Experimental Studies on Low Speed Converging Nozzle Flow with Sudden Expansion

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Abstract—This paper presents the results of experimental studies conducted to study the base pressure field from a convergent nozzle to ascertain the effect of micro jets, the length to diameter ratio, Mach number and area ratio in a suddenly expanded flow. The Mach numbers of the present study are 0.2, 0.4, 0.6, 0.8 and 0.9, respectively. From the results it is found that the micro jets are effective. 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 L/D ratio of the sudden expansion duct varies from 10 to 1, and tests were conducted for L/D 10, 8, 6, 5, 4, 3, 2 and 1. To study the quality of flow in the enlarged duct wall pressure was measured and it is found that the flow field remains undisturbed in the presence of micro jets.

Keywords—Micro jets, Base pressure, Wall Pressure, Mach number, Sudden expansion.

I. INTRODUCTION

For a body having a blunt base, the major part of the total drag usually consists of base drag, which originates, because the pressure acting on the base of the body is substantially lower than the atmospheric pressure. Due to the importance of the problem connected with fluid dynamic drag, a vast number of investigations, both theoretical and experimental, considering base pressure and base drag have been performed. The rapid growth of interest in supersonic drag problems associated with the development of supersonic aircraft, projectiles, missiles, and spacecrafts.

The problem of sudden expansion of external compressible flow over the rear of projectiles and its relationship with the base pressure, since the base drag, which is a considerable portion of the total drag is dictated by the sub-atmospheric pressure at the base. The experimental study of an internal flow apparatus has a number of distinct advantages over usual ballistics test procedures. Huge volume of air supply is required for tunnels with test-section large enough so that wall interference, etc., will not disturb flow over the model. ‘Stings’ and other support mechanism required for external flow tests are also eliminated in the internal flows.

II. LITERATURE SURVEY

According to Hoerner [1] the boundary layer was an insulating layer that reduces the effectiveness of the jet as a pump. The base corner was thought of as a sump with two supplies of mass. The first was the boundary layer flow around the corner and the second source was the back flow in the boundary layer along the wall of expanded section. This back flow occurred because of the pressure difference across the shock wave originating where the jet strikes the wall. He concluded that the mechanism of internal and external flow was principally the same and base pressure phenomenon in external flow could be studied relatively easily by experiments with internal flow. Badrinarayanan [2] investigated experimentally the base flows at supersonic speeds. Detailed measurements in the wake flow behind blunt based two-dimensional and three-dimensional bodies were made at M = 2. The results throw some light on the behaviour of separated flows and indicate the importance of flow reversal. The effect of air injection at the base shows that the base pressure increases significantly with air injection. Mueller et al. [3] studied analytically the influence of initial flow direction on the turbulent base pressure in supersonic axisymmetric flow.
Howe [4] studied the influence of mean shear on unsteady aperture flow, with application to acoustical diffraction and self-sustained cavity oscillations. He used linearized theory of unsteady flow through a two-dimensional aperture in a thin plate in the presence of a grazing mean flow on one side of the plate. The mean shear layer was modeled by a vortex sheet, and it was predicted that at low mean-flow Mach numbers there is a transfer of energy from the mean flow to the disturbed motion of the vortex sheet provided (i) the Kutta condition is imposed at the leading edge, and (ii) the width of the aperture 2s satisfies 1/2 < 2s/λ < 1.1, where λ is the hydrodynamic wavelength of the disturbance on the vortex sheet within the aperture. The theory was used to examine the effect of mean shear on the diffraction of sound by a perforated screen, and to predict the spontaneous ex-citation and suppression of self-sustained oscillations in a wall-cavity beneath a nominally steady mean flow. Bar-Haim and Weih [5] studied boundary-layer control as a means of reducing drag on fully submerged bodies of revolution. He concluded that the drag of axisymmetric bodies can be reduced by boundary-layer suction, which delays transition and can control separation. The boundary-layer transition was delayed by applying a distributed suction technique. Optimization calculations were performed to define the minimal drag bodies at Reynolds numbers of 10^7 and 10^8. The reduction in drag relative to optimal bodies with non-controlled boundary-layer was 18 and 78 per cent, at Reynolds numbers of 10^7 and 10^8.

Tanner [6] studied the influence of base cavity at angles of incidence on the base pressure. He concluded that a base cavity could increase the base pressure and thus decrease the base drag in axisymmetric flow. He varied the angle of incidence from 0 to 25°. At α = 2°, he found the maximum drag reduction. Rathakrishnan [7] studied the effect of splitter plate on bluff body drag. It was concluded from his experimental results that, for a plate at the center, a backward plate results in a significant increase of base pressure when compared to a forward plate, for all l/h tested. This is because the backward splitter plate divides the wake into two parts, thereby preventing the formation of strong vortices at the base and resulting in a significant increase of the base pressure. For the splitter plate at the symmetrical plane where there exists a critical l/h beyond which the effect of l/h on base pressure co-efficient is irrelevant. For Reynolds number 0.98 x 10^7 the critical l/h is about 1.0. Further, Reynolds number 0.58 x 10^7 the forward splitter plate located at h/4 from the top is more effective in increasing the base pressure when compared to other locations.

Also, the plate located at the rear h/4 also results in a significant increase in base pressure compared to the plated position at forward center though this increase is much smaller compared to that of the forward position at h/4. Hence, l/h > 1 is also effective in reducing base suction, even though the effect is very small compared to that for l/h < 1.

Khan and Rathakrishnan [8] 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 axisymmetric 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. The effectiveness of micro jets to control the base pressure in suddenly expanded axisymmetric ducts is studied experimentally by Syed Ashfaq et al. [9] 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 found that the micro jets do not disturb the flow field in the enlarged duct.

III. 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 1, four of which are (marked c) were used for blowing and the remaining four (marked m) were used for base pressure (Pb) 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 main settling chamber with the control 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 figure 1) resulting in Pb 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 (i.e. 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 L/D = 10. The lower L/Ds were achieved by cutting the length after testing a particular L/D.

PSI model 9010 pressure transducer was used for measuring pressure at the base, the stagnation pressure in the main settling chamber and the pressure in the control chamber. It has 16 channels and pressure range is 0-300 psi. It averages 250 samples per second and displays the reading. The software provided by the manufacturer was used to interface the transducer with the computer. The user-friendly menu driven software acquires data and shows the pressure readings from all the 16 channels simultaneously in a window type display on the computer screen. The software can be used to choose the units of pressure from a list of available units, perform a re-zero/full calibration, etc. The transducer also has a facility to choose the number of samples to be averaged, by means of dipswitch settings. It could be operated in temperatures ranging from -20° to +60° Celsius and 95 per cent humidity.

IV. RESULTS AND DISCUSSION

All The measured data consists of base pressure (P\textsubscript{b}); wall static pressure (P\textsubscript{w}) along the duct and the nozzle pressure ratio (NPR) defined as the ratio of stagnation pressure (P\textsubscript{0}) to the back pressure (P\textsubscript{atm}). The measured base pressures have been made non-dimensional by dividing them by the pressure of the atmosphere to which the flow from the enlarged duct was discharged.

The parameters considered in the present study are the area ratio, L/D ratio, and the jet Mach number.

We need to keep in our mind before we go further in details to discuss the results of the present investigation. The Mach number range of the present study is for subsonic Mach numbers to a maximum value of the Mach number is 0.9 with correct expansion. Even though we have conducted the tests for correct and under expanded cases. It is also to be noted that in general the assumptions, feeling, and perception of the researchers working in the field of compressible and high speed jets that jets for correctly expanded cases for the Mach numbers in the range of low subsonic, sonic, and supersonic Mach numbers will be free from the waves, since they are correctly expanded (i.e. ideally expanded case in which the flow is isentropic) but this concepts has been proved wrong. It has been proved that the waves are present in the flow for the correctly expanded case too. Keeping this information in mind we need to analyze the present results. The base pressure results for subsonic jets with Mach number 0.2, 0.4, 0.6, 0.8, and 0.9, suddenly expanded into the ducts of ratio 2.56, 3.24, 4.84, and 6.25 are shown in Figs. 2 to 6.

Fig. 2 presents the base pressure results for Mach number 0.2 for all the four area ratios of the present investigation. It is seen that Mach 0.2 jet does not generate any suction at the base. The physical reasons for this trend are as follows. For a given Mach number the nozzle pressure ratio (NPR) which dictates the level of expansion has a strong role to play on the value of the base pressure. Also, it is seen that with increase of Mach numbers results in decreasing the base pressure for all area ratio. From Fig. 2 it is difficult to draw any conclusions from these results due to the flow being incompressible and having very low level of inertia.
The results for Mach = 0.4 are shown in Fig. 3, it is seen that the base pressure assumes very high value and decreases with L/D up to L/D = 5 or 6 and then it becomes independent of L/D ratio, which defines the minimum duct length required for the flow to be attached with the duct wall. At Mach = 0.4, the flow has become compressible and here also base pressure becomes independent of L/D for L/D = 6 and above.

Fig. 4 presents the base pressure results for Mach 0.6. It is seen that with the increase in the Mach number there is a significant decrease in the value of the base pressure, because at higher value of inertia the base vortex sitting at the base will be able to create suction at the base. It is also seen that with further increase in the area ratio, the base pressure assumes higher values due to the increase in area ratio, this increased area ratio will lead to increased re-attachment length which ultimately will lead to high value of base pressure.

Base pressure results for Mach 0.8 are shown in Fig. 5. It is evident due to the increased Mach number, the inertia will be more, and strength of the vortex also will be more. In view of the above conditions the base pressure further assumes low value compared to previous cases. However, minimum duct length requirement still remains between L/D = 5 to 6 as discussed above.

The results for highest value of Mach 0.9 are shown in Fig. 6. It is seen that due to the highest value of inertia the base pressure assumes very low value as compared to the previous results for lower Mach numbers. Also, it is seen that for larger area ratio namely 4.84 and 6.25 at L/D = 4 there is a sudden drop in the base pressure value. This sudden decrease may be due to the influence of the back pressure.
It can be visualized that, if there is a shock at the nozzle exit the shear layer coming out of the nozzle will be deflected towards the nozzle centre line by the shock. This will delay the reattachment and will result in a larger reattachment length compared to a case without shock. It is well known that the reattachment length is a parameter strongly influencing the base vortex, the increase or decrease of reattachment length will modify the value of the base pressure.

It is to be noted that in addition to influence of wave at the nozzle lip, the relief effect due to increase of area ratio also will influence the base pressure. Furthermore, it should be kept in mind that for area ratio 2.56, the micro jets at the base were located at mid pitch circle diameter (pcd) of the base, whereas for area ratio 3.24 (and also for area ratios 4.84 and 6.25) the micro-jets are closer to the nozzle exit (not at the middle of the base). This is because pcd for micro jets was kept constant for all the area ratios.

It should be emphasized here that, L/D range from 3 to 6 has been found to be optimum resulting in minimum base pressure for without control in the subsonic and transonic Mach number regime in the literature [10].

From the above discussions, it is evident that in addition to area ratio and NPR, the inertia at the nozzle exit (i.e. Mach number) has a very strong influence on the base pressure.

Since the Mach number is incompressible as well as low, it indicates the effect of area ratio is marginal. From Fig. 8 it is seen that there is a progressive increase in the base pressure value with area ratio for all L/D ratios.

Results for Mach 0.4 are shown in Figs. 9 to 11. Fig. 9 presents base pressure results for Mach 0.4 and L/D = 1, 2, 3, and 4. It is seen that for the entire area ratio the base pressure increases with area ratio. Fig. 10 presents results for L/D = 5 and 6. The base pressure value for L/D = 5 is higher compared to L/D 6 then trend is reversed from area ratio 4.84 onwards. This may be due to the combined effect of L/D ratio, area ratio, and reattachment length. Similar results are seen in Figs. 12 to 14 for Mach 0.6. For Mach 0.8 the base pressure variation with area ratio is shown in Figs. 15 to 17. From Fig. 15 it is seen that for Mach 0.8 due to increase in the inertia the suction has increased and as expected the base pressure increases with area ratio.

Figs. 7 to 20 presents the base pressure results as a function of area ratio for all the L/D ratios and the Mach numbers discussed in this paper. For Mach 0.2 the results are shown in Figs. 7 and 8.
Figure 10: Base pressure variation with area ratio $A_2/A_1$

Figure 11: Base pressure variation with area ratio $A_2/A_1$

Figure 12: Base pressure variation with area ratio $A_2/A_1$

Figure 13: Base pressure variation with area ratio $A_2/A_1$

Figure 14: Base pressure variation with area ratio $A_2/A_1$

Figure 15: Base pressure variation with area ratio $A_2/A_1$
Similar results are seen in Fig. 16 for L/D = 5 & 6. Fig. 17 presents the results for L/D 8 & 10. From the figure it is seen that the trend is different compared to the results discussed earlier. This increase and decrease and the reversal in the trend may be due to the effect of Mach number, L/D ratio, area ratio, variations in the reattachment length, and due to the influence of the back pressure.

Base pressure results as a function of area ratio are shown in Figs. 18 to 20 for Mach 0.9. Fig. 18 presents results for L/D = 1, 2, 3, and 4. Here once again the results are on the similar lines as discussed earlier with increase in the Mach number the nature becomes wavy. This behavior may be due to the presence of the waves at the nozzle lip, interaction with the free shear layer as Mach 0.9 comes in the transonic zone. Fig. 19 presents the results for L/D = 5 & 6. The L/D ratio effect is visible for lower area ratio, whereas, for higher area ratio the variation is only marginal. Fig. 20 presents the results for L/D = 8 & 10. At L/D = 8 the base pressure are higher than those at L/D = 10 and then trend is getting reversed at area ratios 4 & 6.

These results are expected due the Mach number being in the transonic zone. From all these figures it is evident that the trend remains the same however; there is progressive reduction in the magnitude of base pressure.
It is found that this Variation in base pressure value is because of increase in Mach number and the area ratio. Wall pressure distribution for area ratio 2.56 for Mach 0.9 and L/D Ratio 10, 8, 6, 5 and 4 is shown in Figs. 21 to 25.

Fig. 21 presents the wall pressure distribution for L/D = 10. It is seen from the figure that initially the wall pressure is fluctuating however, the flow field with and without control does not get augmented. These fluctuations may be due to the presence of waves, interaction of the vortex with the base flow, interaction of the shear layer and with the dividing stream lines. All the activities are taking place within the base region which happens to be within the reattachment length.

Fig. 22 presents the wall pressure results for L/D = 8. The trend is similar as discussed earlier for Fig. 21 with the exception that for this case nature of the curve is more oscillatory. However, once the flow has crossed the reattachment length the recovery of the wall pressure is very fast.

Wall pressure results for L/D = 6 & 5 are shown in Figs. 23 and 24.

In both the figures the trend is the same, the reattachment length ends at 40 per cent from the upstream of the duct and beyond the reattachment point which is also a saddle point, the wall pressure recovery is quick and smooth.
Wall pressure results for L/D = 4 is shown in Fig. 25. It is seen from the figure that there are no fluctuation in the wall pressure field; however, the reattachment length is still around 40 per cent from the leading edge of the enlarged duct.

From the above discussion it is observed that the control has got no adverse effect on the enlarged duct wall pressure field. With this it can be taken that the micro jets can serve as base pressure controller without imposing any adverse effect in the pressure field in the enlarged duct.

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

REFERENCES