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Experimental studies of base pressure regulation via tiny jets at high inertia levels

Abstract

The current investigation presents results from an investigation aimed at controlling the base pressure in the flow detached area. The investigation intends to estimate the efficiency of the stream controllers in regulating the base pressure pipes. Microscopic jets of 0.5 mm in radius are sited at a gap of 90^0 at 13 mm starting from the principal axis of the central jet. The inertia levels considered in the present study are M = 1.8, 2.0, 2.5, and 3.0. Axi-symmetric circular pipes were used with the nozzles, and D_2/D_1 1.6 to 2.5. The L/D ratio was varied from unity to 10, and the level of expansion from 3-11. The base pressure depends on the NPR and the speed. When deciding on pressure in the recirculation area, the level of expansion plays a significant role in determining its size. Also, when the jet was released into the pipes with a fixed relief to the flow, the flow attached to the duct for all Mach numbers, and the NPRs were tested. Furthermore, the expansion level significantly affects the base pressure & the controller's capability.

Keywords: microscopic jets, aerodynamic, mach, geometric

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Introduction

In today's high-tech world, aerodynamics plays an increasingly vital role in both industrial and scientific research. Its principles extend beyond aerospace and automotive fields, finding important applications across various everyday technologies. A key example is the nozzle, a mechanism that transforms high-pressure fluid into high-velocity jets. Flow-accelerating devices are essential in many systems that require accelerating gases. The second type is the diverging nozzle, in which the area increases from the entrance to the exit. Although this design is not typically used to accelerate subsonic flows on its own, it plays a crucial role in specific aerodynamic applications. The third and significant type, with aerospace relevance, is the CD nozzle. This flow-accelerating device combines the functions of both increasing and decreasing the nozzle's cross-sectional area.

Moreover, a key element of supersonic nozzle flow is the behavior of the stream in the base region, situated in the downstream section. This section can be divided into 2 main regions by the viscous layer, which serves as an edge between the high-speed jet & the adjoining stationary fluid. The shear layer is a dynamic region where robust vortices form in response to velocity gradients, significantly aiding in drag. Notably, base pressure and base drag are inversely related: as base pressure grows, base drag falls. Reducing base drag is vital because it enhances total system performance.

To enhance stream behavior and minimize drag, stream-control techniques are utilized, primarily in the tube. These approaches are divided into active and reactive types. Active regulation involves blowing and suction. Passive control methods are simpler and more economically effective, depending exclusively on geometric changes to alter stream behavior. Once incorporated into the geometry, passive control devices provide permanent, dependable solutions for steady-flow enhancement at high speeds.

The present study uses dynamic control in the form of micro jets having a diameter of 1 mm at pcd 13 mm. These micro jets use the air from the main settling chamber for blowing. Due to the blowing in the recirculation region, the base vortex, which is very strong, sits at the base and creates base suction, is broken which results in a reduction in the suction and an increase in the base pressure resulting in an increase in the base pressure and a decrease in the base drag and ultimately resulting in a decrease in the fossil fuel consumption and global warming (Figure 1).

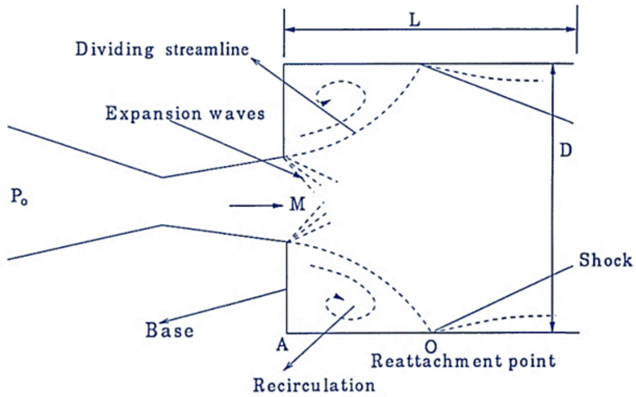

Figure 1 Flow Field with abrupt increase in area.

Literature review

The literature review shows that researchers primarily focus on reactive flow procedures—such as integrating ribs, cavities, and other shape modifications—to mitigate these effects and increase base pressure. For instance, Khan et al.,[1] conducted experiments with semi-circular ribs in streams experiencing sudden expansion at incooperative speeds, with M > 1 and M = 1. They compared their test results with estimates from single-layer and DNN methods, confirming that ribs effectively enhanced base pressure and reduced stream partitioning.

Khan et al.,[2] studied in what manner ribs serve as reactive control devices that influence base pressure at critical Mach numbers. They found that ribs notably boost base pressure by interrupting the separated region and encouraging prior flow reattachment. A recent investigation by Khan et al.,[3] investigated different rib profiles in a flow at sonic Mach M = 1 with an abrupt change in area. This work showed that certain rib designs and arrangements can increase base pressure resurgence, emphasizing the impact of shape in control methods. Furthermore, CFD played a vital part in identifying flow behavior. Khan et al.,[4] modeled streams from a converging nozzle where there is a sudden increase in the area at Mach 1, offering insights into velocity shapes and their effects on base pressure. The findings stressed the effect of nozzle profile and NPR on flow attributes.

Developments in CFD enabled a more thorough assessment. Khan et al.,[5] performed a CFD investigation on base-pressure regulation applying a 1/4th -circle rib design with a sudden expansion tube at Mach unity. Their conclusions showed that quarter ribs effectively reduce stream area, raising base pressure and lowering drag. Moreover, Khan et al.,[6] examined ribs using semi-circular shapes across a range of inertia levels, highlighting their ability to effectively regulate base pressure at specific inertia levels.

Nurhanis et al.,[7] examined base-pressure changes at high-inertia levels during sudden expansion, emphasizing how reactive mechanisms can affect shock and shear layer interfaces. Their findings indicated that well-designed control mechanisms can reduce the impact of opposing conditions. Fakhruddin et al.,[8] conducted numerical simulations to study base pressure regulation at M = 1.2, demonstrating how ribs alter stream configurations and enhance pressure dissemination. This investigation underscores the efficacy of reactive control procedures in administering supersonic flows.

Khan et al.,[9] studied the speed pattern and base pressure in a nozzle through favorable pressure at M = 1.0. Their results provided crucial insights into flow behavior in these environments, thereby advancing efficient control tactics. Meanwhile, Mishra et al.,[10] investigated shock spaces for wedges in a high stream, thereby improving the interpretation of shock interactions at high speeds.

Chaudhary et al.,[11] studied base-pressure management with 1/4-rib configurations in an enlarged tube at Mach 1.8, showing that the rib can reduce large-scale sound effects and improve stream permanency. Mahaboobali et al.,[12] examined reactive manipulation of base flows, focusing on in what way the dimension and location of quarter-ribs influence flow at sonic Mach numbers. Their outcomes emphasized the importance of rib shape and placement for efficient flow management. Chaudhary et al.,[13] analyzed stream management through quarter ribs in an 11 mm-radius tube at Mach 2, highlighting the significance of flow relief in the design of reactive control strategies. Khan et al.,[14] showed a CFD study of high-stream manipulation using quarter ribs, providing a thorough understanding of their performance across various settings. Shetty et al.,[15] conducted a thorough CFD replication of base pressure control using quarter ribs at Mach M = 1.3, checking their effectiveness among several Mach numbers. Bellary et al.,[16] modeled base pressure regulation in a rapidly expanding tube at Mach 1.6 using one-fourth round ribs. Their results helped optimize rib designs for improved flow control.

Baig et al.,[17] studied the base flows using monor jets, showing their potential to adjust base pressure & reduce drag. Rehman et al.,[18] dedicated to regulating base pressure via microjets, giving insights into the device and operation of dynamic flow management.

In light of these assessments, we can conclude that this investigation will contribute new knowledge to the technical database and will be beneficial for the blueprint of an aerospace vehicle.

Experimental facility

The analyses were carried out using the test setup depicted in Figure 2 at the Supersonic Aerodynamics Research Laboratory (HSAL) at BIT, Mangalore, India. The diagram indicates that the nozzle lip features 8 holes: 4 (denoted c) were designated for propulsion, while the others were used to measure base pressure. These marked holes enable control of the base pressure by blowing and using the container pressure, connected through a tube interfacing with the tank and pressure gaps (c). Figure 3 displays the air storage space. The provision includes 2 storage capacities, each of which can store air at nearly 15 bar. Figure 4 depicts the experimental setup, comprising a stagnation tank, a model frame, a three-dimensional track, and a regulation compartment. Figure 5 indicates the nozzles and pipes used in the investigation.

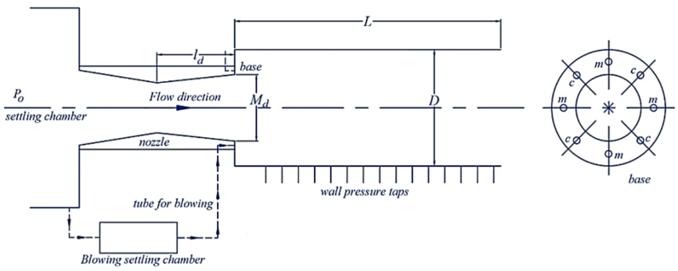

Figure 2 Test setup.

Figure 3 Storage tank.

Figure 4 Laboratory view.

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Figure 5 Nozzle and tube.

Results and discussion

This study investigates the efficacy of active regulation using microjets positioned at the base of suddenly expanded axisymmetric pipes to alter base pressure. The factors examined include the duct-diameter ratio, the L/D ratio, the jet-inertia magnitude, and the expansion level (NPR). Base pressures are non-dimensionalized by partitioning by atmospheric pressure, which is the pressure of the flow discharged from the tube. The results compare base pressure values with and without flow regulation. In this research, the inertia level and NPR range are such that, at Mach 1.8 and 2.0, the flow experiences over-, correct, and under-expansion conditions. In contrast, at Mach numbers 2.5 and 3.0, the flow remains over-expanded across all NPR values. While nozzles are over-expanded, a shock forms at the nozzle lip, and its formation, recombination, and reflection against the duct wall continue until the pressure matches the ambient pressure.

The expansion level for M = 1.8 in the NPRs examined is (i.e., P_e/P_a = 0.52, 0.87, 1.21, 1.6, and 1.91). For Mach 2.0, the (P_e/P_a) are 0.4, 0.64, 0.89, 1.15, and 1.4. Similarly, for Mach 2.5 (P_e/P_a), they are 0.18, 0.29, 0.41, 0.53, and 0.64. Lastly, for Mach 3.0 (P_e/P_a), they are 0.08, 0.14, 0.19, 0.25, and 0.3.

Effect of expansion level on base pressure and regulation effectiveness

Figure 6 to Figure 9 show cross-plots that illustrate how jet Mach (M), tube L/D, and expansion level collectively affect the base pressure across various parameter sets. Jet Mach numbers above 2.0 significantly affect base pressure, as illustrated in the figures. Highly over expanded jets cause a continuous drop in base pressure, with a sharp decline between L/D values of 3 and 6, followed by a more gradual decrease from 6 to 10. Although control efficiency is limited for extremely under expanded jets, it improves significantly as NPR nears the optimal expansion, leading to a substantial reduction in base pressure and better control. L/D has a small effect on both base pressure and control effectiveness, especially for under expanded jets, with this effect becoming more noticeable at higher under-expansion levels. Control works best at the highest under-expansion level, specifically at NPR 11.

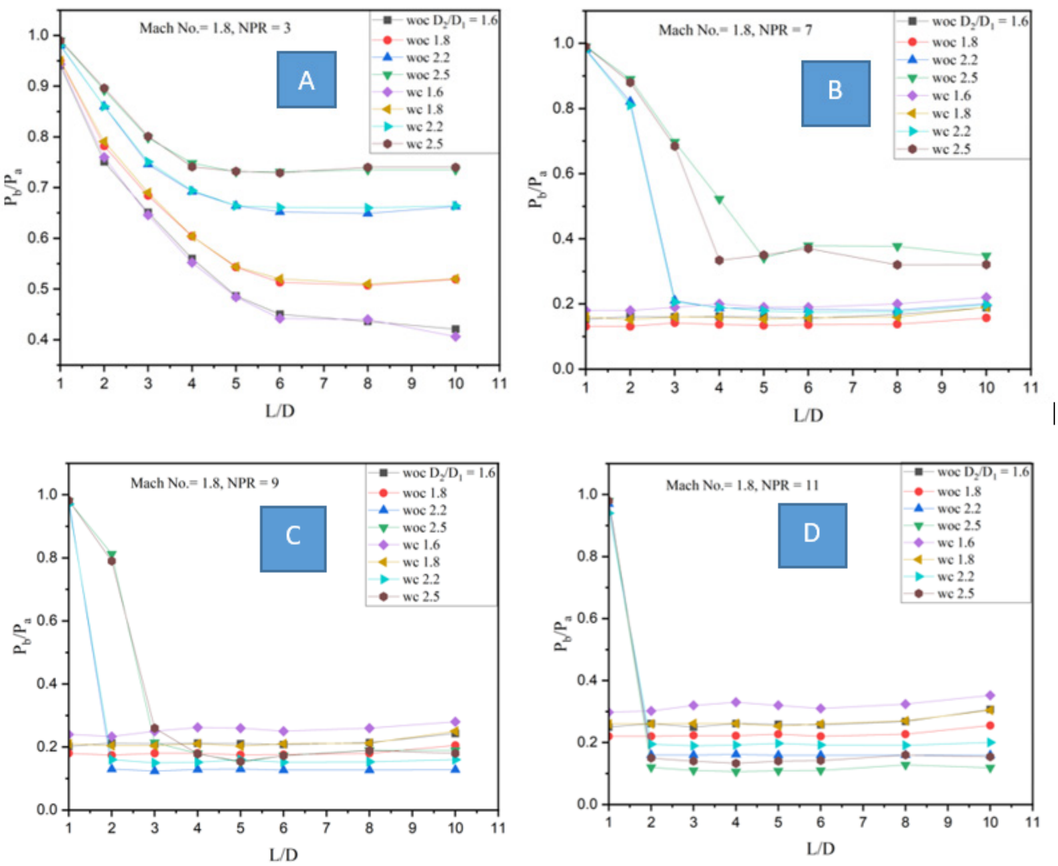

Figure 6 Pb/Pa Vs. L/D for various NPRs and duct diameters.

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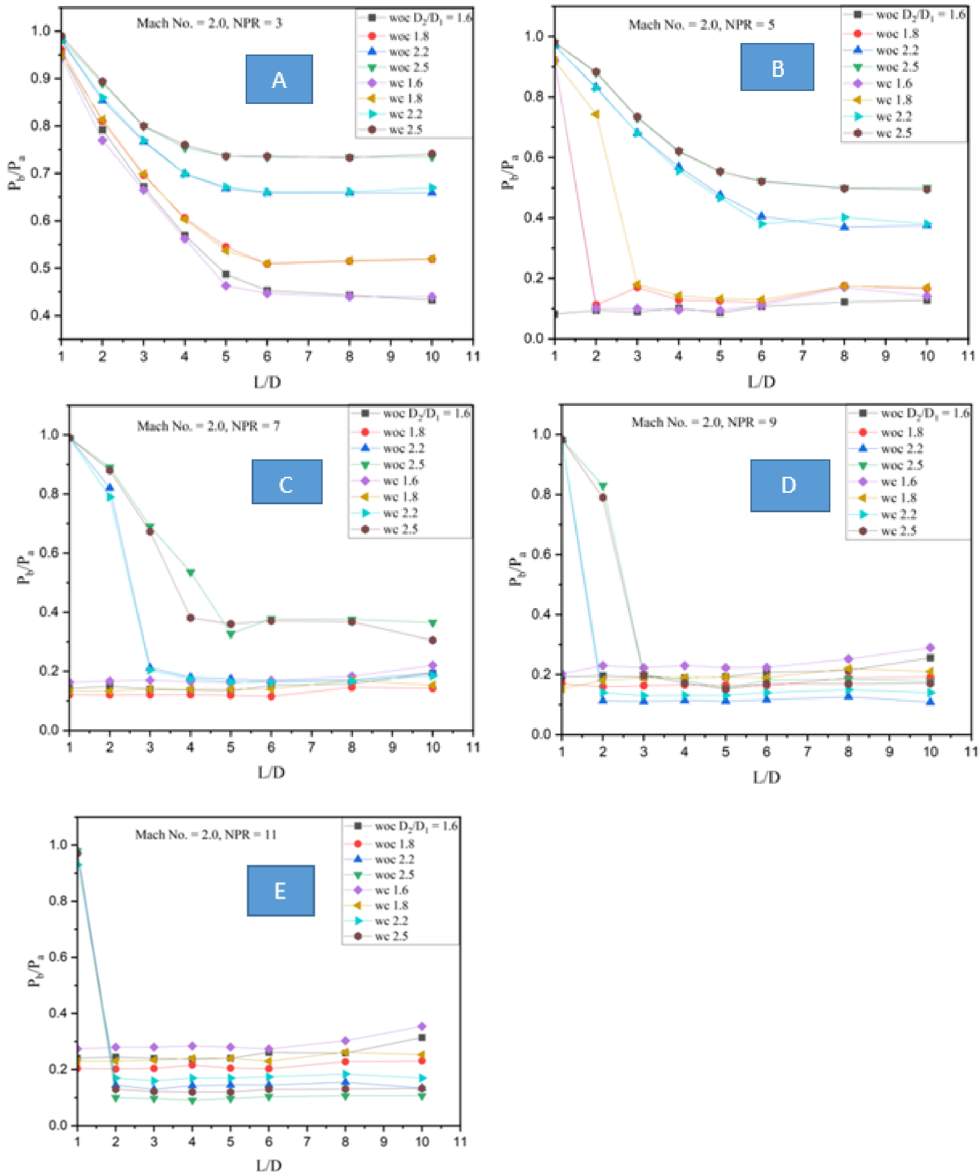
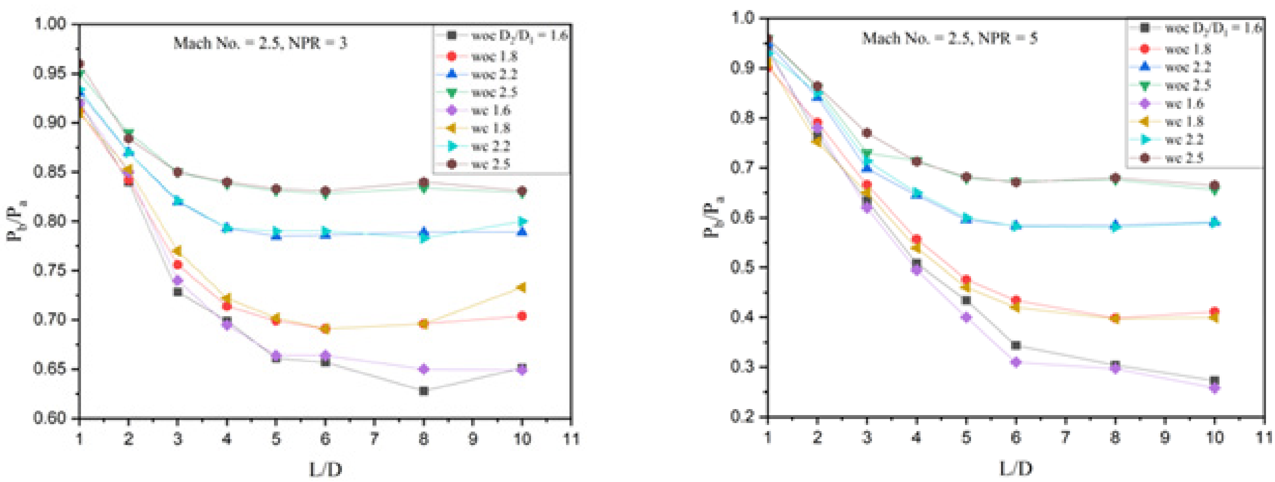


Figure 7 Pb/Pa Vs. L/D at various NPRs and duct diameters.



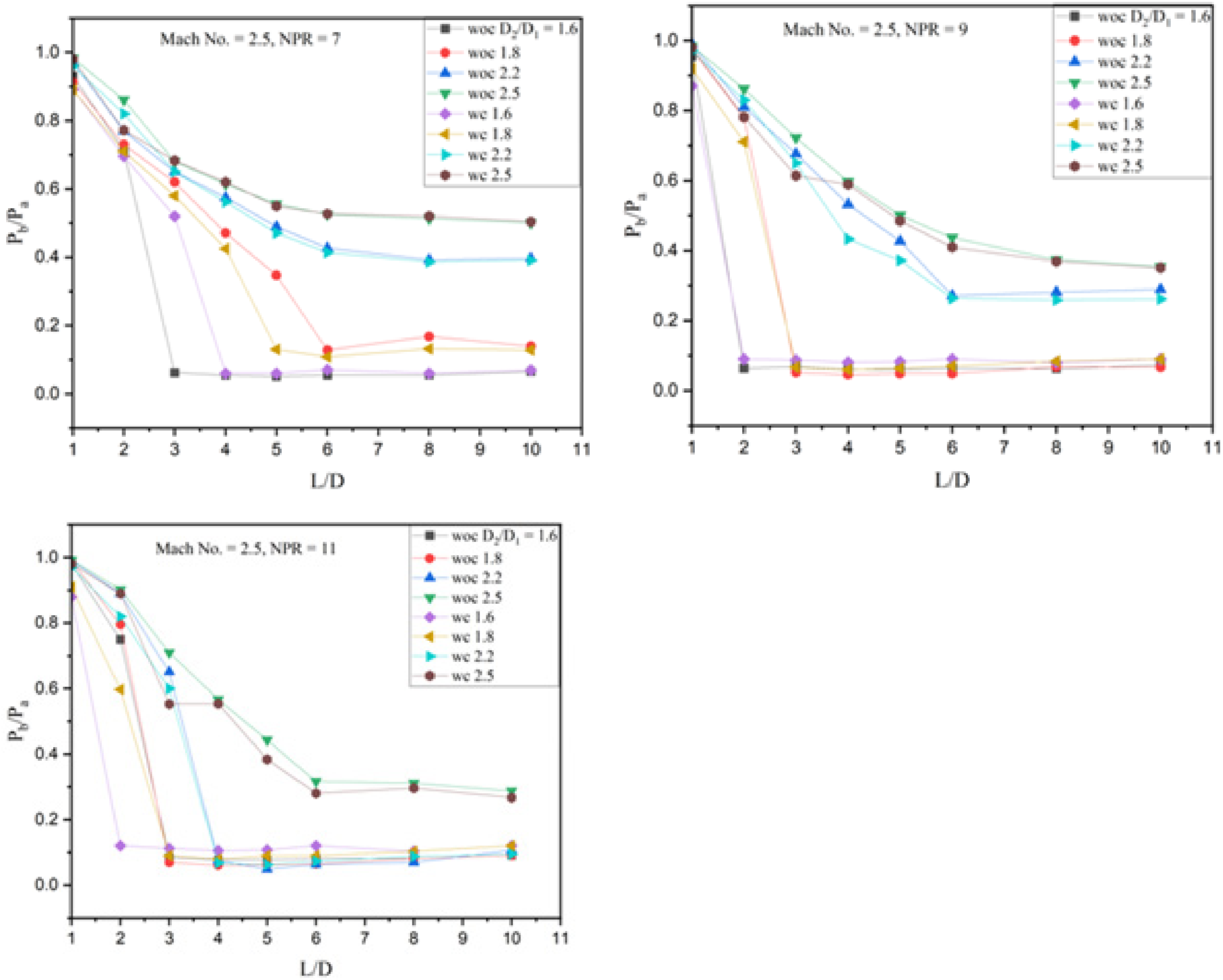
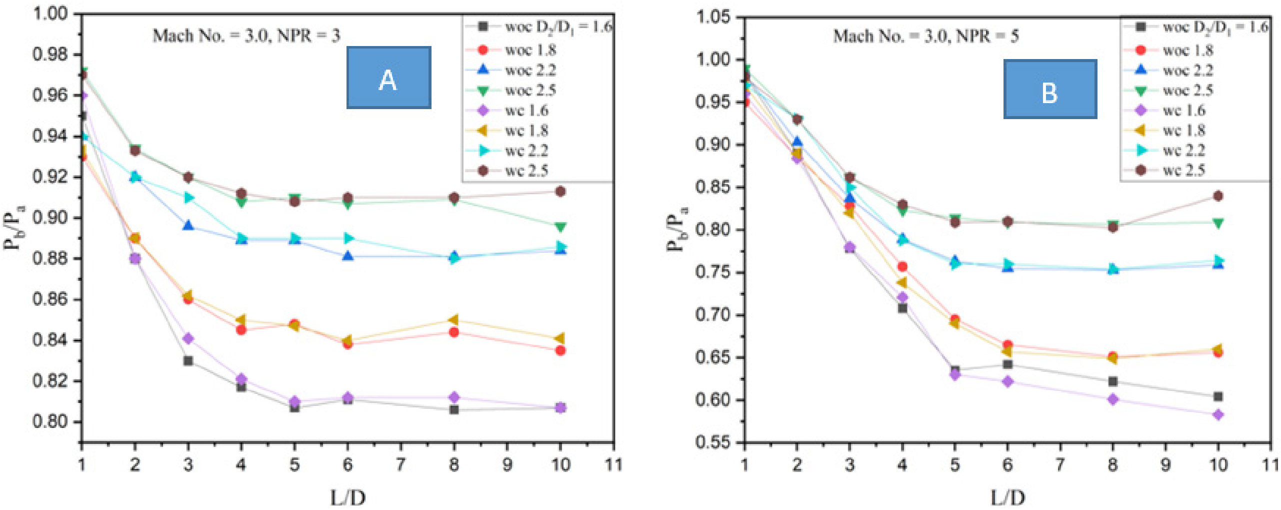


Figure 8 Pb/Pa Vs. L/D at various NPRs and duct diameters.



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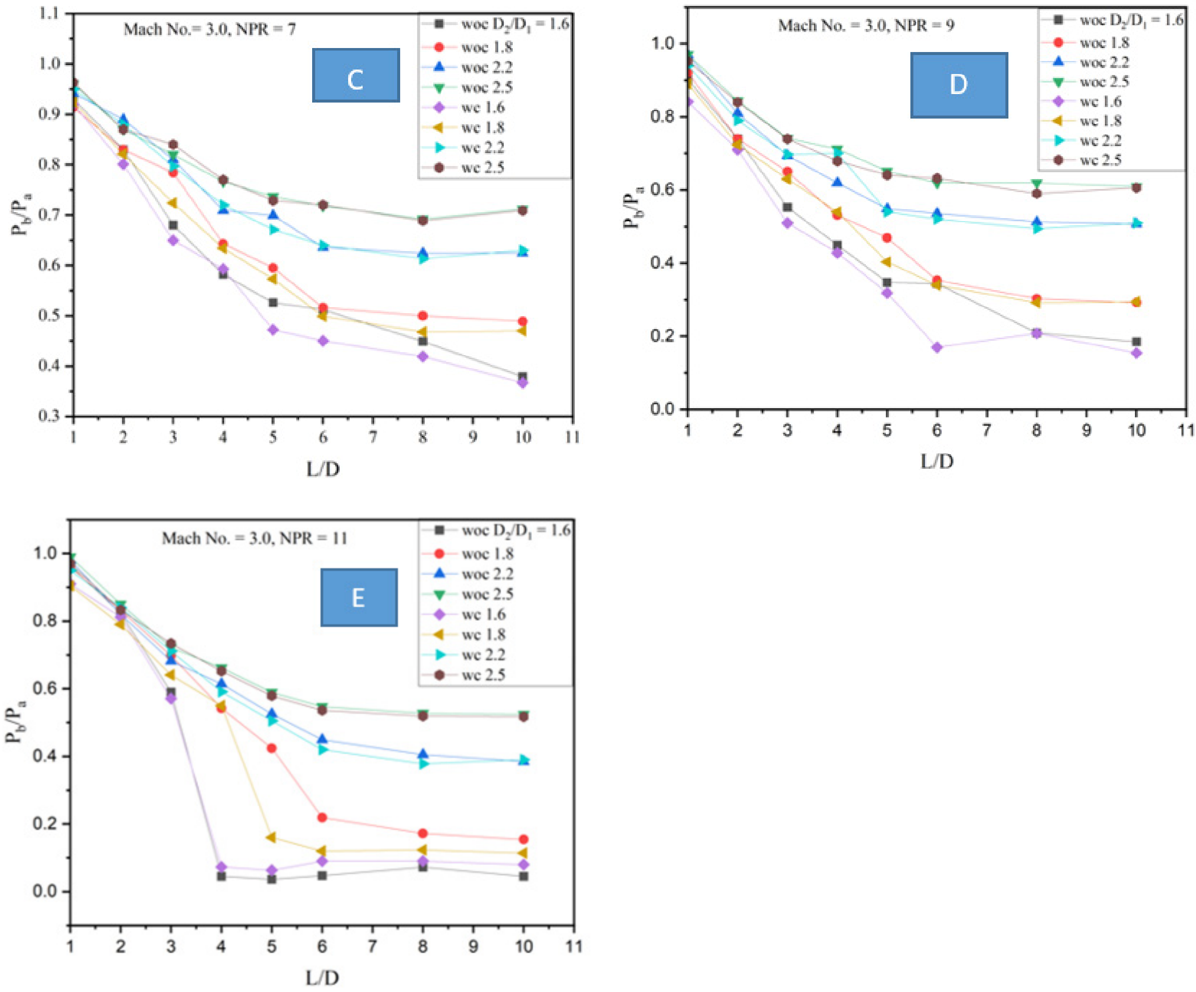

Figure 9 Pb/Pa Vs. L/D at various NPRs and duct diameters.

Since the nozzles are over-expanded across the entire NPR stretch. In view of the limitations of the experimental set-up, we were unable to run the tunnel at NPRs above 11. That has hampered the assessment of the micro jets at high NPRs, namely Mach 2.5 and above. However, if we perform numerical simulations for NPRs greater than 11, once the nozzles are operated beyond the NPR essential for ideal expansion, it is expected that dynamic regulation through tiny jets will become operative, increasing the base pressure. Any rise in base pressure will reduce base drag, leading to an increase in the missiles' and rockets' range and, hence, a decrease in fuel consumption and a reduction in global warming.

Similar outcomes are seen for M = 2.0. For M = 2.5 and 3.0, all the NPRs examined generate overexpanded jets. Notably, at M = 2.5, NPRs 3 and 5 exhibit base pressure fluctuations similar to those at lower Mach numbers, whereas NPRs 7, 9, and 11 keep the base pressure steady with L/D. Control effectiveness appears to increase with NPR, as measured by NPR. For M = 3.0 (see Figure 9), all NPR values show a decline in base pressure as L/D increases. Notably, at these Mach numbers, certain NPRs (NPR = 7 for M = 2.5 & NPR = 11 for M = 3.0) have low base pressure at L/D = 3, and in this condition, the jet noise drops significantly.

The same holds for M = 2.5 and 3.0, except that control effectiveness has decreased even at the highest NPR of 11 at Mach 3.0. The end result for the area ratio 6.25 is displayed in Figure 8

These results confirm that, once again, the base pressure remains unaffected by L/D in under-expanded jets. For M = 2.5 and 3.0, the control decreases the base pressure at NPR 11. However, this decrease cannot be directly linked to the overexpansion level, as the control's effectiveness is greater at M = 2.5 than at M = 3.0 for NPR 11. The discussion shows that both L/D and NPR significantly impact the base pressure and control effectiveness. Nevertheless, the trend cannot be generalized because it varies on a case-by-case basis. This variability results from the combined influence of the expansion level and relief caused by increased duct area on the base pressure.

Collective consequence of expansion level and relief on base pressure

This study examines the combined influence of NPRs and the area ratio by presenting base-pressure cross-plots that show how base pressure varies with L/D across diverse relief-to-stream and inertia levels (see Figure 6 to Figure 7). Only NPRs 3 and 11 are highlighted for various inertia levels and relief. Notably, the base pressure level changes when the NPR is switched from 3 to 11. For instance, at M =

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1.8 and NPR = 3, the lowest base pressure occurs at an area ratio of 2.56, whereas at NPR = 11, the same Mach number yields the highest base pressure for this area ratio. Conversely, the lowest base pressure is observed at an area ratio of 6.25, which was the highest at NPR 3. Despite this, the increase in control effectiveness with higher NPR remains consistent at a given jet Mach number. This suggests that identifying the optimal combination of jet-inertia level, relief, NPR, and L/D is essential to achieve the desired base pressure, regardless of whether control is used.

Conclusion

From the above deliberations, the inferences are as follows:

a) The base pressure is induced by the NPR and the inertia of the nozzle. When calculating the base pressure, the NPR is crucial in establishing its value.

b) The location of reattachment is influenced by the expansion level, Mach number, and flow relief. A higher area ratio leads to a longer reattachment length and, consequently, higher base pressure. Conversely, a decrease in stream relief results in a strong vortex and reduces base pressure.

c) The active control mechanism performs least effectively when nozzles experience an adverse pressure gradient. Conversely, its efficiency increases significantly under a favorable pressure gradient. These findings reaffirm that stream regulation—whether static or dynamic—is most effective when nozzles are subjected to a favorable pressure gradient.

d) With a progressive rise in NPR, the strength of the oblique shock diminishes, which enhances the control efficiency of the control mechanism.

e) The smallest tube segment required for the stream to continue to attach to the tube wall is L/D = 2 at Mach M = 1.8 & 2.0. However, for Mach 2.5 & 3.0, the lowest tube dimension needed appears to be L/D = 3.

Recommendations for future work

Based on the discussion and experience gained, it is recommended that one try to adjust the PCD of the micro jets to account for their locations. This change in the radial location of the micro jets may give some interesting results. In this case, even though NPRs are quite high, the micro jets remain at Mach unity; hence, it is suggested that one can use a micro-converging-diverging nozzle for the micro jets instead of a circular orifice. When the dynamic control is operated at supersonic Mach numbers rather than sonic Mach numbers, it yields interesting results.

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Conflict of interest

Author has no conflicts of interest.

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