Experimental Examination of Micro Jet Impact on Sonic Flow Expansion Control

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ABSTRACT

This study presents experimental data aimed at regulating base pressure emanating from a convergent nozzle under the influence of a favorable pressure gradient at sonic Mach numbers. To modulate the base pressure, a four-micro jet active control system featuring 1 mm orifice diameters was strategically positioned at 900 intervals along a pitch circle with a diameter 1.3 times that of the nozzle exit diameter. Diferent area ratios were computed as the ratio of the abruptly expanded duct's area to the nozzle exit area. The length-to-diameter (L/D) ratio of the rapid expansion duct ranged from 10 to 1. A significant observation from the data indicates that, contrary to passive controls, active control mechanisms like micro jets do not inherently improve control effectiveness in the presence of a favorable pressure gradient. To assess the influence of micro jets on flow quality within the larger duct, wall pressure was measured. Interestingly, in certain cases, the presence of micro jets was found to enhance flow quality.

Keywords- Base pressure, Mach number, Micro jets, Sudden expansion, Wall pressure

I. INTRODUCTION

Research into base flows at high Reynolds numbers remains paramount due to advancements in space travel and missile technology. Initially, focus centered on base heat transfer and near-wake structure before shifting towards the hypersonic speed regime. Despite progress, many aspects of base flow characteristics, especially under significant pressure gradients, remain elusive. Various studies detailed in the literature aim to mitigate base drag penalties through energetic and passive strategies, primarily by manipulating the near-wake flow field to augment base pressure.

A complex phenomenon, characterized by abrupt axi-symmetric expansion, involves flow separation, recirculation, and reattachment, delineated into distinct zones by a shear layer: the flow recirculation region and the main flow region.Vortex shedding, following bluff bodies, is a crucial flow phenomenon, particularly behind isolated two-dimensional segments with blunt trailing edges, leading to the formation of vortex streets at subsonic and transonic speeds. This, in turn, increases drag due to reduced pressure.

Base flows at high Reynolds numbers retain significant research interest, particularly in projectiles, missiles, and fighter aircraft after bodies. The base drag resulting from flow separation at the blunt base of a body can constitute a substantial portion of total drag, reaching up to 50% in cases such as missiles lacking power. Large-scale flow unsteadiness associated with turbulent separated flow can induce additional issues like base buffeting, which are undesirable in aerodynamics.

The immediate consequence of this phenomenon is an increase in drag, primarily attributed to reduced pressure. Moreover, the study of base flows at high Reynolds numbers remains crucial in exterior aerodynamics. In the context of projectiles, missiles, and fighter aircraft after bodies, base drag resulting from flow separation at the blunt base can represent a significant portion of total drag. For instance, the base drag component can comprise up to 50% of the total drag for a missile devoid of power (i.e., lacking jet flow at the base). Large-scale flow unsteadiness, commonly associated with turbulent separated flow, can lead to additional challenges such as base buffeting, which are undesirable in aerodynamic applications.

II. LITERATURE REVIEW

The earlier researcher conducted experimental investigations into the impact of boundary layers on sonic flow through abrupt cross-sectional expansions [1]. He noted a correlation between pressure in the expansion corner and the type and thickness of the boundary layer upstream of the expansion, regarding the boundary layer as a fluid source for corner flow. Anderson J. S. et al. [2] emphasized the significance of base-pressure variations, particularly where pressure fluctuations are substantial. James A. Kidd et al. [3] conducted free-flight tests on spin-stabilized projectiles and fin-stabilized missiles with various base configurations, observing that a stepped base can notably reduce aerodynamic drag compared to a flat base at subsonic speeds.

N. Menon and B. W. Skews [4] analyzed shock structures in under-expanded gas jets from rectangular and elliptical exits via numerical methods, highlighting the significant impact of nozzle corner effects on shock structure. Viswanath P. R. [5] experimentally investigated zero-lift drag characteristics of multi-step after-bodies, identifying key geometric parameters affecting drag and highlighting the potential for substantial drag reduction compared to blunt bases.

Khan and Rathakrishnan [6-10] conducted experimental investigations into the effectiveness of micro jets under various expansion conditions, finding significant increases in base pressure, particularly at Mach 2.58, without adverse effects on wall pressure distribution. Jagannath et al. [11] utilized fuzzy logic to study pressure loss in suddenly expanded ducts, identifying an optimum length-to-diameter ratio for minimal pressure loss. Lovaraju P. et al. [12] experimentally investigated passive controls such as tabs and cross-wires in axi-symmetric sonic jets, finding effective reduction in supersonic core size with both control methods.

Farrukh S. Alvi et al. [15] conducted experimental investigations on the flow and acoustic properties of supersonic impinging jets, while Pandey and Kumar [16] employed fuzzy set theory to study base pressure in suddenly expanded circular ducts, obtaining results in close agreement with experimental data. Vikram Roy et al. [17] conducted numerical analysis of turbulent fluid flow through sudden expansion passages, observing variations in recirculation bubble size and strength with changes in Reynolds number and expansion ratio.

M. Ahmed Ali Baig et al. [18] experimentally assessed the effect of Mach number on base pressure and control effectiveness in suddenly expanded ducts, noting an increase in base pressure with Mach number. Additionally, Baig et al. [19] investigated base pressure control in suddenly expanded passages, observing a 30% increase and 40% decrease in base pressure under different conditions.

Syed Ashfaq et al. [20] experimentally evaluated the effectiveness of micro jets in controlling base pressure in suddenly expanded ducts, finding that micro jets can serve as active controllers without disrupting flow field in the enlarged duct

III. EXPERIMENTAL METHOD

Figure 1 illustrates the experimental setup utilized in this investigation. Positioned around the exit periphery of the nozzle are eight holes, as depicted in the figure. Among these, four are designated for blowing (marked as 'c'), while the remaining four are allocated for base pressure (Pb) measurement (marked as 'm'). Base pressure control was accomplished by directing airflow through the designated control holes ('c') using pressure sourced from a settling chamber via a connecting tube.

Additionally, wall pressure taps were integrated into the duct to facilitate the measurement of wall pressure distribution. The first nine holes were spaced at intervals of 3 mm each, while the remaining holes were spaced at 5 mm intervals. It's noted from literature that the typical length-to-diameter ratio (L/D), as depicted in Figure 2, resulting in maximum Pb usually ranges from 3 to 5 without control mechanisms. However, given the utilization of active controls in this study, L/D ratios of up to 10 were employed

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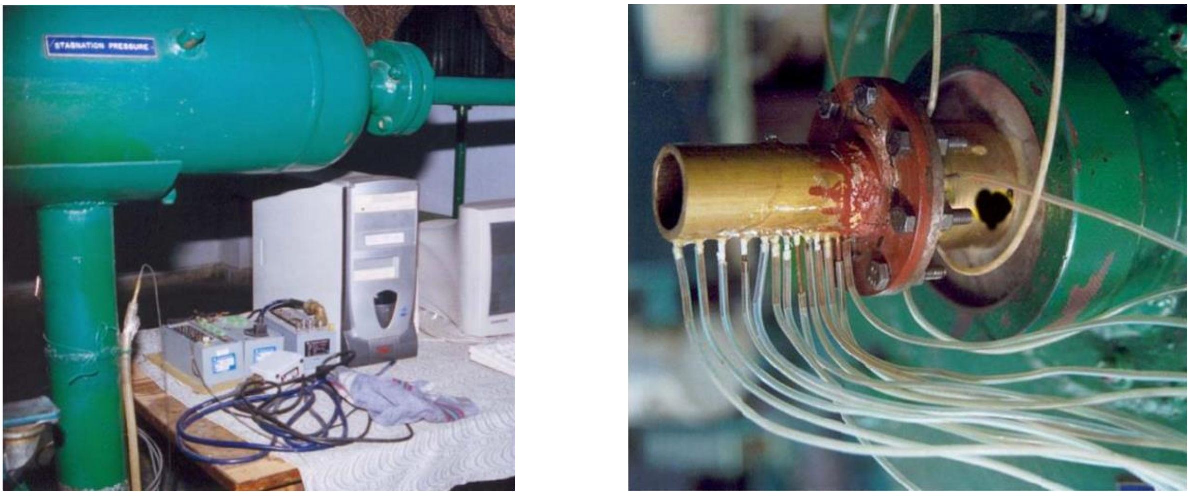


Fig. 1: Experimental Setup

The experimental setup consist an axi-symmetric nozzle followed by a concentric axi-symmetric duct with a larger cross-sectional area. The exit diameter of the nozzle remained constant, while the area ratio of the model, defined as the ratio of the cross-sectional area of the enlarged duct to that of the nozzle exit, was varied to 2.56, 3.24, 4.84, and 6.25 by adjusting the diameter of the enlarged duct. The suddenly expanded ducts were constructed from brass pipe material. The length of the model was set to ten times the inlet diameter to achieve a maximum length-to-diameter ratio (L/D) of 10. Lower L/D ratios were achieved by trimming the length of the duct after testing specific L/D configurations.

Pressure measurements at the base and stagnation pressure in the settling chamber were conducted using a PSI model 9010 pressure transducer. This transducer features 16 channels with a pressure range of 0-300 psi, averaging 250 samples per second and displaying the readings. The manufacturer-provided software facilitated the transducer's interfacing with the computer, offering a user-friendly menu-driven interface for data acquisition. The software allowed for simultaneous display of pressure readings from all 16 channels in a window-type format on the computer screen. Additionally, it provided options to select pressure units from a list, perform re-zero/full calibration, and more. The transducer was operable in temperatures ranging from -20°C to +60°C and 95% humidity, offering versatility across varying environmental conditions

IV. RESULTS AND DISCUSSION

The measured data comprises base pressure (Pb), wall static pressure (Pw) along the duct, and the nozzle pressure ratio (NPR), defined as the ratio of stagnation pressure (P0) to the back pressure (Patm). To normalize the pressures, all measured values will be divided by the ambient pressure (i.e., the back pressure). In this study, the blow pressure will be set equal to the NPR of the respective runs, as air is drawn from the main settling chamber. Thus, no additional energy source is required for micro jets as an active control, representing a major advantage. The primary concern with active control methods is typically the source of energy.

Since the jets in this study are under-expanded, there will be an expansion fan positioned at the nozzle lip, and the flow will pass through this expansion fan before expanding into the duct. Consequently, the flow becomes wave-dominated in the vicinity of the base region, where recombination and reflection of the expansion wave occur.

It's noteworthy that for this under-expanded sonic jet, an L/D ratio of 1 is insufficient for the flow to attach to the duct wall, even for the lowest area ratio of 2.56. This is attributed to the fact that although the Mach number at the nozzle exit is one, due to the under-expansion level of 1.5, the equivalent local Mach number may be supersonic. This supersonic Mach number deflects the flow away from the base region, resulting in an increase in reattachment length. The higher inertia of the flow prevents it from reattaching to the duct wall, even for the smallest area ratio.

For area ratios of 4.84 and 6.25, the base pressure increases with increasing L/D ratios. However, for lower L/D ratios, specifically 3.24 and 2.56, the base pressure reaches a minimum value at L/D ratios of 3 and 2, respectively. Subsequently, the base pressure shows only marginal variation with L/D ratios up to L/D = 6. Further increases in L/D from 6 to 8 result in an increase in base pressure, although the variation is only marginal. Interestingly, for L/D ratios between 8 and 10, the variation in base pressure is minimal across all conditions.

Across all L/D ratios and area ratios, the effectiveness of control is only marginal. This suggests that the minimum duct length required for flow attachment to the duct wall is L/D = 2 for an area ratio of 2.56, whereas for an area ratio of 3.24, this requirement is L/D = 3. However, for area ratios of 4.84 and 6.25, the minimum duct length required is L/D = 6.

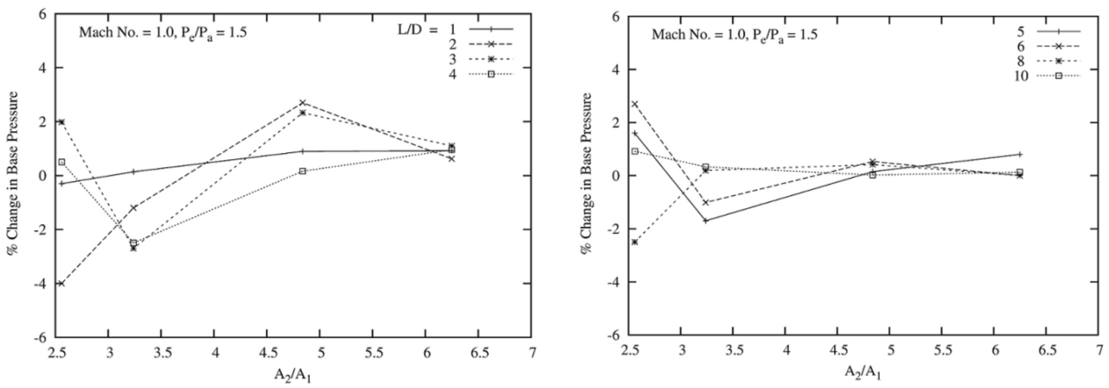
The observed behavior can be attributed to the influence of the wave at the nozzle lip and the relief effect due to the increase in area ratio. The enlargement of the duct area leads to an increase in reattachment length, weakening the base vortex and reducing the base suction created by it. Consequently, lower area ratios exhibit lower base pressure, while higher area ratios exhibit higher base pressure.

Additionally, the location of the micro jets at the base plays a role in influencing the flow field. For area ratio 2.56, the micro jets are positioned at the mid-pitch circle diameter (p.c.d.) 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 and not positioned in the middle of the base. This difference in micro jet location may contribute to the varied behavior of base pressure observed for higher area ratios compared to area ratio 2.56

An important observation to highlight is that, unlike passive controls, a favorable pressure gradient does not necessarily guarantee an increase in control effectiveness for active control methods. It is noted that despite the presence of a favorable pressure gradient, the maximum increase achieved is only about 3%, and the maximum decrease is approximately 4%. This underscores the sensitivity of wave-dominated jets expanded into a duct to factors such as area ratio, expansion level, L/D ratio, and jet Mach number.

The reattachment length is a critical parameter strongly influencing the base vortex, and any change in reattachment length will modify the base pressure. With an increase in the area ratio, the reattachment length increases, leading to a larger flow area and volume of air available in the base region to interact with the base vortex. Consequently, the base vortex's ability to influence the base region weakens, resulting in a higher suction value for higher area ratios compared to lower area ratios. Since the Mach number remains constant, the strength of the vortex remains consistent across all cases.

From Figures 2 (a) & (b), it's evident that the percentage change in base pressure is low for the lowest area ratio for the tested L/D ratios. Additionally, with an increase in L/D, the base pressure decreases for all tested area ratios. This observation underscores the intricate interplay of various factors influencing base pressure and highlights the complexities involved in optimizing control strategies for wave-dominated jets.



(a) (b)

Fig. 2: Percentage Change in Base Pressure Variation with Area Ratio A_2/A_1

It is observed that the minimum duct length required for an area ratio of 2.56 is L/D = 2, while for an area ratio of 3.24, this requirement is L/D = 3. However, for area ratios of 4.84 and 6.25, the minimum duct length needed appears to be L/D = 6. This observation aligns with the findings of Rathakrishnan & Sreekanth [13]. Despite these variations, the control effectiveness remains marginal.

It's important to note that when an expansion fan is present, the shear layer exiting the nozzle is deflected more towards the base, resulting in a decrease in reattachment length compared to a case without the expansion fan. The trend in control effectiveness appears to be wavy in nature, and no definite conclusion can be drawn due to the influence of waves at the nozzle lip, which in turn affects the base vortex and consequently, the base pressure

V. CONCLUSIONS

The analysis of the results reveals that the effectiveness of micro jets in controlling base pressure remains marginal, even under the influence of a favorable pressure gradient. Unlike passive controls, a favorable pressure gradient does not guarantee an enhancement of control effectiveness for micro jets.

Furthermore, it is observed that the minimum duct length required for flow attachment to the enlarged duct wall appears to be L/D = 2 for an area ratio of 2.56 and L/D = 3 for an area ratio of 3.24 in the present study. For area ratios of 4.84 and 6.25, the minimum required duct length is L/D = 6.

Analysis of the wall pressure distribution in the duct indicates that micro jets do not disrupt the flow field in the enlarged duct. However, there is observed waviness within the reattachment length, while downstream, the flow becomes smooth across all cases in the study. This behavior can be attributed to the influence of the base vortex, with this region, constituting 30 percent of the duct length, being within the reattachment length.

All non-dimensional base pressures presented in the paper are within an uncertainty band of ± 2.6 percent. Moreover, the results demonstrate repeatability within ± 3 percent. These findings underscore the reliability and consistency of the experimental data obtained in the study.

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