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Effectiveness of Micro-Jets at Different Level of Expansion

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Abstract: *An experimental investigation was conducted to study the effectiveness of micro jets to control base pressure in suddenly expanded axi-symmetric duct. Since active control is used to control the base pressure and hence the base drag the air is drawn from the main settling chamber to the control chamber to control the base pressure, hence it doesn't require additional source of energy for the control mechanism. The flow parameters considered in this investigation are the Mach number (1.2, 1.3, 1.5, 1.9, 2.2, 2.6, and 3.0) at the exit of the nozzle, and the ratio of the pressure in the main settling chamber to the ambient pressure (NPR). The geometrical parameters considered are the area ratio between the sudden expansion duct cross-section and the nozzle exit area, and the duct length-to-diameter ratio (10 to 1). The area ratio considered was 3.24. The experiments were done for NPRs in the range from 3 to 11 in a step of 2 for all the Mach numbers. The wall pressure distribution in the suddenly expanded duct was also measured and it is seen from the static wall that the control does not affect the wall static pressure adversely. When the micro jets were activated they were found to influence the base region, taking the base pressure to considerably higher values compared to that for without control, for most of the cases. However, there are certain combinations of parameters for which the active control results in decrease of base pressure.*
Keywords: *Axi-symmetric Duct, Base Pressure, Micro-jets , Mach Number, Nozzle Pressure Ratio (NPR)*

I. Introduction

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 spacecraft was one reason for the fact that the theory made greater advances at high Mach numbers than at low speeds and that more experiments were performed in this velocity range to verify the theoretical results.

Because of its vide applicability, suddenly expanded flows have studied extensively. Many researchers attempted to control the base pressure with passive means and some of the works relevant to the present study are reviewed in the section to follow. Therefore, in the present study an attempt is made to investigate the effect of level of expansion, Mach number, Nozzle Pressure Ratio (NPR), L/D ratio and area ratio on base pressure with and without control in the form of micro jets.

Flow field of sudden expansion is very complex which is characterized by the separation of the flow at the base, flow re-circulation at the base and the reattachment in the downstream of the enlarged duct. A shear layer which is exiting from the nozzle may be divided into two main regions, one is being the flow recirculation region at the base of the duct and the other is the main flow region as shown in (Fig. 1).

II. Literature Review

Nusselt [1929] appears to be one of the first to study experiments with high speed flow through ducts with abrupt increase in area. From his more extensive experiments with sonic and supersonic flow he concluded that the base pressure will be equal to the inlet pressure if the entrance velocity is subsonic but if the entrance flow is supersonic, the pressure could be equal to, lower than, or more than the entry pressure. If the entrance Mach number is unity, no area of the jet will be affected by the expansion waves from the opposite corner.

Wicks [1953] studied experimentally the effect of boundary layer on flow through sudden expansion at critical Mach number. From their studies they found that the base pressure at the base region is function of the boundary layer thickness and type before the expansion. He assumed boundary layer as a source of fluid in the base region.

Korst [1956] studied the problem of base flow for Mach number equal to one and greater than one for cases in which the flow downstream of the base is sonic or supersonic downstream of the wake. He developed a model based on the concepts of interface between the dispersive shear stream and the neighboring free stream and the conservation of mass in the wake.

Hall and Orme [1956] investigated variable density flow during a sudden expansion in a pipe theoretically as well as experimentally and they have shown a good agreement between theory and experiments. They developed a correlation to predict the level of inertia in the downstream location of abrupt expansion for known values of inertia level at the exit of the entrance tube, with the flow where density is changing.

Badrinarayanan [1961] conducted experiment in the wake flow behind blunt based bodies at M = 2. He concluded that a small quantity of air injected into the 'dead air' region affected the base pressure significantly causing an increase of 21% and 24% in 3-D laminar and turbulent cases.

Anderson and Williams [1968] studied the base pressure and noise attenuation by the sudden expansion of air in the enlarged duct. They found that for an attached flow case the base pressure which was having minimum value, depends on the enlarged duct to flow accelerating area ratio and on the geometry of flow accelerating device. The measurement of overall noise was minimum for a jet pressure equal to that required for producing the minimum base pressure.

Vishwanath and Patil [1990] studied the effectiveness of passive devices for base drag reduction at Mach 2. They examined base cavities and ventilated cavities. They found from their results that the ventilated cavities can be significant for base drag reduction. From their studied they observed fifty per cent increase in base pressure and three to five percent total drag reduction at Mach number greater than one.

Rathakrishnan [2000] studied the effect of splitter plate on bluff body drag. It was concluded 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.

Rathakrishnan [2001] studied the effect of ribs on suddenly expanded flows. He concluded that passive controls in the form of annular ribs reduce the base pressure significantly, compared to that for plain passage. Annular ribs with aspect ratio 3:1 seems to be best combination for the given parameters. Further, it is found that the ribs in the form of passive control do not introduce any instability in the low field of the suddenly expanded duct and increase in pressure loss compared to plain duct is less than 6%. It was also observed that ribs with aspect ratios 3:2 and 3:3 result in increase of base pressure.

Khan and Rathakrishnan [2002] conducted experiments to control the base pressure at high supersonic Mach numbers. The studies were conducted at an over-expansion level of $(P_e/P_a) = 0.277$. From their experiments they found that the base pressure attains the lowest value for the lowest area ratio namely 2.56 and the length to diameter ratio namely L/D = 6 for all the inertia levels of Mach numbers (2.0, 2.5 and 3.0). The micro jets are found to be effective at M = 3.0 and $A_2/A_1 = 2.56$. It was observed that the micro jets increase the base suction at these combinations of parameters, resulting in an 83% reduction in base pressure.

They further investigated active control with air injection at 4 locations with jet Mach numbers 1.87, 2.2 and 2.5 and L/D ratio ranging from 10 to 1 in [2003]. It was observed that the control by the micro jets is effective in modifying the pressure at the base.

From the above reviews it is evident that the control of the flow through the nozzle with sudden expansion seems to be of interest having various practical applications. Further, it is found that a very little studies have been done with the active control. Therefore, it is decided to conduct the experiments to control the pressure at the base with micro jets.

III. Experimental Set up

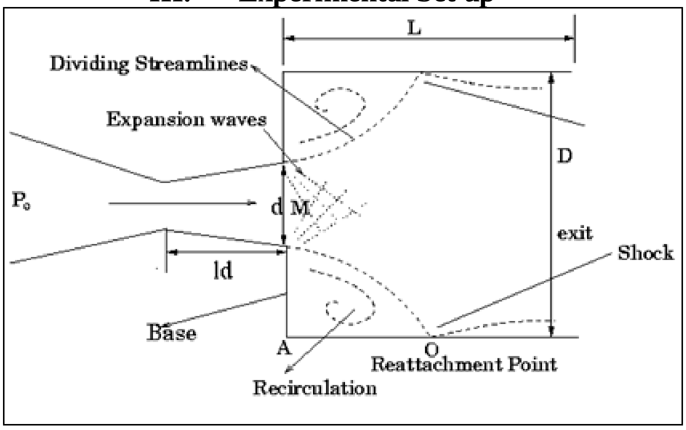


Fig. 1 Sudden Expansion Flow Field

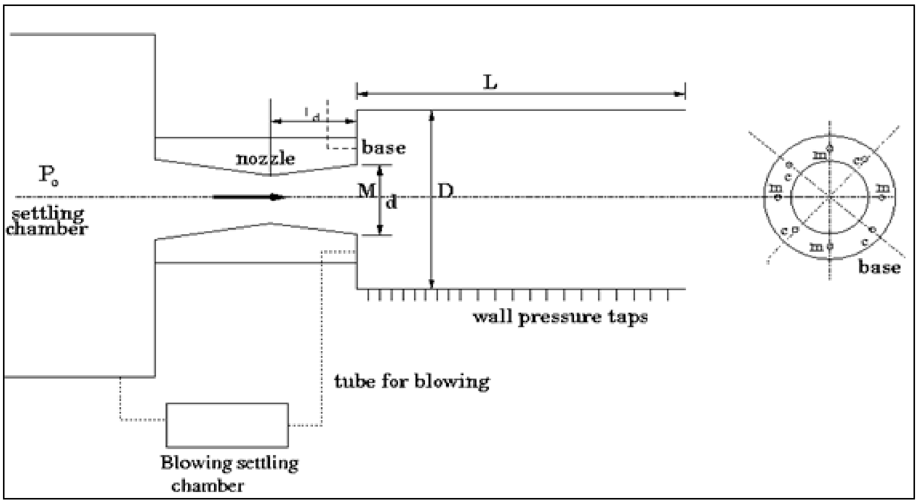
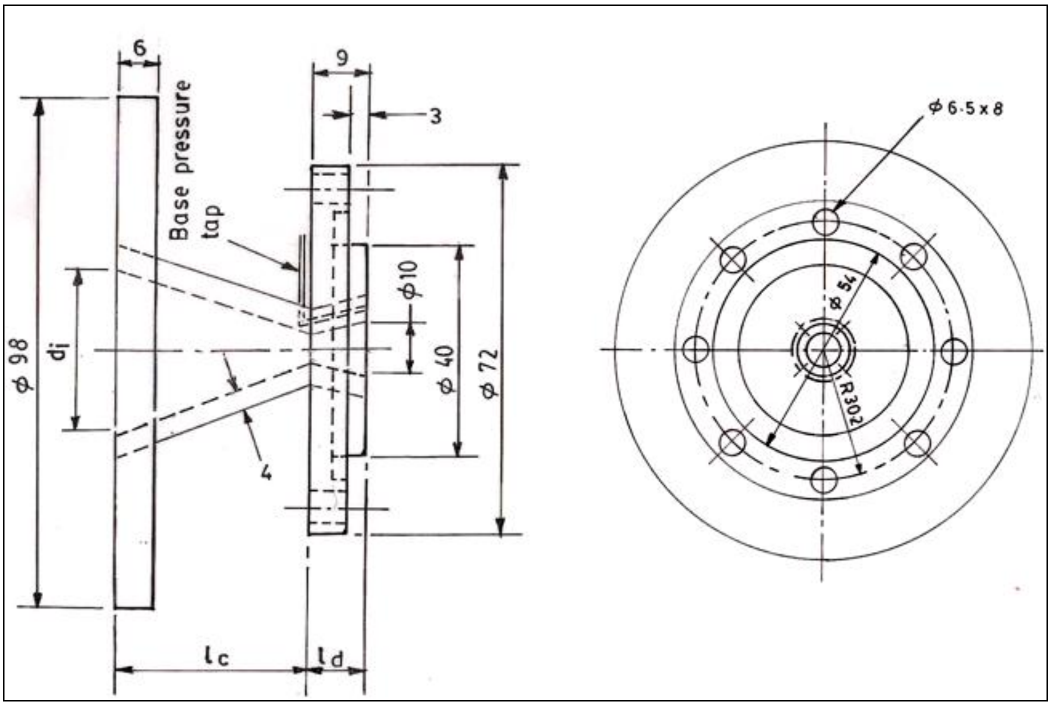


Fig. 2 Experimental Setup

Figure 2 exhibits the investigational setup used for the current study. At the outside edge of the nozzle there are 8 openings as shown in figure, 4 of them (marked as "c") were used for blowing and the other 4 (marked as "m") were used for base pressure (P_b) acquisition. Control of base pressure was carried out by blowing through the control openings (c), taking pressure from a settling chamber with the help of a tube. Tapings were used on the vessel to acquire the wall pressure at defined locations. First 9 openings were made at a distance of three millimeter each and the rest were made at a gap of five millimeter each and remaining was made at an interval 8 mm each.

Convergent-divergent nozzles of exit diameter of 10-mm and design Mach numbers of 1.1, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, and 3.0, were fabricated. After fabrication when the nozzles were calibrated to ascertain the exit Mach number, they were found to deliver the flows with the Mach numbers in the range from 1.2, 1.3, 1.5, 1.9, 2.2, 2.6, and 3.0. In the present studies all the suddenly enlarged duct was made out of brass tube of internal diameter eighteen mm, which is compatible to the area ratio of 3.24. The suddenly expanded duct and the base region were provided with the static pressure taps as shown in Figure 2. The Measurements were done for base pressure as well as the wall static pressure along the duct length for cases with and without control cases. This procedure of data acquisition were repeated for all the cases of inertia levels and the Nozzle pressure ratios. After taking the data for all the cases the duct length was reduced by cutting the length.



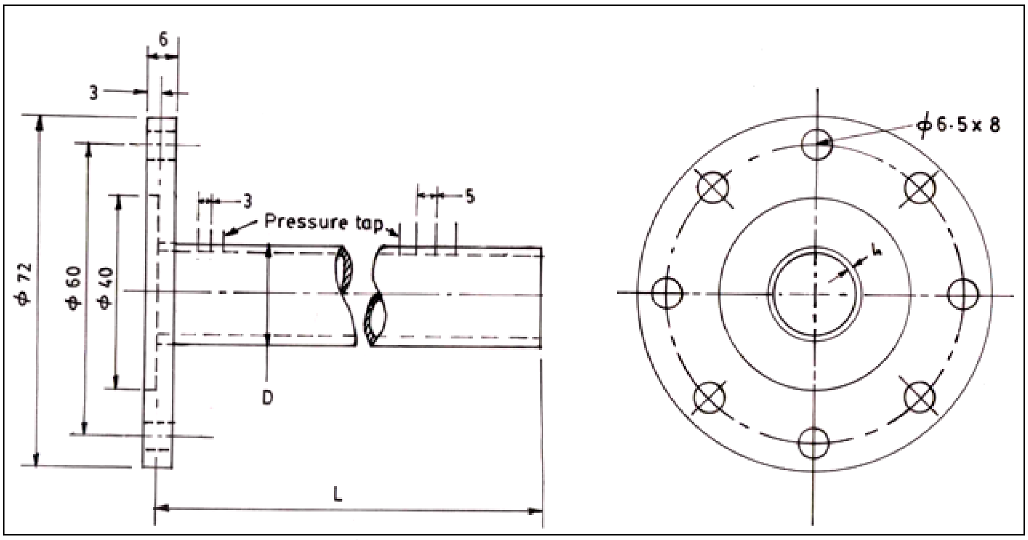


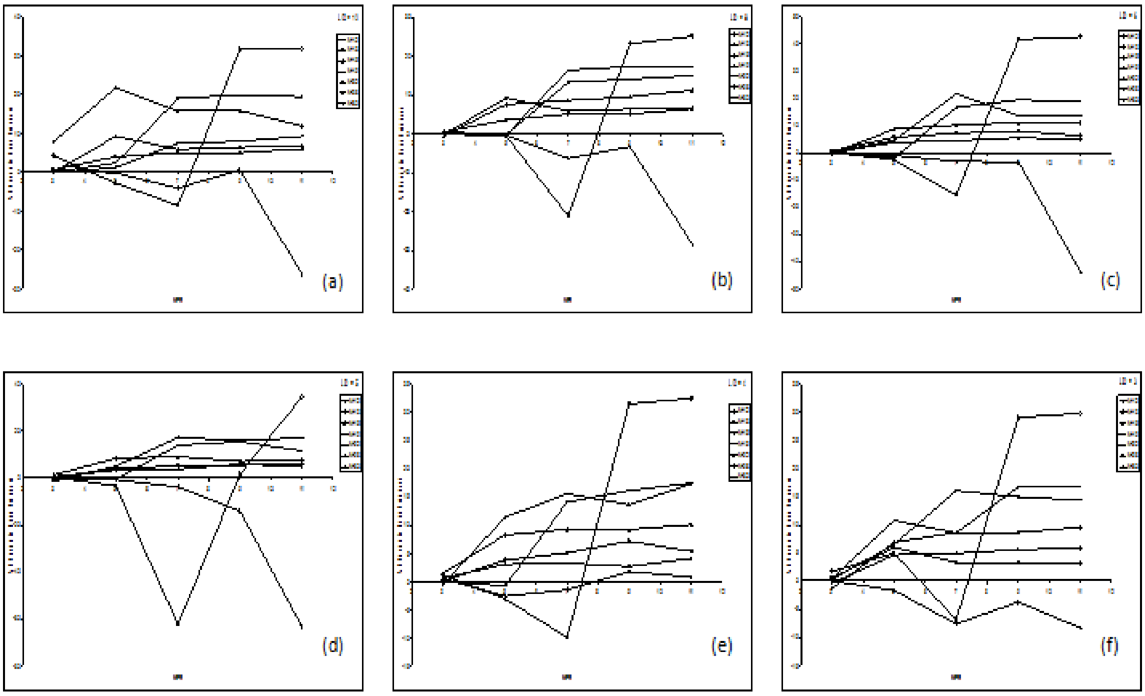
Fig 3 View of Nozzle (Top) and Enlarged Duct (Bottom)

This was done to ascertain the surface finish for all the L/D ratios being the same. This was well known that the flow is highly sensitive to the level of surface finish. With the above mentioned procedure, experiments were made for L/D ratio from 10 to 1. In the present study the base pressure and the wall pressure of initial ten taps were measured with Pressure transducer.

Figure 3 shows a view of the nozzle and the suddenly expanded duct of the present investigation. When we scan the literature it is observed that, the earlier researchers have used peculiar L/D which results in maximum base pressure is usually from L/D ratio from 3 to 5 for the cases where passive controls are employed. As in this investigation control is used, length to diameter ratio up to ten have been used. Hence the experiments were conducted for each Mach number, and the L/D ratios were from 10 to 1 and for each value of length to diameter ratio the NPRs used were from 3 to 11 in steps of 2.

IV. Result and Discussion

The present study is concerned to ascertain the productiveness of control by micro jets, placed at the base region of an enlarged duct, to control the base pressure. The control parameters considered in the present study are the L/D ratio, Mach number and the Nozzle Pressure Ratio (NPR).



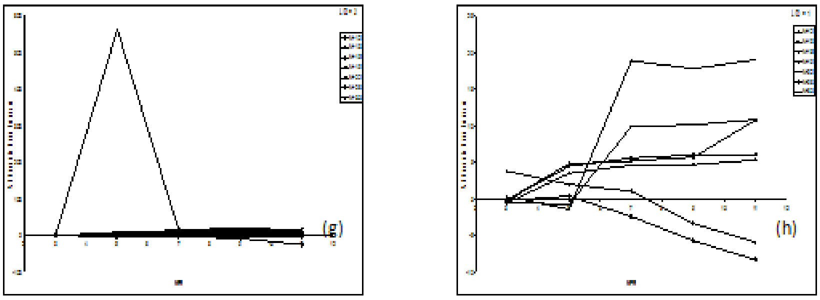


Figure 4. Percentage change in Base Pressure with NPR

In the present study the measured data were the base pressure, the wall static pressure in the suddenly expanded duct and NPR defined as the ratio of stagnation pressure (P_o) to back pressure. All measured pressures were non-dimensionalised with the atmospheric pressure (i.e. back pressure). Area ratio considered in the present investigation is 3.24 and the control pressure was equal to the NPR of respective runs as the air was drawn from the main settling chamber.

To get an insight into the effect of NPR on base pressure at different Mach numbers and L/Ds, base pressure as a function of NPR, Mach number and L/D are analyzed. Percentage change in base pressure is shown in Fig.4.

Base pressure results for L/D = 10 (Fig. 4(a)), the maximum gain is 30 percent for M = 2.6 and at NPR = 11. For Mach numbers from 1.2 to 2.2, it is seen that the base pressure has increased when the control in the form of the micro-jets are used for all the levels of expansion but for M = 3.0 the active control leads to reduction in the base pressure.

To understand the physical phenomenon taking place; we need to analyze the flow field in the base region. When the flow is coming out from the nozzle there will be a shear layer accompanying the flow, though the region of the shear layer will very small as compared to the main flow. Further, the Nozzle Pressure Ratio in the present investigation falls under the category of correct, under and over expansion. The flow remains over expanded for Mach numbers 2.2, 2.6 and 3 of the present study as it was not possible to conduct the tests for correct expansion due to the limitation of the experimental facility. For all the Mach numbers where the flow remains over expanded there will be an oblique shock at the nozzle exit and when the flow will pass through this oblique shock the pressure will continue to increase till it becomes ambient pressure. During this process the flow will go away from the base region resulting in larger reattachment length and under these circumstances; the vortex positioned at the base is not able to create the suction which otherwise it is able to do so at lower Mach numbers. It is evident from all the results that whenever; the flow is over expanded it results in higher values of the base pressure.

For the remaining Mach numbers; the flow will be correct, over and under expanded. In the case of jets being under expanded there will an expansion at the nozzle exit and the expansion of the flow will continue to take place till it becomes atmospheric pressure, and hence, the flow will deflect towards the base resulting in reduced reattachment length leading to higher level of suction and low values of base pressure. However, when the flow from nozzle is correctly expanded, weak waves will be positioned at the nozzle lip which will not result in very high pressure gradient rather the flow across these Mach waves will be isentropic.

The percentage change in base pressure for L/D = 8 are shown in (Fig. 4(b)). These results are on the similar lines as discussed above except that length to diameter ratio has reduced and the flow is more exposed to the atmospheric pressure. As in the case of L/D = 10, for L/D = 8 and at higher Mach numbers, the base pressure decreases with control. For NPR = 11, the base pressure increases considerably when the micro jets are activated except for M = 3.0.

The base pressure results for L/D = 6 are presented in (Fig 4(c)). Once again it is seen that for the lower values of inertia results in enhancement of base pressure and the trend reverse for higher Mach numbers. As for L/D = 10 and 8, the increment in the base pressure for L/D = 6 is appreciable for NPR equal to nine and eleven for all the Mach numbers except M = 3.0.

Base pressure results for L/D = 5 are shown in (Fig. 4(d). Here again the results are very much similar to that for L/D = 6. Similar trend continues for L/D =4 and 3 (Fig. 4(e & f)).

Base pressure results for L/D = 2 is shown in Fig. 4(g), it can be observed that for M = 2.6 and 3.0, the base pressure decreases continuously as NPR increases. For L/D = 1 and 2 (Figs. 4 (g-h)), the length is sufficient for the flow to reattach at lower Mach numbers and hence a vortex is formed at the base in this case but for higher Mach numbers (2.6 and 3.0), the length of the duct is found to be insufficient for the reattachment of flow and the flow is exposed to ambient conditions; hence, the base pressure decreases continuously irrespective of the change in NPR.

V. Conclusion

In the present study, it is seen that the micro jets affect the base pressure favourably as well as adversely. The favourable and adverse nature of influence was found to be governed by the NPR and hence the level of expansion. For lower Mach numbers the base pressure tends to increase with the increase in NPR. The effective gain in base pressure is in the range of 10–40 per cent, which is very considerable. This can be considered as a great advantage since for supersonic vehicles, the base drag (base pressure [suction] × base area) can be as high as 60 % of the total drag. Therefore, even a small increase in base pressure will result in significant reduction of the total drag.

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