment of the after-body and its influence on drag manipulation which is the greatest challenge of the base flows and hence drag involved in it. In his review paper he conducted a thorough study about the various passive methods used for the base pressure regulation and hence the base drag reduction which is the major contributor. Being from NAL Bangalore he has access to the experimental facility which he utilized to arrive at the optimum aerodynamic shape and hence the minimum drag offered by the body of revolutions?

Exhaustive tests were conducted at different expansion level to assess the efficacy of the flow manipulator [7]. From the outcome of the test it is observed that there is significant enhancement in the pressure at the base with the dynamic flow manipulator without affecting the flow in the duct. Further, it was reckoning that the pressure at the nozzle lip dictates the flow in the presence and absence of the control mechanism.

To analyze the laminar flow in a sudden increased pipe subjected to uniform suction speed, numerical simulations has been carried out for this investigation [8]. Different finite element methods have been employed to solve the viscous effects of the flow and then the results are compared with the available results in the literature. It was concluded that the vortices generated near the step wall dwindles along the length for progressive values of blowing speed applied at the walls. Additionally, to date, separation control using micro jets had primarily been examined in canonical flows such as a modified backward facing ramp [9] and for aircraft-related applications for two dimensional (at least geometrically) airfoils [10], [11]. Khan et al. [12]–[21] did experimental examination to assess the performance of the control mechanism by the tiny jets at various level of expansion to regulate the base pressure in abruptly expanded circular ducts at moderate and high supersonic speeds. The result thus produced showed that the highest gain in the base pressure by more than 100 percent for Mach number 2.58.

Jaimon et al. [22]–[24] studied the base flows by numerical simulation as well as using the concept of process parameters and obtained good results. Their results were within the acceptable limits. V. Sethuraman and S. A. Khan [25], [26] studied the converging, and converging-diverging nozzle flow at sub-sonic, sonic, and supersonic Mach numbers . They conducted the experiments and the results were discussed.

K. A. Pathan et al. [27]–[30] carried out numerical simulations for different NPRS, fixed area ratios in the range from 2 to 8, Mach number, at fixed value of L/D = 5. Their results from the numerical simulations were in good agreement with the experimental results.

M. Asad Ullah et al. [31]–[37] experimentally investigated the passive control of the base pressure from rectangular nozzle exhausted in to the square duct of area ratio 9. In their study they used static cylinder, rotating cylinder clockwise as well as the anti-clockwise to regulate the base flow and the square duct field at Mach 2. Results indicate that the static cylinder is effective when it is placed in recirculation zone provided the jets are correctly expanded or under expanded.

S. A. Khan et al. [38] investigated supersonic flow from converging-diverging nozzle at screech prone supersonic Mach number using k-ε turbulence model for area ratio of 3.24. Simulated results were matching very well with the wind tunnel results.

A. Saleel et al. [39] experimentally investigated at the flow from C-D nozzle at low supersonic Mach numbers for different area ratios. The flow was regulated by the tiny jets. The flow control was dependent on inertia level, duct length, level of expansion, and the relief available to the flow.

The above literature uncovers that although a bulk of the study carried out on this area of research on sudden expansion, vast writings of them comprise of work study without control. In fact, of the available data on the research of base flows regulation, majority of them are limited to the passive control by means of the geometrical changes in the shape. Thus, it can be deduced that just a handful of the study are on with the active
control. Hence, more insight view at the performance of active controlled base flows, specifically at high Mach will be of immense use because of their significance in many situations of applied gas dynamics like, missiles/rockets and aerospace vehicles for diminishment of the base drag, base heating control etc. To achieve this goal, the current project examines the same with micro jets, also, effect of locations of micro jets.

II. EXPERIMENTAL SETUP AND MODEL DESIGN

High Speed Aerodynamics Laboratory (HSAL) of Mangalore Institute of Technology, Karnataka housed the tests in its experimental facility as depicted in Figure 3. It displays Nozzle exit perimeter comprises of eight holes out of which four (marked c) were used to blow and rest (marked m) were employed to estimate base pressure (Pb). Base pressure controls by the tiny jets via control holes with the help of pressure from the primary storage tank by engaging a tube joining the main storage tank with control tank and the flow regulation mechanism as the holes (c) along with pressurized taps set up along the duct wall to estimate the static wall pressure along the circular duct. With intermediate gap as 4 mm nine holes were punched initially and rest are done with a gap of 8 mm each. Mach numbers 1.25 and 1.3 are used to perform laboratory tests with NPR range as 3, 5, 7, 9, and 11 for both.

Results and Discussion

The model is designed by using solid edge as design tool. The Nozzle used in experiment is a C-D nozzle. All the ducts are designed with circular cross-section with internal diameter of 16 mm, the lengths of the ducts are from 1D to 10D.

Fig. 2. Experimental setup, Ducts, and the nozzles

The procedure for the data analysis was followed as in Ref. [17]. In this paper, the step height is 3 mm having area ratio as 2.56 and the level of expansion in the control tank is similar to that of the storage tank. The aim of this research is to study and quantify the possibility of the flow regulation where tiny jets are used as the blowing in the base area as the flow regulation mechanism for restraining the base pressure.

The non-dimensionalized base pressure function vs. Mach value at different Nozzle Pressure Ratio’s and L/D 10 to 1 respectively are presented in Figs. 3 to 10.

Essential and rooted target of this examination is to contemplate the achievability to engage smaller scale jets blow as a regulating mechanism to control base pressure. The reliance of this pressure with respect to Mach number and NPR over the values of 3 to 11 at ratio of areas as 2.56 is depicted in Figs. 3 to 6. Consequent outcomes of base pressure in the presence and absence of control are then analyzed and it is evident from those outcomes that in high speed flows the inertia level of the nozzle flow has extremely solid impact on the base pressure. Also, with increment in NPR the control evidently turns out to be more efficient in hiking the pressure at base for M = 1.87. However, for the case of higher Mach numbers the outcomes suits diminishing of base pressure in comparison with the case when control was missing were observed for Mach numbers 2.2 to 2.58 with NPR’s ranging from 5, 7, 9 and 11. A possible explanation behind this might be the impact of the shock at exit of the nozzle which curves away the spill out of the base locale, in this manner debilitating the vortex situated at the base which experiences the mass stream infused by the miniaturized scale jets. In any case, at Mach numbers 1.87, 2.2 and NPR 11 gives to the highest level of expansion of base pressure in comparison with and the without control case which can be on account of as the NPR which signifies the level of expansion; leading to weaker oblique shock at the nozzle lip noticeably than at low NPRs.

Fig. 3. Base Pressure Distribution at different NPR with and without micro jet control at L/D = 10

Along these lines the bending nature of the approaching stream diminishes that will leave the vortex practically unaffected. At this circumstance when the tiny jets are used they may proliferate with no diverting propensity, in this manner some amount of air gets entrained from the base vortex and moving it far downstream from the base, making the base pressure expect higher esteem than those for when the control was not used.
At L/D = 6 and 5, the performance efficiency of control is practically unimportant, and its increments with increment of NPR. The NPR for correct expansion at Mach 1.87 is 6.4. Hence, till NPR = 6.4 the jets are undergoing the adverse pressure gradient when the stream enters the duct. For NPR > than 6.4 ideal pressure gradient exists at the nozzle exit. For NPR < 6.4, within the sight of Pe/Pa < 1 the control adequacy is minimal. Likewise, when the NPR has been raised from 3, i.e., when the level of unfavorable pressure gradient diminishes, the performance efficiency of control boosts. For the NPRs setting up for large NPR the control turns out to be logically more viable with increment of ideal pressure gradient.

The outcome of this work for L/D ratio = 4 are depicted in Fig. 7 which exemplifies for NPR 3 the effectiveness of the control is less. For lower Mach, the base pressure takes abrupt jump, followed by gradual increment. Whereas for greater values of NPRs the control is capable of decreasing the base suction. At Mach 2.2 trend shows decline in pressure at the base corner up to NPR 9.5 and then reverses. At L/D = 4, the control leads in diminishing the base pressure at all NPRs but for NPR 3. But the trend is found only up to Mach number 2.4. There will be a pressure rise across flow over an oblique shock. However, the base vortex leads to build up a low pressure at the base locale. In this manner, the negative value of the gauge pressure due the presence of the vortex and the stream with atmospheric pressure of diagonal shock need to exist together at the base, before getting entrained and mixed up with the fundamental stream. This procedure directs the numerical value of the pressure at the base.
A significant issue related with base stream is the fluctuations happening in the duct flow field of the abrupt duct channel of the base area in the downstream. The above issue in such a duct can be comprehended by filtering the wall pressure over its length. Current examination also has a, consideration to ponder the impact of the dynamic control on the duct flow field. For understanding this wall pressure flow field for all the Mach numbers, tested were organized with and without controls.

Figures 11 to 12 present the wall pressure in the abrupt duct for AR 2.56, for some selected combination of Inertia level. The measured wall pressure has been made non-dimensional with the atmospheric pressure $P_a$ to which the flow was discharged. The axial distance of the enlarged duct from the base location $X$ has been non-dimensionalized with the duct diameter $D$. To quantify the effect of control on wall pressure distribution $P_w/P_a$ for with and without control have been compared for all the NPRs, Mach values, and L/Ds tested for a fixed Mach and the step height.

It is seen from these test results that, for $L/D = 10$ and $M = 1.1$ the control does not negatively affect the wall pressure (as in the case of Figs. 11(a) or influences the wall pressure only marginally). Further, it is seen that for NPR 3 the fluctuations in the wall pressure are at its lowest level and they are limited within 10% distance from the exit of the nozzle, whereas for all the NPRs the flow field by itself is oscillatory in nature due the effect of area ratio, this area ratio being 2.56 lowest of the study, due to small relief available to the flow there will be inherent oscillatory nature of the flow and the control has only marginal effect on the flow field. The physics behind this trend seems to be due to the combined effect of the Mach number, NPRs (level of expansion), and the L/D ratio. Major contributor for this oscillatory nature is the lowest area ratio, which will be visible when we discuss the wall pressure distribution for other Mach numbers as well as the area ratio.

Wall pressure results for Mach 1.5 are depicted in Figs. 12. It is seen from the results that, for $L/D = 10$ and $M = 1.5$ the control neither results in increase nor decrease of the wall pressure (as in the case of Figs. 12(a) and it does not influence the wall pressure adversely. There is change the wall pressure values for the highest NPR. Further, it is seen that for NPR 3 the fluctuations in the wall pressure are at minimum level and they are limited within 5% distance from the exit of the nozzle, whereas for all the NPRs the static wall pressure flow field by itself is oscillatory in nature due the area ratio being small, and hence, due to small relief available to the flow, the flow will be oscillatory in nature as the shear layer exiting from the nozzle
does not get sufficient area to expand and the control effectiveness is only marginal. The physics behind this trend seems to be due to the net effect of the Mach number, NPRs (level of expansion), and L/D ratio. Major contributor for this oscillatory nature is the area ratio which is the lowest for the present study and also the effect of inertia level being higher as compared to the previous Mach number.

Fig. 12 (b) presents the similar wall pressure results for L/D = 8 as was observed in the previous figure. Figs. 12((c) to (d)) represent the wall pressure results for L/D = 6 and 5 with the exception that due reduction in the L/D ratio there is some influence of back pressure and the peak pressure values are higher than that those were for higher L/D ratios namely (L/D = 10 and 8) respectively. Nevertheless, the flow field once again has smoothened in the duct and the wall pressure values with and without control are the same. This trend continues till L/D = 4, 3 and 2 (Figs. 12((e) to (g)), then later for lowest L/D like L/D = 1, it is evident that this duct length does not satisfy the necessary condition for the flow to stick with the wall of the duct.
Fig. 11 Wall Pressure Vs X/D
Fig. 1 presents the results for Mach 2.1. From the results it is seen that the results for higher Mach number are behaves differently. This trend seems to be due to the level of over expansion at these NPRs. In case of lower Mach numbers, the NPRs are such that favorable pressure gradient exists, and the jets were under expanded for the most of NPRs tested, which is not the case for this Mach number. For most of the NPRs tested the jets are over expanded. Under these circumstances when the jets are exiting from the nozzle into the enlarged duct the wall pressure values do not fluctuate violently as the jets are already over expanded and they attain higher wall pressure values, hence the peak values are 20% above the ambient pressure. At L/D = 10 and M = 2.1 the control results in increase of the wall pressure for NPRs 11, for the rest of the NPRs the control effectiveness is only marginal. The trend which was seen at NPR 3 at lower Mach numbers this trend continues at Mach 2.1 for NPRs from 3 to 5, the reason for this trend may be as discussed above (Figs. 13(a)).

Fig. 13 presents the results for Mach 2.1. From the results it is seen that the results for higher Mach number are behaves differently. This trend seems to be due to the level of over expansion at these NPRs. In case of lower Mach numbers, the NPRs are such that favorable pressure gradient exists, and the jets were under expanded for the most of NPRs tested, which is not the case for this Mach number. For most of the NPRs tested the jets are over expanded. Under these circumstances when the jets are exiting from the nozzle into the enlarged duct the wall pressure values do not fluctuate violently as the jets are already over expanded and they attain higher wall pressure values, hence the peak values are 20% above the ambient pressure. At L/D = 10 and M = 2.1 the control results in increase of the wall pressure for NPRs 11, for the rest of the NPRs the control effectiveness is only marginal. The trend which was seen at NPR 3 at lower Mach numbers this trend continues at Mach 2.1 for NPRs from 3 to 5, the reason for this trend may be as discussed above (Figs. 13(a)).

Fig. 13 (b) presents the similar wall pressure results for L/D = 8 as was observed in the previous figure with the exception that the wall pressure magnitude has reduced considerably due to the effect of smaller duct length. Figs. 13((c) to (d)) represent the wall pressure results for L/D = 6 and 5 with the exception that due reduction in the L/D ratio there are oscillations in the wall.
pressure due to the influence of back pressure and the peak pressure values are less than that those were for higher L/D ratios namely (L/D = 10 and 8) respectively. It is also seen that the flow field has smoothened in the duct and wall pressure values with and without control are identical. This trend continues till L/D = 4, and 2 (Figs. 13((e) to (f)), then later for lower L/Ds like L/D = 2 and 1, it is evident that this length is not sufficient for the flow to remain attached with the duct wall and it is suggested that the values for the lower L/Ds may be ignored.

(a) Mach No. = 2.1, L/D = 10

(b) Mach No. = 2.1, L/D = 8

(c) Mach No. = 2.1, L/D = 6

(d) Mach No. = 2.1, L/D = 4

(e) Mach No. = 2.1, L/D = 3

(f) Mach No. = 2.1, L/D = 2
Figs. 14 presents the results for Mach 2.8. From the results it is seen that the results at Mach 2.8 are behaving differently since the jets remained over expanded throughout for the NPRs tested. Due to the very high level of over expansion the starting values of wall pressure are very close to the atmospheric pressure. Under these circumstances when the jets are exiting from the nozzle into the enlarged duct the wall pressure values do not fluctuate violently as the jets are already over expanded and they attain higher wall pressure values at exit of the nozzle, hence the peak values are 5% above the ambient pressure as the major wall pressure recovery has taken at the initial stage itself, therefore, further jump in the wall pressure is not observed. As discussed earlier at Mach 2.1, the similar results are seen at Mach 2.8. At L/D = 10 the control results in increase of the wall pressure for NPRs 11, for the rest of the NPRs the control effectiveness is marginal. The trend which was seen at NPR 3 at lower Mach numbers this trend continues at Mach 2.8 for NPRs from 3 to 9 (Figs. 14(a)).

Fig. 14 (b) presents the identical wall pressure results for L/D = 8 as was observed in the previous figure with the exception that the wall pressure fluctuation has reduced considerably due to the effect smaller duct length. Figs. 14((c) to (d)) represent the wall pressure results for L/D = 6 and 5 with the exception that due reduction in the L/D ratio there are no oscillations in the wall pressure due to the influence of back pressure and the peak pressure values are less than that those were for higher L/D ratios namely (L/D = 10 and 8) respectively. Also, the flow field has smoothened in the duct and wall pressure values with and without micro jets are identical. This trend continues till L/D = 4 (Figs. 13((e)), then later for lower L/Ds like L/D = 3, 2, and 1, it is evident that this length is not sufficient for the flow to remain attached with the duct wall and it is suggested that these values may be ignored.
III. CONCLUSIONS:

From the tests results and the discussions above of this experimental investigation presented in the previous chapter, the following conclusions can be drawn.

• Base pressure is highly impacted by the geometrical variables like the area ratio of the passage, the L/D ratio, nozzle exit Mach number. Level of expansion at the nozzle (i.e. before sudden expansion) impacts the base pressure very strongly. In other words, it can be stated that the nozzle pressure ratio, NPR, very strongly influences the base pressure. When the tiny jets are used they were found to influence the base region, taking the base pressure to considerably higher values compared to that for the case when the control is missing, for most of the cases. However, there is certain combination of parameters for which the active control augment the base pressure negatively.

• Base pressure is found to increase with increasing Mach number in the supersonic regime.

• This study indicates that for a fixed value of the Mach number and NPR one can find the optimum length of the duct as well as the step height, which will result highest increase/decrease in the pressure at the base.

• Normally, wall pressure distribution of the ducts is fluctuating in nature, but with presence of controls, this doesn’t
impact negatively micro jets.

- In general duct L/D = 3 appeared to be the limit for base vortex strength manipulation and L/D less than 3 proved to be insufficient for the flow to get attached in most of the cases.

REFERENCES


