Studies on Wall Pressure of Sonic Flow through the Converging Nozzles for Different Area Ratios

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ABSTRACT

The experimental studies were conducted to ascertain the effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts. However, in this paper our main aim was to study the influence of the micro jets on the development of the flow field in the duct wall as well as the control effectiveness of the micro jets. As it is well known that whenever, control is used it is mandatory on the part of the researcher to make sure that the control whether; active or passive control, the control does not disturb or made oscillatory the flow field in the enlarged duct. To achieve this an active control in the form of four micro jets of 1 mm orifice diameter located at 90° intervals along a pitch circle diameter of 1.3 times the nozzle exit diameter in the base region was employed. A convergent nozzle was used and the Mach number at the nozzle exit was unity. The area ratio (ratio of area of suddenly expanded duct to nozzle exit area) studied are 2.56, 3.24, 4.84 and 6.25. The length-to-diameter (i.e. L/D) ratio of the sudden expansion duct was varied from 10 to 1. From the experimental results, it is found that the micro jets can be used as an active controller for base pressure and wall pressure flow field. Further, from the results it is found that the flow field in the suddenly expanded duct is identical for with and without control cases and to quantify the effect of micro jets on the quality of flow in the duct wall pressure was measured and it is found that the micro jets do not disturb the flow field.

Key words: Wall pressure, Sudden expansion, Mach number, Active Control, Area ratio

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INTRODUCTION

Suddenly expanded flow fields find application in many engineering problems of practical importance, such as combustors and combustion chambers, propulsion systems, parallel diffusers, and so on. The need for controlling such flow fields has motivated studies of these flows. Passive control mechanisms have always attracted researchers because they give the desired results without the need for separate mechanisms, as in the case of active control.

Base pressure at the base of high-speed jet has long been one of the important issues from both the view points of fluid dynamics as well as practical engineering applications. The base pressure characteristics of incompressible flows have been well known to date as this value is very small normally it is 10 percent of the skin friction drag. However, the base
pressure at sub-sonic, transonic, and supersonic speeds would be different due to the compressibility effects and shock waves present in the flow field. It is also well known that the base pressure at the transonic speed could be as high as 50 percent of the total drag. Hence, a small increase in base pressure will result in considerable decrease in the base drag which, in turn will result in increase in the range of missiles, shells, projectiles, and air-crafts. We if scan the literature on the total drag penalty then it is concluded that if the nose fineness ratio is in the range of between 2.5 to 4 then this will result in minimum wave drag which will be present only for transonic and supersonic flows. However, the component of skin friction drag and base drag will be present for the moving objects in the absence of wave drag. The component of the skin friction will be by default as we need a bare minimum volume of the projectiles to carry the war-heads, fuselage in case of the air-crafts, and the propulsion systems as well as the war-heads for missiles. There is vast amount of information about suddenly expanded flow problems in the literature, describing the mechanism governing the flow. Several scientists have made an attempt to deal with the problem of drag reduction techniques, various methods like base cavities, ribs, ventilated cavities at the blunt base, splitter plate at the base, boattailing, and step bodies etc. are the few of the passive means are attempted by the researchers working in the field of drag reduction techniques. No attempt has been made to use the active control. Hence, in the present paper, an attempt has been made and experiments were performed to understand the base pressure characteristics at sonic speeds. An active control in the form of Micro jets has been used at the base as a control mechanism to control the base pressure emphasis is placed on the control of the base pressure using a simple orifice. A variety of supersonic jet plumes have been explored to investigate the flow variables influencing the base pressure. The results obtained were validated with existing experimental data and discussed in terms of the base pressure and discharge coefficient of the orifice. However, since the air is being drawn from the main settling chamber, hence, the maximum value of the control pressure will be the stagnation pressure in the main settling chamber. To have a variable control pressure which more than the stagnation pressure of the main settling chamber then in that case we need to have a separate source of the energy so that we can ascertain the effectiveness of the micro jets under the variable control pressure, however, in the present study no such attempts were made. The present study is focusing attention on the flow development in the enlarged duct, effect of the control on the wall pressure distribution and as well as the control effectiveness in the form of micro jets.

LITERATURE REVIEW

One study that has direct relevance to the present study is that of Anasu and Rathakrishnan [2], who studied the flow through a convergent axisymmetric duct with annular rectangular cavities at specified intervals. They concluded that the introduction of secondary circulation by cavity reduces the oscillatory nature of the flow in the enlarged duct, thereby enabling the flow to develop smoothly from the base pressure to the atmospheric pressure at which the expanded jet was discharged. Subsequently, Rathakrishnan et al. [3] extended the study to cover the range of aspect ratios and concluded that the cavity is of considerable effect in the enlarged duct and that the effect is more pronounced for longer ducts than for shorter ducts. However, these investigations were only for sub-sonic Mach numbers. Further when passive controls in the form of a cavity are employed for flow control, there is a possibility of the cavity behaving like a closed cavity, thereby becoming ineffective as a control device. Therefore, it was felt that it may prove to be advantageous over cavities if the control is in the form of annular ribs. The idea of using projections instead of cavities as passive control. Rathakrishnan [4] used annular ribs to...
control base pressure, wherein the secondary vortices generated by the projections yield a better wall pressure distribution. They found optimum geometry of the ribs for the minimum possible base pressure, over a range of Mach numbers from low subsonic levels to sonic.

Khan and Rathakrishnan[5-9] done experimental investigation to study the effectiveness of micro jets under the influence of Over, Under, and Correct expansion to control the base pressure in suddenly expanded axi-symmetric ducts. They found that the maximum increase in base pressure is 152 percent for Mach number 2.58. Also they found that the micro jets do not adversely influence the wall pressure distribution. They showed that micro jets can serve as an effective controller raising the base suction to almost zero level for some combination for parameters. Further, it was concluded that the nozzle pressure ratio has a definite role to play in fixing the base pressure with and without control.

Jagannath et al. [10] studied the pressure loss in a suddenly expanded duct with the help of Fuzzy Logic. They observed that minimum pressure loss takes place when the length to diameter ratio is one. Further it was observed that the results given by fuzzy logic are very logical and can be used for qualitative analysis of fluid flow through nozzles in sudden expansion.

The effect of offset position of the annular rib on suddenly expanded supersonic flow studied by Rajaguru Nathan et al. [11]. The flow from Convergent- Divergent (CD) nozzle expanding into circular pipe has been investigated experimentally. They found that the position of rib was of considerable influence over the base pressure and wall pressure distribution in the enlarged duct. For each NPR, the increase in rib position increases the base pressure. With the increase in NPR, the increase in base pressure with rib position also increases. Wall pressure distribution changes tremendously with the change in rib position. The wall pressure increases upstream of rib with an increase in NPR and rib position.

An experimental investigation to study the effectiveness of micro jets to control the base pressure in a suddenly expanded axi-symmetric ducts when the micro jets are placed at different location (i.e. at the base, at the duct, and at base as well as in the duct) presented by Baig et al. [12]. The area ratio of the study was 3.24. They found, as high as 60 percent increase in base pressure was achieved for Mach number 2.58 at NPR 11.

Baig et al. [13] carried an experimental investigation to control the base pressure in a suddenly expanded axi-symmetric passage. The tests were conducted for Mach numbers 1.25, 1.3, 1.48, 1.6, 1.8, 2.0, 2.5 and 3.0. The area ratio of the study was 6.25. On the positive side the gain was 30 percent whereas on the negative side the decrease in base pressure was 40 percent.

Pandey et al. [14] have done the analysis of wall static pressure variation with a fuzzy logic approach to have smooth flow in the duct. Three area ratios chosen for the enlarged duct were 2.89, 6.00 and 10.00. The primary pressure ratio was taken as 2.65 and the cavity aspect ratio was taken as 1 and 2. The study was analyzed for length to diameter ratio of 1, 2, 4 and 6. The nozzles used were de Laval type and with a Mach number of 1.74 and 2.23. The analysis based on fuzzy logic theory indicates that the length to diameter ratio of 1 was sufficient for smooth flow development if only the basis of wall static pressure variations was considered. The effectiveness of micro jets to control the base pressure in suddenly expanded axi-symmetric ducts is studied experimentally by Syed Ashfaq et al. [15] for flow through the nozzle at sonic Mach number. From the experimental results, it was found that the micro jets can serve as active controllers for base pressure. From the wall pressure distribution in the duct it was found that the micro jets do not disturb the flow field in the duct.

**EXPERIMENTAL METHOD**

Figure 1 shows the experimental setup used for the present study. At the exit
periphery of the nozzle there are eight holes as shown in figure, four of which are (marked c) were used for blowing and the remaining four (marked m) were used for base pressure ($P_b$) measurement. Control of base pressure was achieved by blowing through the control holes (c), using pressure from a settling chamber by employing a tube connecting the settling chamber, and, the control holes (c). Wall pressure taps were provided on the duct to measure wall pressure distribution. First nine holes were made at an interval of 3 mm each and remaining was made at an interval 5 mm each.

From literature it is found that, the typical L/D (as shown in Fig. 1) Resulting in $P_b$ maximum is usually from 3 to 5 without controls. Since active controls are used in the present study, L/D ratios up to 10 have been employed.

The experimental setup of the present study consisted of an axi-symmetric nozzle followed by a concentric axi-symmetric duct of larger cross-sectional area. The exit diameter of the nozzle was kept constant 10 mm and the area ratio of the model was 2.56, 3.24, 4.84, and 6.25 defined, as the ratio of the cross-sectional area of the enlarged duct to that of the nozzle exit, was achieved by changing the diameter of the enlarged duct. The suddenly expanded ducts were fabricated out of brass pipe. Model length was ten times the inlet diameter so that the duct has a maximum of $L/D = 10$. The lower L/Ds were achieved by cutting the length after testing a particular L/D value.

RESULTS AND DISCUSSION

The measured data consists of base pressure ($P_b$); wall static pressure ($P_w$) along the duct and the nozzle pressure ratio (NPR) defined as the ratio of the ratio of stagnation pressure ($P_0$) to the back pressure ($P_{atm}$). All the measured pressures will be non-dimensionalized by dividing them with the ambient pressure (i.e. the back pressure). In the present study the blow pressure will be the same as the NPR of the respective run since we intend to draw the air from the main settling chamber. The measured wall pressure has been made non-dimensional with the atmospheric pressure $P_{atm}$ 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 length $L$.

One of the common problems encountered in suddenly expanded flow field is that the pressure field in the enlarged duct becomes oscillatory because of the “Ejector Pump” action (Wicks [1]) at the base region i.e. the vortices are getting formed at the base because of expansion of the shear layer from the nozzle and getting ejected to the main flow continuously. This action was referred to as the “Jet Pump action” by Wicks [1]. This action renders the flow in the duct to become oscillatory. These oscillations are reflected as variation...
in the wall pressure distribution of the enlarged duct. Therefore, it becomes mandatory on the part of a researcher working on sudden expansion problems to monitor wall pressure distributions in the enlarged duct. In other words when we employ a control, to modify the base pressure level, there is a possibility that the control might augment the oscillatory nature of the flow field in the enlarged duct. To account for this undesirable effect (aggravating the oscillatory nature of the flow field) wall pressure distribution in the enlarged duct was measured for all combination of parameters of the present investigation. To quantify the effect of control on wall pressure distribution $P_w/P_a$ for the two cases, namely with and without control have been compared.

Figures 2(a) to (h) present the wall pressure distribution in the enlarged duct for area ratio 2.56, for $L/D$ 10 to 1. It is seen from these results that there is some influence on the wall pressure field in the base region and the wall pressure values with and without control remains the same and this oscillatory nature starts in the vicinity of the base region extending up to $x/L = 0.4$ (Fig. 2(a)). This condition falls under the category of correctly expanded case therefore, the shear layer which is expanding freely from the nozzle is strongly influenced by the waves standing at the nozzle exit. Therefore, flow coming out of the nozzle will have a tendency to deflect towards the shock. Under such circumstances, if micro jets are activated the entrainment of the micro jets is bound to carry some mass from the surrounding.

Fig. 2(b) presents wall pressure distribution results for $L/D = 8$. Here again the wall pressure is highly oscillatory within a reattachment length which starts from the leading edge and continue up to $x/L = 0.35$. It is well known that the reattachment length will depend on area ratio, and area ratio 2.56 is the lowest value of area ratio studied in the present case. The reason for this oscillatory nature of the flow may be due to the short reattachment length, where as the inertia level remains the same, and the duct length is getting reduced. For $L/D$s in the range 10 to 8, the influence of the back pressure will be the minimum.

Fig. 2(c) to (d) presents the wall pressure results for $L/D = 6$ and 5. The wall pressure behavior in these figures is different from the previous figures. At $x/L = 0.4$ there is jump in the wall pressure and later in the downstream the wall pressure recovery is smooth, it is also seen that the flow field with and without control remains the same. Results for $L/D = 4$ are shown in Fig. 2(e), from the figure it is seen that the magnitude of wall pressure for the initial pressure taps is constant, the oscillations and sudden jumps which were seen for the higher $L/D$s are no more present here, however, a small jump is seen at the end of the reattachment point and later in the downstream of the duct flow is developed smoothly.

Similar results are seen in Fig. 2(f) for $L/D = 3$, the only difference in the results between $L/D = 4$ and that of for $L/D = 3$, is that initial wall pressure value has increased by around 10 percent and the main reason for this increase is the influence of back pressure due to the short length of the duct. Wall pressure results for $L/D = 2$ are shown in Fig. 2(g), from the result it is seen that there is a jump in the initial value by 25 percent which implies that for short duct the flow is exposed to atmospheric pressure which is not only effecting the flow development in the duct but the flow at the base is getting affected. For $L/D = 1$, the results are shown in Fig. 2(h) these results clearly indicate that this length of the duct is not sufficient and the flow is detached and exposed to atmosphere.

Results for area ratio 3.24 are presented in Fig. 3(a) to (h). For this area ratio the relief enjoyed by the flow is slightly more than what it was for area ratio 2.56. Hence, the level of expansion causing the formation of shock or expansion fan at the nozzle lip will have a strong effect on the base pressure as well as wall pressure and its control effectiveness. Fig. 3(a) to (h) show the similar results as we have seen for area ratio 2.56 for $L/D$s in the range of 10 and 8 with minor variation in the oscillations. This is because when the free shearlayer
expanding into the suddenly expanded passage finds additional relief, it reattaches downstream of the reattachment point as compared for lower area ratios. This increase in reattachment length helps in modifying the flow field in the base region in turn able to suppress the oscillations which were there for lower area ratio. Figs. 3(c) to (d) presents results for L/D = 6 and 5. It is seen that the trend is almost identical to that of Fig. 2(c) and (d) with the exception that the magnitude of wall pressure is more compared to that of for area ratio 2.56, for area ratio 2.56 the reattachment length will be small as compared to the area ratio 3.24 this will lead to the formation of a powerful vortex at the base causing slightly high base/wall pressure since the level of inertia is the same. Figs. 3(e) to (f) show the results for L/D = 4 and 3, here again we see the similar results as that of for area ratio 2.56 with initial increase in the value of the base/wall pressure since for the initial taps which are within the base region, hence, wall pressure as well as the base pressure are the same. For L/D = 2 and 1, the results are shown in (Fig. 3(g) to (h)). From the figure it is seen that for L/D = 2 (Fig. 3(g)) the wall pressure assumes very high value and control results in increase of base/wall pressure, hence, due to increase in wall pressure will result in increase in the noise level as observe by Anderson and Williams. The physical reason for this may be the influence of the shock at nozzle exit which turns the flow away from the base region, thereby weakening the vortex positioned at the base. This results in increase of wall pressure since the weakened vortex at the base encounters the mass flow injected by the micro jets will result in higher value of wall pressure.

Further, the wall duct length L/D = 1 seems to be insufficient for the flow to be attached with the duct wall.

The wall pressure variation with the duct length for area ratio 4.84 are presented in Figs. 4(a) to (h) for L/D = 10, 8, 6, 5, 4, 3, 2 and 1, respectively. Figs. 4(a) to (b) present the results for L/D = 10 & 8. If we compare these results with those for area ratio 3.24, it is found that due to the increase in the area ratio there is an increase in the wall pressure of around 23 percent, also, it is seen that the oscillations in the base region are suppressed. The reasons for this behaviour may that for this area ratio the relief enjoyed by the suddenly expanded flow is much more than what it was for area ratio 3.24. Hence, the same level of expansion causing the formation of shock or expansion fan at the nozzle lip will have a strong effect on the wall pressure as well as its control effectiveness. These results imply that the flow field becomes sensitive to the relief effect at the expanded plane. However, it should be realized that increase of area ratio beyond some limiting value will not ensure the effects mentioned above for suddenly expanded flows both in subsonic and supersonic flows. The flow will tend towards free jet nature and under such circumstances the base suction enjoyed in sudden expansion will not be present. Similar results are seen in Figs. 4(c) to (d) for L/D ratios 6 and 5. Here, again there is about 23 percent increase in initial value of the wall pressure as compared to the area ratio 3.24. Fig 4(e) presents the results for L/D = 4, from the figure it is seen that there is increase in the oscillations in the flow as compared to the results for same L/D for lower area ratios. The reasons for this behavior may be due to the increase in relief to the flow, increased reattachment length, and influence from the back pressure. Fig. 4(f) presents the results for L/D = 3, the trend is same as that of for lower area ratios and there is increase in the value of wall pressure as compared to the previous cases for the same L/D ratio.

The results for the highest area ratio of the present investigation namely, 6.25 are presented here. Figs. 5(a) to (h) present the wall pressure variation as function of non-dimensional duct length, and NPR for different L/D ratios of the present study. For this area ratio the relief enjoyed by the suddenly expanded flow is much more than what it was for area ratio 4.84. Hence, the level of expansion causing the formation of shock or expansion fan at the nozzle lip will have a strong effect on the base/wall pressure as well as its control
effectiveness. This is because when the free shear layer expanding into the suddenly expanded passage finds sufficient relief, it re-attaches downstream of the reattachment point for lower area ratios. This increase in reattachment length helps the formation of a powerful vortex at the base causing high base/wall pressure. But for lower area ratio as well as for L/D = 10 & 8 they are unable to have that much effect on the base region due to the short height of the backward facing step, since, the inertia remains the same, leading to same strength of the shock wave at the nozzle exit. With, further, increase of area ratio causing the flow to deflect towards the shock wave. This causes hindrance to the formation of a strong vortex at the base. Because of this the base pressure shoots up with increase of area ratio & for higher L/Ds namely L/D = 10 & 8. Also, the control becomes ineffectivesince the shock strength dominates the flow process.

Results for L/D = 10 & 8 are shown in Figs. 5(a) to (b). In Fig. 5(a) for L/D = 10 it is seen that the initial value of the wall pressure is quite high as compared to that of the lower area ratios, and nearly 33 percent increase in the wall pressure is achieved and this increase is because of the increase in the area ratio from 2.56 to 6.25. It is also observed for both the L/Ds namely L/D = 10 & 8 that within the 20 percent of the duct length the flow field is oscillatory in nature, this may be due to the suction which was created by the vortex at the base as well as due to the range of L/D ratio and reattachment length. Results for L/D = 6 and 5 are shown in Figs. 5(c) to (d), respectively, they, also exhibit the similar trends as it was seen for lower area ratios, however, the starting value is increased by 34 percent with that of for the lowest area ratio, but this increase in initial value is only 7 percent when compared with the area ratio 4.84. Similar results are seen in Figs. 5(e) & (f) with slight increase in the initial value of the wall pressure. The results for L/D = 2 & 1 are shown in Figs. 5(g) and (h), as expected they do not show any trend, they indicate that the duct length is insufficient and the jet behaves almost like a free jet and the base vortex present is unable to reflect in any change in the flow field. Hence, these results imply that the flow field becomes sensitive to the relief effect at the expanded plane. However, it should be realized that increase of area ratio beyond some limiting value will not ensure the effects mentioned above for suddenly expanded flows both in subsonic and supersonic flows. This limit may for area ratio more than 6 and above. The flow will tend towards free jet nature and under such circumstances the base suction enjoyed in sudden expansion will not be present.

CONCLUSION

From the above discussion the following conclusions can be drawn:

- The relief and L/D combination results in control effectiveness at various NPRs taking the base/wall pressure above or below the value of the with and without control case. This simply implies that level of base/wall pressure is sensitive to the combination of parameters under study. If the base suction enhancement is desired then area ratio in the range 2.0 to 3.5 and L/D 10 to 4 seem to be the choice and if high value of base/wall pressure is required to achieve then the area ratio in the range 4 to 6 and the L/D ratio in the range 5 to 4 is the choice.
- When relief effect due to increase of area ratio is beyond some limit, the flow from the nozzle discharged into the enlarged duct tend to attach with reattachment length other than the optimum for astrong vortex at the base. This process makes the NPR effect on base/wall pressure to become
insignificant. However, NPR in the range 3 to 7 still will have some influence on the base/wall pressure and also the control will be considerably effective.

- Furthermore, the Mach number and NPR at which the base/wall pressure starts increasing or decreasing will depend on increase or decrease of area ratio. This is so because as the area ratio goes up the flow which is expanding from the nozzle finds sufficient space to relax and propagate downstream without encountering the flow at the base region and the enlarged duct wall. When L/D is beyond some limiting value the relaxing flow re-attaches with the duct and a boundary layer grows downstream of the reattachment point. For area ratio 6.25 this limiting value appears to be around L/D = 3.

- These results once again emphasize that the control effectiveness is casesensitive and one has to identify the proper combination of NPR, area ratio,
Fig. 2: Wall Pressure Distribution for Area Ratio 2.56

(g) NPR = 1.89, M = 1.0, L/D = 2

(h) NPR = 1.89, M = 1.0, L/D = 1

(a) NPR = 1.89, M = 1.0, L/D = 10

(b) NPR = 1.89, M = 1.0, L/D = 8

(c) NPR = 1.89, M = 1.0, L/D = 6

(d) NPR = 1.89, M = 1.0, L/D = 5

(e) NPR = 1.89, M = 1.0, L/D = 4

(f) NPR = 1.89, M = 1.0, L/D = 3
Fig. 3: Wall Pressure Distribution for Area Ratio 3.24

(a) NPR = 1.89, M = 1.0, L/D = 10

(b) NPR = 1.89, M = 1.0, L/D = 8

(c) NPR = 1.89, M = 1.0, L/D = 6

(d) NPR = 1.89, M = 1.0, L/D = 5

(e) NPR = 1.89, M = 1.0, L/D = 2
Fig. 4: Wall Pressure Distribution for Area Ratio 4.84

(a) NPR = 1.89, M = 1.0, L/D = 10

(b) NPR = 1.89, M = 1.0, L/D = 8

(c) NPR = 1.89, M = 1.0, L/D = 6

(d) NPR = 1.89, M = 1.0, L/D = 4
Fig. 5: Wall Pressure Distribution for Area Ratio 6.25 and L/D ratio for a given Mach number to achieve the desired controller effect. 

- From the results it is found that the control in the form of micro jets do not disturb the flow field or make oscillatory. It is also seen that for the lower L/D ratio namely 2.56 and 3.24 the L/D = 1 and 2 are sufficient for the flow to be attached with wall duct and due to the influence of the back pressure there is much variation in the values of the wall pressure. However, for higher L/D ratios namely L/D = 8 and 10 up to 30 percent increase in the wall pressure value for the initial length of the duct and the flow is oscillatory.

All the non-dimensional wall pressure presented in this paper are within an uncertainty band of ±2.6 per cent. Further, all the results are repeatable within ±3 per cent.

REFERENCES


