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EFFET OF LEVEL OF OVEREXPANSION IN A SUDDENLY EXPANDED FLOW

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ABSTRACT

This paper presents an experimental investigation to study the effectiveness of micro jets under the influence of adverse pressure gradient to control the base pressure in suddenly expanded axi-symmetric ducts. Four micro jets of 1mm 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 as active controls. These tests were conducted at a fixed level of over expansion of 0.56 for Mach numbers 1.87, 2.2, and 2.58. The jets were expanded suddenly into an axi-symmetric tube with cross-sectional area 2.56 times that of nozzle exit area. The L/D ratio of the sudden expansion tube was varied from 10 to 1. From the present studies, it was found that the maximum increase in base pressure is 152 percent for Mach number 2.58. It is found that the micro jets do not adversely influence the wall pressure distribution.

Keywords: Base pressure, Nozzle flow, Micro jets, Wall Pressure, Sudden Expansion.

1. INTRODUCTION

As a result of developments in space flights and missile technology, the base flows at high Reynolds numbers continues to be an important area of research. Following these, the interest shifted to the hypersonic speed regime from the point view of base heat transfer and near-wake structure. Our understanding of many features of base flows remains poor, due to inadequate knowledge of turbulence, particularly in the presence of strong pressure gradient. 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 energetic as well as passive techniques, these aim in manipulation/alteration of the near wake flow field for increasing the base pressure.

Flow field of abrupt axi-symmetric expansion is a complex phenomenon characterized by flow separation, flow re-circulation and reattachment. A shear layer into two main regions may divide such a flow field, one being the flow recirculation region and the other the main flow region. The point at which the dividing streamline Strikes the wall is called the reattachment point and the features of sudden expansion flow field are shown in Fig. 1.[i]

The effect of boundary layer on sonic flow through an abrupt cross-sectional area was studied experimentally by Wicks (1953). 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 flow.

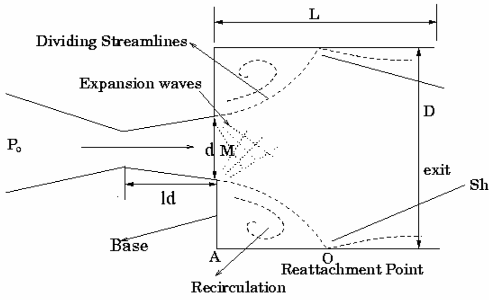

Fig. 1 Sudden Expansion Flow Field

Anderson and Williams (1968) worked on base pressure and noise produced by the abrupt expansion of air in duct. With an attached flow the base pressure was having minimum value, which depends mainly on the duct to nozzle area ratio and on the geometry of the nozzle. The plot for overall noise showed a minimum at a jet pressure approximately equal to that required producing minimum base pressure.

Rathakrishnan and Sreekanth (1984) studied flows in pipe with sudden enlargement. They concluded that the non-dimensional base pressure is a strong function of area ratios, the overall pressure ratios and the duct length-to-diameter ratios. They showed that for a given overall pressure ratio and a given area ratio, it is possible to identify an optimal length-to-diameter ratio of the enlargement that will result in maximum exit plane total pressure at the nozzle exit on the symmetry axis (i.e. minimum pressure loss in the nozzle) and in a minimum base pressure at the sudden enlargement plane. The separation and reattachment seemed to be strongly dependent on the area ratio of the inlet to enlargement. For a given nozzle and duct area ratio, the duct length must exceed a definite minimum value for minimum base pressure.

The effectiveness of passive devices for axi-symmetric base drag reduction at Mach 2 was studied by Vishwanath and Patil (1990). 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 (1996) 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.

Suddenly expanded flow with control seems to be of interest with many applications. This will help in minimizing the base pressure in the case of combustion chamber to maximize the mixing, and maximize the base pressure in the case of rockets, projectiles, aircrafts bombs and missile to result in base drag reduction. Therefore, an attempt has been made to control the base pressure field with micro jets for flows from over expanded nozzles.

2. EXPERIMENTAL SETUP

Figure 2 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 done 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 3mm each and remaining was made at an interval 5mm each. From literature it is found that, the typical L/D (as shown in Fig. 2) resulting in P_b maximum is usually from 3 to 5 without controls. Since active controls were used in the present study, L/D ratios up to 10 have been employed. For each Mach number, and L/D ratios used were 10, 8, 6, 5, 4, 3, 2, and 1 and for each value of L/D ratio NPRs were 3, 5, 7, 9, and 11 and also for correct, under, and over expansion. However, the results presented here are for a fixed level of over expansion only (i.e. $P_e/P_a = 0.56$).

PSI model 9010 pressure transducer (interfaced with a PC386) was used for measuring pressure at the base and the stagnation pressure in the settling 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 -20^0 to $+60^0$ and 95 per cent humidity. The transducer had measurement resolution of ±0.003 and the readings were accurate up to ±1 percent. Mercury manometer was used for the measurement of wall pressure.

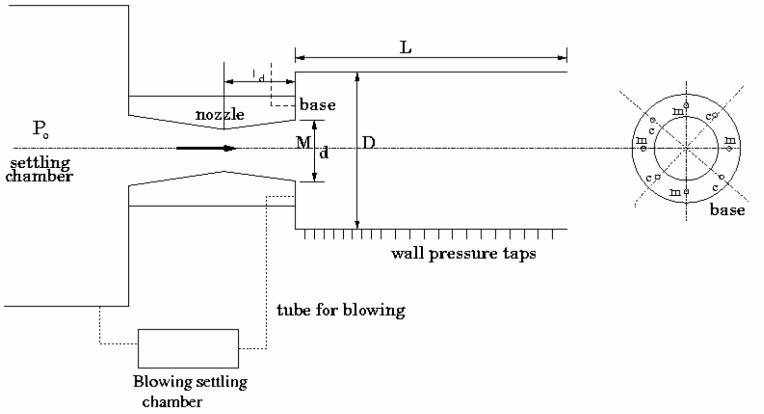

Fig. 2 Experimental Setup

3. 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 were non-dimensional zed by dividing them with the ambient pressure (i.e. the back pressure). In addition to the above pressures, the other parameters of the present study are the jet Mach number (M), length to diameter ratio of the duct (L/D), and the control pressure ratio.

To quantify the increase in base pressure achieved with active control, cross plots of base pressure in the form of percentage increase in base pressure is used for presenting the results. The percentage change in base pressure as a function of L/D ratio has been shown in Fig. 3 at Mach 1.87, 2.2, and 2.58 under the influence of adverse pressure gradient. Results of base pressure with and without control are compared. At Mach 1.87 there is no definite trend of the base pressure. Since the Mach number and level of over expansion is such when the micro jets are activated it is not very effective. And the maximum gain is ± 20 percent and it becomes independent of L/D after L/D = 8. At Mach 2.2 the maximum gain is 55 percent at L/D = 3 whereas at it remains at 30 percent for rest of the L/Ds. At Mach 2.58 as high as 150 percent increase in base pressure is achieved at L/D = 3. However, at other L/Ds it remains at 50 percent. It is seen from these results that in supersonic regime the Mach number has got very strong influence on the base pressure. For a given Mach number and the nozzle pressure ratio (NPR), which dictates the level of expansion, has a strong role to play on the control effectiveness of the micro jets.

The physical reason for this may be the influence of the oblique shock at the nozzle exit, which turns the flow away from the base region, thereby weakening the vortex positioned at the base. This results in increase of base pressure since the weakened vortex at the base encounters the mass flow injected by the micro jets. However, Mach 1.87, 2.2, and 2.58 results in continuous decrease of base pressure for the entire range of Mach numbers tested. This may be because as the Mach number increases the level of suction comes down, hence the oblique shock at the nozzle exit becomes weaker than those at lower Mach numbers. Therefore, the turning away tendency of incoming flow comes down leaving the vortex almost intact. At this situation when the micro jets are introduced they may propagate without any deflecting tendency, thereby entraining some mass from the standing vortex and convecting it away from the base causing the base pressure to assume higher values.

Non-dimensionalized base pressure variation with L/D ratio at Mach 1.87 is shown in Fig. 4. It is seen that the control tends to modify the base pressure level at all L/Ds. Also, the control effectiveness in modifying the level of base pressure gets enhanced with increase of Mach number and L/D. At lower L/D and Mach numbers the control is insignificant. However, it is effective for higher Mach numbers. The reason for this trend may be when Mach number increases the level of over expansion decreases. It is evident from these results that, the L/D has a definite role in the control of base pressure with micro jets. It can be stated that the base pressure due to recirculating flow at the base is dictated by the reattachment length, which is the distance from the beginning of the enlargement to the point where the free shear layer from the nozzle attaches with the duct wall. For this to take place the duct should have a definite length. It has been proved by Rathakrishnan and Sreekanth [4] that this minimum length is L/D = 3, for subsonic and sonic flows. It is in agreement of the above findings.

One of the major problems associated with base flows is the oscillatory nature of the pressure field in the duct just downstream of the base region. This can be understood by scanning the wall static pressure along the duct. In the present investigation also, attention was focused to study the effect of the active control in form of micro jets on the enlarged duct wall pressure field. To study this wall pressure distribution for all the Mach numbers, tests were conducted with and without controls as shown in Fig. 5. It is found that the pressure field with and without control behaves almost identically. This ensures that the active control does not influence the wall pressure adversely rendering it to oscillate violently. This can be considered as one of the major advantages since the major problem faced while using active control on a pressure field is that it will augment the oscillatory nature of the wall pressure field.

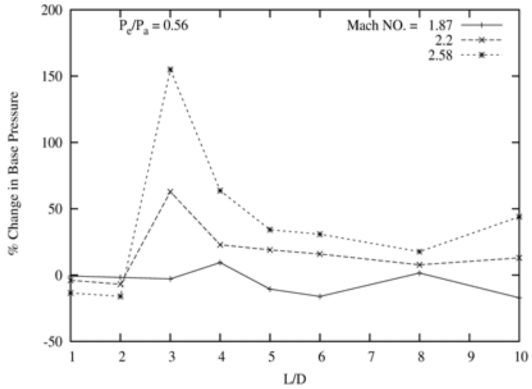

Fig. 3. Percentage Change in Base Pressure with L/D Ratio

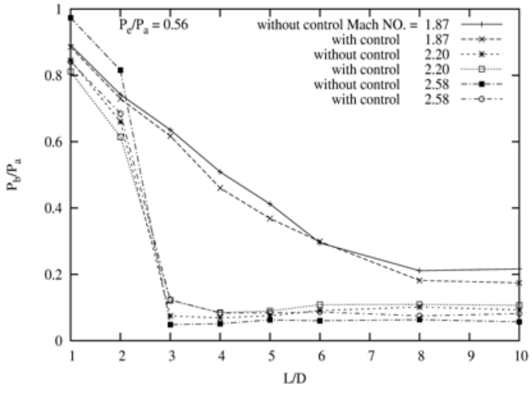

Fig. 4. Base Pressure Variation with L/D Ratio

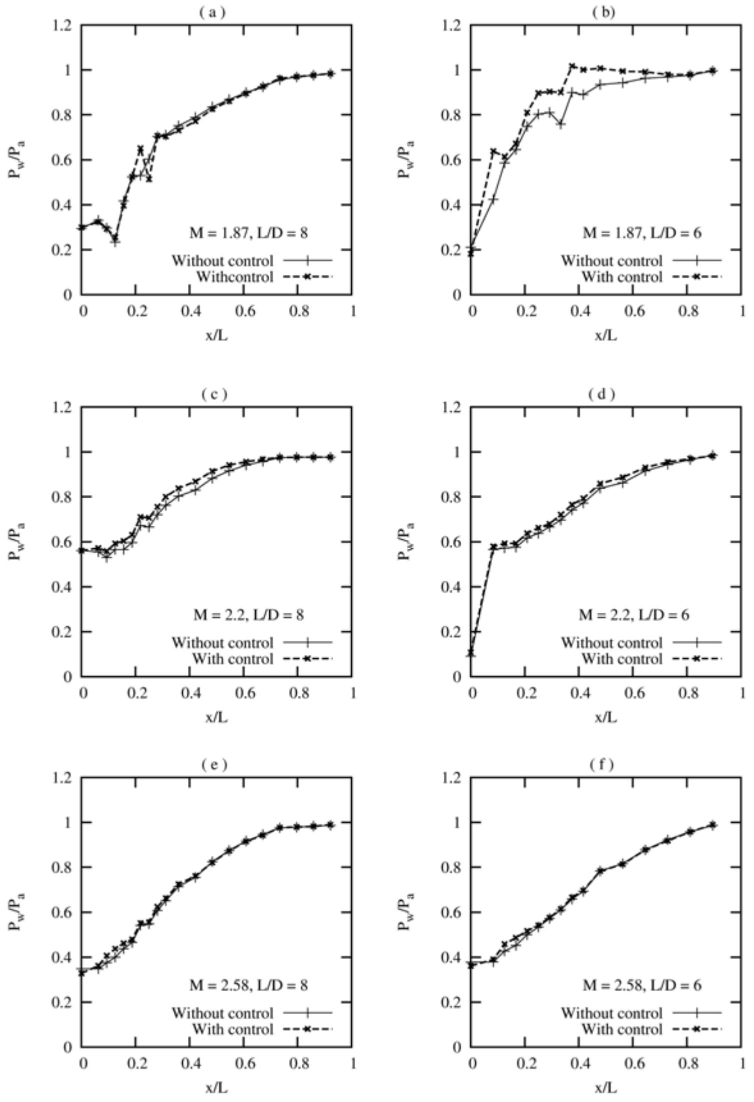

Fig. 5 Wall Pressure Distribution

4. CONCLUSIONS

The micro jets can serve as an effective controller raising the base suction to almost zero level for some combination for parameters. The NPR has a definite role to play in fixing the base pressure with and without control. There is no adverse effect of the micro jets on the flow field in the enlarged duct.

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