Influence of Microjets on Flow Development at Supersonic Mach numbers with Sudden Expansion

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Abstract. This paper presents the control of suddenly expanded flow using four microjets at the base recirculation zone for a diameter ratio of 1.8. Eight Mach numbers are considered for investigations from 1.25 to 3. The NPRs for which the tests were conducted were from 3 to 11. The duct length considered was \( L = 10D \) to 1D. This article has shown only selected results when there is significant variation in the duct's flow field; only those cases are considered. For most of the cases, the flow remains identical with and without control. For Mach \( M = 1.25 \) to 2.5, the control results in decline in the duct's pressure when the flow is within the reattachment length. Later there is a progressive rise in the duct pressure. However, the trend is reversed at Mach \( M = 3.0 \). The least duct stretches necessary intended for the stream to continue to relate to the pipe is \( L = 1D, 2D, \) and \( 3D \) for the study's Mach number. The first section in your paper

1. Introduction

In specific applications, such as aircraft or rockets/missiles, the nozzle flow is connected to a large duct with sudden expansion. After the nozzle, the enlarged duct is provided to maximize the stream of the nozzle. Because when the flow is expanded in a dilated duct, the separated zone's pressure is usually lesser than ambient pressure, resulting in colossal base drag. Figure 1 represents the distinct features of a suddenly expanded duct. The viscous layer emerging from the nozzle is mended to the circular duct, renowned as the reattachment juncture. The distance between the exit of the nozzle (A) and the moment the flow hits the enlarged duct wall (O) is recognized as the reattachment distance. The reattachment position will be contingent on the L/D ratio, the NPR, the Mach (M), and the enlargement zone accessible to the shear layer. The suction generated in the base corner by the availability of a dominant tidal wave in the circular duct’s base area causes recirculation of the flow [1]. After the nozzle, the stream is exhausted to the inflated duct. A literature review shows that the reattachment length is a function of step height, the NPR, duct length, and the Mach number. The degree of flow expansion from the nozzle results in an increased nozzle pressure ratio [1], [2]. Quadros et al., [3]–[6] applied various techniques to study the suddenly expanded flows, base pressure
behaviors, and different Mach numbers. Their study shows area ratio is of the least significance. Azami et al., [7], [8] reported that the utilization of microjets as active monitor does not disturb static pressure inside the conduit. The L/D ratio of the duct's sudden expanse, degree of dilation, pressure rate of the nozzle (NPR), and inertia level as Mach (M) all influence the pressure in the separated zone if the flow is unprotected to the suddenly expanded area of the shear layer.

Faheem et al. [9] investigated the effect of microjets using a Mach 1.1 nozzle. The results conclude that though microjets' use resulted in reduced pressure at the base and decreased corresponding drag, these parameter groupings contributing to an 83 % rise in overall pressure.

In the brief literature review present above, many researchers have controlled base pressure and wall pressure using various combinations of Mach numbers, nozzle pressure ratios, and length to diameter ratios to explore suddenly expanded flows' characteristics. Previous studies reveal that there is still scope in optimizing the size to diameter ratio of enlarged ducts. In the recent research of Pathan et al. [10], a numerical analysis was done using three Mach numbers and four nozzle pressure values. Therefore, the present study is an experimental investigation to optimize the enlarged duct length concerning wall pressure and microjets to investigate the flow's control effect.

2. Experimental Procedure
The schematic CD nozzle block and the circular duct used in the present work are shown in figure 2. At the exit perimeter, there were eight micro-holes drilled. Four holes are marked a “c,” and the remaining four are marked as “m.” Microholes “c” is used to blow secondary flow as microjets by controlling the blowing settling chamber. At the same time, “m” holes are used to evaluate base pressure. Sixteen pressure taps are placed side-by-side on the circular duct to record the duct's pressure variation. The nozzle block and duct are machined in brass material using CNC machines.

Figure 3 represents the schematic of the high-speed jet Lab used in the present investigation. The facility is located at IIT Kanpur, India. The facility's main features are a vast storage capacity of compressed air up to 85m³ and three electric-powered reciprocating compressors that can deliver a pressurized air of 0.17 m³/sec. A mixing length of 2m is available between a cylindrical-shaped
settling chamber and a pressure regulating valve (capable of controlling 0 - 300psi) to minimize flow disturbances [14]–[17]. CD nozzles with Mach numbers 1.25, 1.3, 1.6, 1.8, 2.0, 2.5, and 3.0 are used in the present experimental investigation. Pressure measurements were done for L/D 1 to 10 at NPRs 5, 7, 9, and 11. The experimental results are presented in the next section.

3. Results and Discussion

This section deliberates the examination results in the abruptly expanded duct wherein the enlarged duct the flow is regulated using an energetic control in the type of microjets. The control mechanism was a vent of 1 mm diameter. The jet exiting from the microjets had Mach number unity despite NPR being far beyond the value of 1.89 needed for choked flow conditions. The microjets will be highly under-expanded jet because of the high NPR range. The discussion focuses on the impact of the regulators on the control mechanism stream growth and efficacy. During the experimental investigation, we collected voluminous data. For most of the cases, the flow pattern in the duct was unaffected by the microjets. However, there are some cases where there a considerable change in the flow field. In the discussion to follow, we focus only on such results for deliberations. In the conversation, we consider NPR ranges from 11 to 3, diameter ratio 1.8, Mach number, and the duct size indicating changes in the flow field. In this case, the area ratio 3.24; hence, the microjet's location will be away after the base corner and closer to the core jet, which will impact the control mechanism’s control efficacy.

When Mach M = 1.25, the finding of this study is shown in figure 4 ((a) and (b)) for L = 2D and 6D for NPR = 5. The flow is investigated at the design NPR = 2.59, and the outcomes we are deliberating are for NPR = 5, which is other than the NPR essential for design NPR. This means that the nozzles face a helpful pressure gradient, and the level of under-expansion is 1.93. For a short length of the circular duct, the flow is impacted by the free stream conditions, explaining the fluctuating trend in the control effectiveness and the flow quality inside the duct (figure 4 (a)). Also, the size of the duct L = 2D seems to be sufficient to keep the flow connected to the pipe. In the pipe length, L = 6D, the flow field is oscillatory if the flow remains within the reattachment length. Beyond this point, the pressure rises till it attains the atmospheric pressure value.

![Figure 3. Schematic of the highspeed jet facility [12], [13].](image)

![Figure 4. Flowfield at Mach 1.25.](image)
At Mach \( M = 1.3 \) figure 5((a) and (b)) show the outcomes of the wind-tunnel test data for the highest NPR of the present investigation (i.e., NPR = 11) when the pipe lengths are \( L = 2D \) and 6D. Since NPR = 2.77 is needed for correct expansion and tests are conducted for NPR = 11, with under-expansion level of 3.97 (Pe/Pa = 3.97). As the nozzle is beneath the impact of a beneficial pressure ascent at the duct location \( x/L = 0 \), the pressure is low as the expansion of the flow occurs while the shear layer passes through the expansion fan (figure 5(a)). The shear layer gets reattached with the wall, and shock is reflected, resulting in a sudden leap in the pipe pressure. During shock reflection, the increase in pressure is twice the ambient pressure. Again, due to the expansion of the flow, the pressure decreases. For a location \( x/L = 0.6 \) the flow recovery starts. This trend may be due to the small duct length, as the free stream conditions impact the flow field. When the control mechanism is activated, it decreases pressure along the length till \( x/L = 0.6 \). At the end of the duct from \( x/L = 6 \) and beyond, the control results in the rising pressure. In long duct length \( L = 6D \), the increase in pressure is lower than for \( L = 2D \). The pressure value is decreased by nearly 22%. The pressure values reduction is due to excessive shock wave interaction among themselves and the duct wall. For pipe length \( L = 6D \), the impact of the ambient conditions is minimal. When flow regulators are used, they decrease pressure along the entire length of the tube.

![Graph](image1.png)

**Figure 5.** Flowfield at Mach 1.3.

The findings of the experimental tests for Mach 1.6 are exhibited in figure 6 ((a) and (b)) for duct length \( L = 4D \) and 6D. NPR needed for perfect expansion is 4.25, whereas the results are presented for NPR 5, which implies that the under-expansion level is 1.2 (i.e., Pe/Pa = 1.2). The pressure energy is more than 20% required while considering the flow to be ideally expanded. Having this level of under-expansion when the flow departs, the nozzle sees an expansion fan and gets developed, leading to low pressure at a level of 0.2. Later, owing to the interaction of waves inside the duct, a sudden increase in intensity in the pressure, and this compression and expansion process continues till \( x/L = 0.6 \) (figure 6 (a)). Once the control mechanism is activated, it results in a marginal change in the flow pattern and oscillations. The impact of control is to decrease the pressure with increased intensity. Similar results are observed in figure 6 (b), where duct length is increased by 50%. Even though the initial values of pressure are the same as that for \( L = 4D \), due to the considerable duct length, the shock wave’s strength is more pronounced than the lower size of the duct. Further, it is noticed that inside 50% of the pipe length, the flow in the duct with and with no control is identical later, the pressure retrieval is smooth, and control outcomes in a reduction of pressure. The change in the flow pattern and reversal is attributed due to the impact of the ambient pressure.
Figure 6. Flowfield at Mach 1.6.

Figure 7 ((a) to (b) show the outcomes at Mach 1.6 for duct length 3D and 10D at NPR = 7. The design NPR needed at Mach 1.8 is 5.75. As figure 4 shows results for NPR 7, the nozzles are under the impact of beneficial pressure, and the favorable level is 1.22 (i.e., Pe/Pa= 1.22). Figures 6 and 7 indicate that even though the Mach numbers are 1.6 and 1.8, the under-expansion level is 1.2 and 1.22. When the shear layer departs at nozzle’s exit, the pressure is also the same as the jets pass through the expansion fan, and pressure decreases due to the flow’s expansion. In the case of Mach 1.8, the under-expansion level is marginally high. It is 2% more than at Mach 1.6. Due to a 2% increase in under-expansion level, the pressure is also decreased accordingly. For the duct’s short length, the pressure fluctuations are less than the duct’s long length. This change in these two duct lengths is due to the waves’ excessive interactions with the duct wall at L = 10D.

For shortest duct length L = 1D, NPR = 9 & 11 at Mach 2 are displaced in figure 8 ((a) to (b)). The design NPR for this Mach is 7.82. Therefore, the level of expansion at these two NPRs is 1.2 and 1.4. The nozzle flow is under-expanded and has 20% & 40% more pressure energy at the nozzle’s exit and needs to expand through the expansion fan before attaining the ambient conditions. The trends in the flow fields are on the expected lines. After going through the expansion, pressure attains a low value of 0.2, later due to the shockwave’s interactions and reflections, here is a rapid upsurge in pressure. Later pressure attains a value which 35% and 20% less than the ambient pressure. Even though it was expected that pressure would be equal to the ambient pressure, the backpressure impact is minimal due to the strong shock for this short duct. The effect of NPR is established here. When the control is employed, its influence is changing along the length of the pipe. Initially, up to 45% of the duct length pressure decreases later from x/L = 0.45, and above the control, the impact is to enhance the pressure, and the flow remained attached for this length.
The results for Mach 2 at the duct lengths $L = 3D$, $5D$, and $6D$ are shown in Figure 9 ((a) to (c)) when NPR = 7. For NPR = seven, the nozzle is marginally over-expanded with an adverse pressure level of 0.9. Due to NPRs combined effect, the pipe length, and the backpressure, the duct flow trend differs from when the length is 5D or 6D. The control outcomes in decline in pressure for this length of the pipe. For $L = 5D$ & $6D$, the shock waves reflect at around $x/L = 03$ to 0.4; a strong shock wave is created due to the considerable duct length.

For Mach 2.5, findings at NPRs 9 and 11 having a duct length 1D & 2D are presented in figure 10 ((a) to (d)). The design NPR at Mach 2.5 is 17, where the results are shown for NPR = 9 & 11, resulting in an over-expansion level of 0.53 and 0.65. It is evident from figure 10 ((a) to (b)) that the duct length is inadequate for the stream to continue connected. However, control influences negatively. When the duct length $L = 2D$, the duct's flow is assured, and control results in reduced pressure. For NPR 11, the negative trend is more pronounced. Flow from the nozzle faces adverse pressure, leading to a shock wave at the nozzles exit. When the viscous layer moves across the shock wave, there is a quick leap in pressure depending upon the shock strength. The effect of shock strength and resulting pressure are seen in figure 10 ((c) and (d)), due to the difference in over-expansion level and hence the shock strength. It is observed that the preliminary values of pressure in the absence of a flow regulator are the same. When the control is on, it decreases pressure, and the decrease corresponds to the over-expansion level and hence the shock strength. Further, it is seen that the decrease in pressure is more within the reattachment length due to the interactions of the base vortex with the microjets.
For the same Mach 2.5 and NPRs as discussed above, the present study outcomes for a duct length $L = 6D$ are shown in Figure 11 ((a) to (b)). Since the duct length is considerable, the initial pressure values are significantly low, and a sudden jump in pressure is seen due to the intense shock when it is reflected from the surface of the duct. For NPR 11, when the control has been employed, the decrease in pressure is more than at NPR 9, due to the change adverse pressure jet is undergoing. From the reattachment onwards, the growth in the static pressure is progressive and attains atmospheric pressure.

With a further increase in the duct length of $8D$, the results at NPRs 9 & 11 are displayed in Figure 12 ((a) to (b)). There is an increase in the duct length only, and the rest of the parameters are the same. When the shear layer exits the nozzle, the initial pressure remained the same as the NPRs, but the
pressure jump is marginally more due to the increased length. The oscillations are more in the flow due to the excessive interactions of the incident and reflected shockwaves. As expected, the control mechanism will behave negatively whenever adverse pressure exists, leading to a lower pressure, and the same is seen in the figures. Due to the nominal increase in the NPR, the control efficiency is also marginally modified.

For the most considerable duct length of 10D, the current studies’ finding is depicted in figure 12 ((c) to (d)), keeping the inertia level and the NPR ranges the same. There is little change in the initial pressure data when the flow crosses the nozzle exit. Once the shear layer enters the duct, the shockwave’s strength is reduced considerably, leading to a substantial decrease in the pressure ratio and increasing the magnitude. Here the extent of the pressure jump is reduced by 50%. There is a further rise in the pressure because the shock intensity growth is 50% of the base value. The flow pattern for both the NPRs is almost identical with negligible variations. The control marks a decrease in pressure.

![Graphs showing pressure ratio vs. x/L for different NPRs and duct lengths.](image)

**Figure 12.** Flowfield at Mach 2.5.

Results for largest Mach $M = 3.0$ of the present investigation at duct length $L = 5D, 6D,$ and $10D$ at NPR 9 and 11 in figure 13 ((a) to (f)). The design NPR is 7, but we have done experiments for NPRs in the range from 3 to 11 due to the setup’s limitation keeping in mind the structural integrity. The over-expansion levels at these NPRs are 0.24 & 0.3. This implies that the level of over-expansion is very high.

In figure 13 ((a) and (b)) at $L = 5D$, it is seen that, as usual, the initial pressure is very low for both the NPRs of the present investigations. At NPR 9, there is a sudden increase and decrease in pressure at $x/L = 0.4$. It may be due to the presence of reflected shock waves beyond the reattachment point. In this case, the reattachment point seems to be located at $x/L = 0.2$. Because of the existence of undesirable pressure, the control result in a decrease in the static pressure. Here is a progressive boost...
in the duct’s pressure and becomes identical to the free stream pressure. When we see these outcomes, we see at NPR 11, control efficacy has a mixed trend. The pressure decreases considerably within the reattachment juncture, and outside the reattachment point, there is a considerable increase in the duct’s pressure till it reaches the ambient pressure. This is a peculiar phenomenon that is happening at this NPR. It may be due to the combined effect of the duct length, interactions of the waves, influence of the atmospheric pressure for short duct length, and increase of the NPR from 9 to 11, the decrease of over-expansion level.

When the duct length is increased to 6D, figure 13 ((c) and (d)) indicate that the increased size has created more suction, and hence when the flow interacts with the base vortex, shock waves leading to further reduction in the pressure. Under these circumstances, when the control is activated, the regulator management cannot impress the flow field and get convected without impacting the recirculation zone’s flow field. For NPR 9, the flow with and without control is nearly the same, with a marginal increase in pressure beyond the reattachment point. However, at NPR 11, the trend is different, anticipated to the rise in the level of expansion. Within the recirculation zone, the control has a negative influence. Once the flow has departed the reattachment juncture, there is a progressive growth in pressure due to the regulators’ presence.

For the most considerable duct length 10D, the flow pattern is different. At NPR 9, the flow field is unaffected by the microjets presence except for nominal pressure growth. Nevertheless, at NPR 11, the pressure is further decreased. Within the separated zone, control efficacy is not significant. Once the flow has crossed the flow separated area, it is free to grow. There are Small oscillations in the duct flow in the absence of control when the control is activated, resulting in a minimal rise in the pressure. Near the exit of the duct, the flow becomes identical and attains ambient conditions.
4. Conclusion
The results show that the flow remained attached for lower Mach numbers for duct length as short as \(L = 1D\). For Mach \(M = 2\) and above, this requirement is \(L = 2D\). In most cases, the control decreases the duct's pressure for an initial sixty percent length of the pipe. When ambient pressure influences the duct flow field, the control trend reverses, and there is a rise in the duct pressure. The rise and drop in the pipe pressure are analyzed on a case-to-case basis as the duct's flow field is dominated by excessive shock wave interaction. Hence, we cannot generalize the behavior. The flow pattern is dependent on inertia level, expansion level, relief available to the flow, and the duct length. For Mach \(M = 3\), the control has increased the pressure for all the duct lengths and NPRs. Within the reattachment length, the control has resulted in a reduction of the pressure. The oscillations are relatively at a marginal level for considerable duct length.

References
[1] Pathan, K. A., Dabeer, P. S. & Khan, S. A. An investigation to control base pressure in suddenly expanded flows. Int. Rev. Aeron. Eng. 11, 162–169 (2018).
[2] Pathan, K. A., Dabeer, P. S. & Khan, S. A. Effect of nozzle pressure ratio and control jets location to control base pressure in suddenly expanded flows. J. Appl. Fluid Mech. 12, 1127–1135 (2019).
[3] Quadros, J. D. & Khan, S. A. Prediction of base pressure in a suddenly expanded flow process at supersonic mach number regimes using ANN and CFD. J. Appl. Fluid Mech. 13, 499–511 (2019).
[4] Quadros, J. D., Khan, S. A. & Antony, A. J. Study of base pressure behavior in a suddenly expanded duct at supersonic mach number regimes using statistical analysis. J. Appl. Math. Comput. Mech. 17, 59–72 (2019).
[5] Quadros, J. D., Khan, S. A. & Antony, A. J. Effect of Flow Parameters on Base Pressure in a Suddenly Expanded Duct at Supersonic Mach Number Regimes using Taguchi Design of Experiments. JSME Int. J. 00, (2016).
[6] Quadros, J. D., Khan, S. A. & Antony, A. J. Study of effect of flow parameters on base pressure in a suddenly expanded duct at supersonic mach number regimes using CFD and design of experiments. J. Appl. Fluid Mech. 11, 483–496 (2018).
[7] Azami, M. H., Faheem, M., Aabid, A., Mokashi, I. & Khan, S. A. Experimental research of wall pressure distribution and effect of micro jet at Mach 1.5. Int. J. Recent Technol. Eng. (2019) doi:10.35940/ijrte.B1187.0782S319.
[8] Azami, M. H., Faheem, M., Aabid, A., Mokashi, I. & Khan, S. A. Inspection of supersonic flows in a CD nozzle using experimental method. Int. J. Recent Technol. Eng. (2019)
[9] Faheem, M., Kareemullah, M., Aabid, A., Mokashi, I. & Khan, S. A. Experiment on of Nozzle Flow with Sudden Expansion at Mach 1.1. Int. J. Recent Technol. Eng. 8, 1769–1775 (2019).
[10] Pathan, K. A., Dabeer, P. S. & Khan, S. A. Enlarge duct length optimization for suddenly expanded flows. Adv. Aircr. Spacecr. Sci. 7, 203–214 (2020).
[11] Khan, S. A., Mokashi, I., Aabid, A. & Faheem, M. Experimental research on wall pressure distribution in C-D nozzle at mach number 1.1 for area ratio 3.24. Int. J. Recent Technol. Eng. (2019) doi:10.35940/ijrte.B1182.0782S319.
[12] Faheem, M., Khan, A., Kumar, R. & Khan, S. A. Experimental Study of Supersonic Multiple Jet Flow Field. in 32nd International Symposium on ShockWaves (ISSW32) 2725–2731 (2019).
[13] Faheem, M. et al. Experimental study on the mean flow characteristics of a supersonic multiple jet configuration. Aerosp. Sci. Technol. 108, 1–13 (2021).
[14] Khan, A., Kumar, R., Verma, S. B. & Manisankar, C. Effect of cross wire tab orientation on twin jet mixing characteristics. Exp. Therm. Fluid Sci. 99, 344–356 (2018).
[15] Khan, A., Akram, S. & Kumar, R. Experimental study on enhancement of supersonic twin-jet mixing by vortex generators. Aerosp. Sci. Technol. 96, 105521 (2020).
[16] Khan, A., Panthi, R., Kumar, R. & Mohammed Ibrahim, S. Experimental investigation of the effect of extended cowl on the flow field of planar plug nozzles. Aerosp. Sci. Technol. 88, 208–221 (2019).
[17] Khan, A. & Kumar, R. Experimental Study and Passive Control of Overexpanded Plug Nozzle Jet. J. Spacecr. Rockets. 55, 1–7 (2017) doi:10.2514/1.A34039.