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Effect of High L/D-Ratio and Nozzle Pressure Ratio (NPR) in a Suddenly Expanded Flow

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***Abstract*— This paper presents an investigational analysis of the efficiency of very small jets to control base pressure in abruptly expanded axi-symmetric ducts. 4 very small jets of one millimeter diameter installed at a gap of 90° along a pcd of 1.3 times the nozzle outlet diameter in the bottom region were used as dynamic controls. Mach numbers of the suddenly expanded flows were 1.25, 1.3, 1.48, 1.6, 1.8, 2.0, 2.5 and 3.0. The jets were expanded abruptly into a tube of flow area 2.56, 3.24, 4.84 and 6.25 times that of nozzle outlet area. The length to diameter relation of the abruptly expanding tube was varied from ten to one. However, the results presented are for high L/D ratio; since the flow will remain attached with the duct wall for all the Mach numbers and the NPRs tested. It is observed that the level of expansion plays an important role to fix the value of the base pressure. Whenever, the flow is over expanded, there will be an oblique shock at the nozzle lip which will result in increase of the base pressure and the formation of the shocks will continue till the pressure becomes atmospheric pressure. It is established that the very small jets can be used as dynamic controllers for bottom pressure. Also, the very small jets do not badly effect the wall pressure distribution.**

Keywords*— *Base pressure, Nozzle, Micro jets, Wall Pressure, Sudden Expansion

I. INTRODUCTION

The pressure at the base normally is less than the atmospheric pressure; hence the study of base flows for increased Reynolds numbers remains to be a demanding field of study due to its suitability in outside aerodynamics. Base drag as a result of flow split-up at the bottom of a body, can be large fraction of total drag in transonic/low supersonic speeds in case of projectiles, missiles and after bodies of fighter aircraft; e.g. the base drag part can be as much as sixty percent of the total drag for a missile with no jet flow at the bottom. However, the base drag at low/high subsonic will be around ten percent of the total drag of the projectile/body of revolutions. At subsonic speed the wave drag will be absent in view of the non-existence of the shock wave as the shock will be formed at sonic speed only. Significant flow unevenness,

regularly coupled with a disorderly divided flow, can result in added troubles like base buffeting which are unfavorable.

Because of it's vide applicability, suddenly expanded flows have studied widely. Many scholars tried control the base pressure with passive control like splitter plate, ribs at the base region of the enlarged duct, step body, locked vortex and the vented cavities, and some of the works relevant to the present study are reviewed in the section to follow. Therefore, in the existing case an effort is made to examine the base pressure control with dynamic control with the help of very small jets under the influence favorable pressure gradient, adverse pressure gradient and for ideally expanded cases; at low supersonic Mach numbers, supersonic Mach numbers and high supersonic Mach numbers with micro jets.

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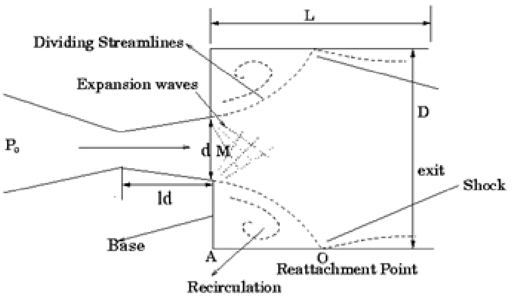

Fig. 1. Sudden expansion flow field

II. LITERATURE REVIEW

Flow area of sudden axi-symmetric growth is a complicated observable fact. It is characterized by a) flow separation b) flow re-circulation and c) reattachment (Fig. 1). A cut off layer into two major regions may split such a flow area, the main flow region and the other flow recirculation region. Reattachment point can be defined as the point at which the separating flow line strikes the wall. The outcome of boundary layer on sonic flow in a sudden cross-sectional region was calculated experimentally by Wicks [17]. He observed that the base pressure in the expansion corner was principally the same and base pressure phenomenon in external flow could be studied relatively easily by experiments with internal flowing.

Anderson and Williams [1] studied the base pressure and sound produced by the sudden development of air flow in duct. The graph for sound exhibited the lowest at a jet pressure nearly similar to that necessary to produce minimum base pressure.

The effectiveness of passive devices for axi-symmetric base drag reduction at Mach 2 was studied by Vishwanath and Patil [16]. The devices examined included primarily base cavities and ventilated cavities. Their results indicated that the ventilated cavities offered significant base drag reduction. They found 50 per cent increase in base pressure and 3 to 5 per cent net drag reduction at supersonic Mach numbers for body of revolution.

Mathur and Dutton [10] studied the effect of base bleed on the near wake flow field of a cylindrical after body at Mach 2.5. They found that with increasing bleed flow rate, the average base pressure increases initially, attains a peak value and then decreases.

Kruiswyk and Dutton [8] studied effects of base cavity on subsonic near-wake flow. They experimentally investigated the effects of base cavity on the near-wake flow-field of a slender two-dimensional body in the subsonic speed range. Three basic configurations were investigated and compared; they are a blunt base, a shallow rectangular cavity base of depth equal to one half of the base height and a deep rectangular cavity base of depth equal to the base height. Schlieren photographs revealed that the base qualitative structure of the vortex street was un-modified by the presence of the base cavity. The weaker vortex street yielded higher pressures in the near-wake for the cavity bases, and increases the base pressure co-efficient in the order of 10 to 14 per cent, and increases in the shedding frequencies of the order of 4 to 6 per cent relative to the blunt-based configuration.

Shafiqur Rehman and Khan [11] studied the suddenly expanded flow at low supersonic as well as high supersonic Mach numbers for area ratio of 4.84. From the results it was observed that in view of the increase of the area ratio resulting in larger re-attachment length leading to high values of the base pressure. Since inertia level was kept constant and only area ratio is increasing resulting in increase in relief to the flow resulting in higher values of the base pressure for the same Mach numbers at the lower area ratios. Micro jets were found to be very effective; whenever the favourable pressure gradient exists. However, when the Mach number is greater than 2, the micro jets were unable to influence the base region and the flow remains unaffected.

Syed Ashfaq et al. [12]-[14] studied the effect of area ratio, nozzle pressure ratio and control effectiveness for area ratio of 2.4. From their result they concluded that the control with the micro jets is very effective. One of the reason for this behaviour could be due the lowest area ratio the space available for the flow to create is the lowest and the vortex sitting at the base whose strength is constant is able to influence the base region very effectively leading to very low level of base pressure and also; when we scanned the wall pressure it is found that the flow is oscillatory in nature and wall pressure is having waviness for all the Mach numbers and L/D ratio. It is also observed that this waviness nature is very strong at highest level NPRs as compared to the lower NPRs.

Suddenly expanded flow with control appeals to be of curiosity with various applications. Further, it is understood that sufficient work has not been carried out in the area of active control of base pressure field. Hence, it is projected to study the control of base pressure field with active control.

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III. INVESTIGATIONAL SETUP

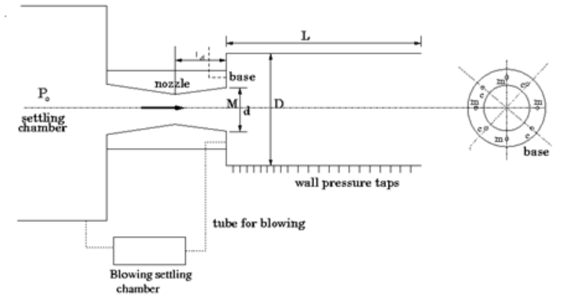

Fig. 2. Investigational Setup

Fig. 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. In the literature it is observed that, the typical L/D (Fig. 2) giving in P_b maximum is generally between three to five without controls. As an active control is employed in the current investigation, length to diameter ratios up to 10 have been studied. For each Mach number, and L/D ratios used were from 10 to 1 excluding 7 and 9. For each value of L/D ratio NPRs were 3, 5, 7, 9, and 11.

PSI model 9010 pressure transducer was employed to acquire the pressure at the base, the stagnation pressure in the main settling chamber and the pressure in the control chamber. It consists of 16 channels & pressure range is 0 - 300 psi. It displays an average of two hundred and fifty readings per second. The software obtains and gives out the pressure readings.

IV. RESULTS AND DISCUSSION

The acquired data comprises of base pressure (P_b); wall static pressure (P_w) at the length of the vessel and the NPR i.e. stagnation pressure (P_0) to back pressure (P_{atm}) ratio. The acquired pressures were converted to non-dimensional values by dividing them with the back pressure. The effect of area ratio with Mach number and NPR is shown in Figs. 3 and 4. It should be noted that increase of area ratio simply implies that relaxation space available for the flow exiting the nozzle is increasing.

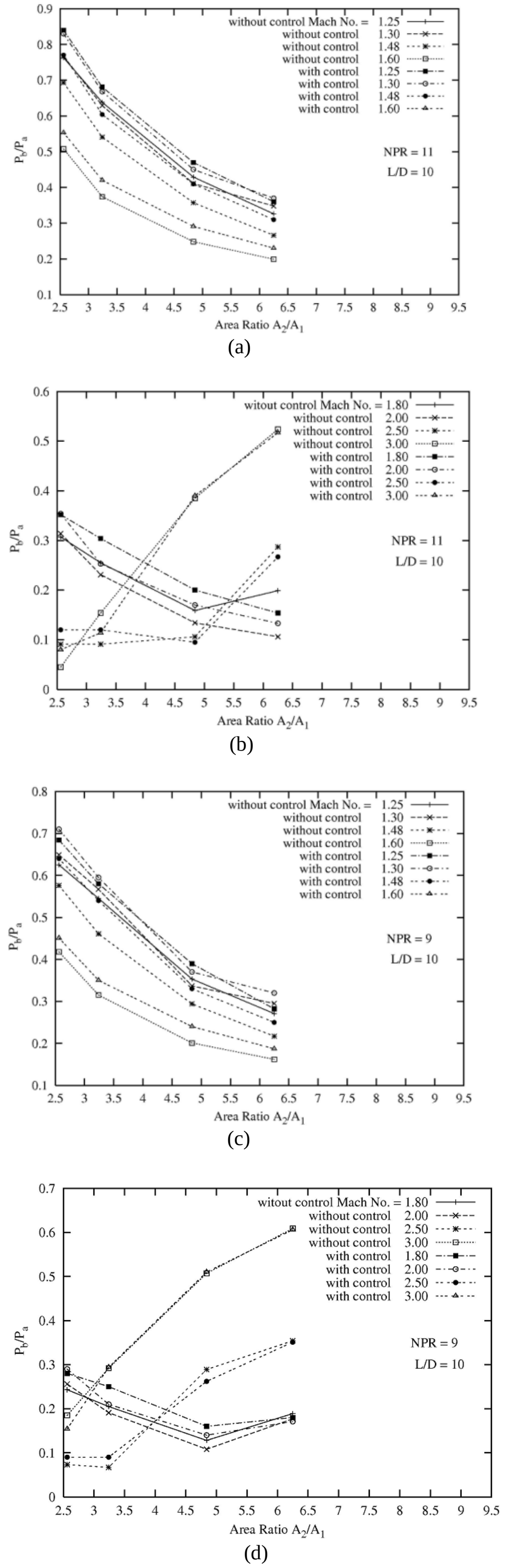

Fig. 3. P_b/P_a deviation vs A_2/A_1

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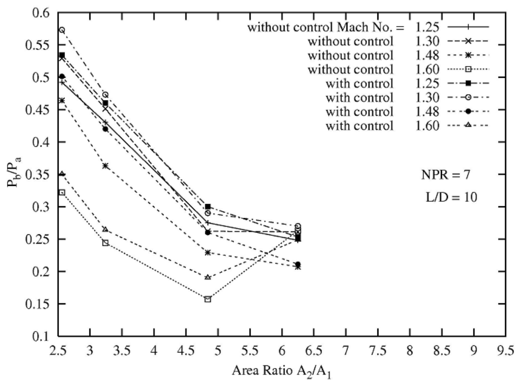
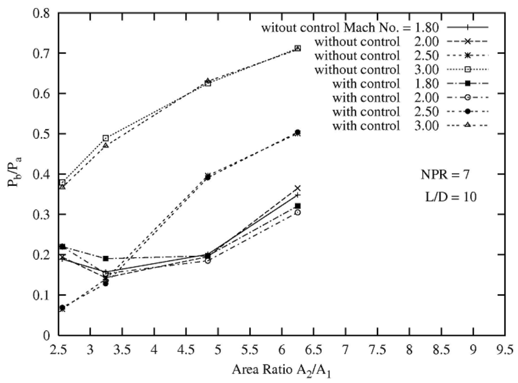
This kind of relief will make the shock/expansion waves at the nozzle lip to propagate relatively freely with increase of area ratio (Fig. 3 (a) - (b)). It is seen that for NPR 11 for Mach 1.25 to 1.6 all these jets are under expanded and hence the free shear layer from the nozzle exit passes through an expansion fan. In such situation increase in reattachment length due to increase of area ratio is seen to result decrease of base pressure with increase in area ratio. Furthermore, the control is found to be effective for these Mach number range taking the base pressure to higher value compared to the corresponding case without control. In Fig. 3(b) Mach number 1.8 and 2 are under expanded, whereas 2.5 and 3.0 are over expanded. For over expanded jets it is interesting to note that the base pressure increases with increase in area ratio.

Similar results for NPR 9 are shown in Fig. 3(c)-(d). Here again the base pressure behavior with area ratio is similar to that for NPR 11, excepting that the magnitudes of base pressure at different conditions are slightly different from NPR 11.

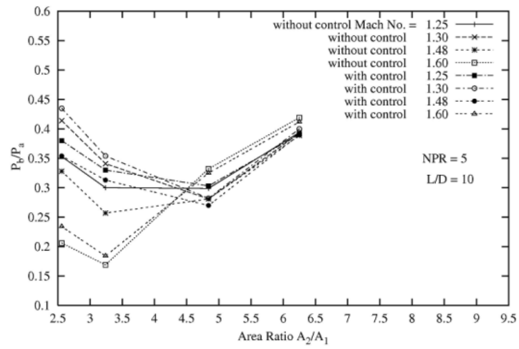
Base pressure results for NPR 7 are shown in Fig. 4(a)-(b) for Mach number ranges 1.25 to 3. Here M = 1.25 to 1.6 are under expanded whereas Mach 1.8 is slightly under expanded and Mach number 2 to 3 are over expanded. The effect due to the transition is clearly seen from these results.



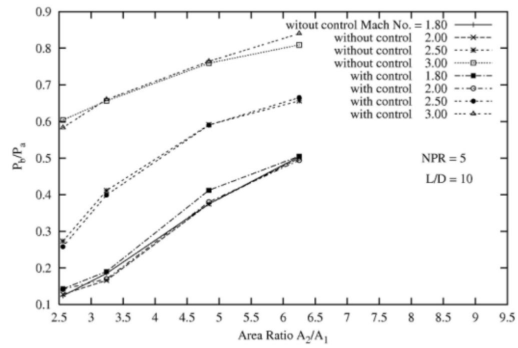
(a)



(b)



(c)



(d)

Fig. 4. P_b/P_a deviation vs A_2/A_1

Similar results for NPR 5 are shown in Fig. 4(c)-(d). Here M = 1.25 to 1.48 are under expanded, Mach 1.6 is slightly under expanded Mach 1.8 is slightly over expanded. The strong effect of area ratio when the jets are almost correctly expanded is clearly seen from these results exhibiting a mixed trend reflecting both under and over expanded situation. This is because when jets are correctly expanded there is an expansion fan at the nozzle exit due to increase in area ratio. This expansion fan has a control over the base pressure depending on the relaxation it enjoys due to area ratio effect.

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V. CONCLUSIONS

Active Control with the help of very small jets to control base pressure has been demonstrated. The flow field in the wall duct is dominated by the presence of the waves. It is seen that the reflection of the waves from the wall, recompression and recombination's are taking place in the base region of the duct wall, thereby making the flow oscillatory. It is found that the flow field is oscillatory within the reattachment length region; later the development of the flow and the wall pressure recovery is very smooth. This happens mostly for L/D = 10, 8, 6, and 5 only for all the Mach numbers of the present test. The micro jets serve as an effective active controller, elevating the base suction to approximately negligible level for some permutation of parameters. The nozzle pressure ratio has a explicit role in deciding the level of base pressure with and without control, in the supersonic jet Mach number regime too.

All the non-dimensional wall pressure values presented in this paper are within an uncertainty band of ± 2.6%. All the investigation outcomes are within the range of ± 3 per cent.

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