SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Effect of Cavity Geometry and Location on Base Pressure in a Suddenly Expanded Flow at Mach 2.0 for Area Ratio 3.24

Farhana Nur Danisyah Mohd Anuar[1], Fharukh Ahmed Ghasi Mahaboobali[2], Ambareen khan[3], Mohammad Nishat Akhtar[3], Sher Afghan Khan[1,*]

[1] Department of Mechanical and Aerospace Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia
[2] Government Engineering College, Huvinahadagali, Vijayanagar District, Karnataka, 583219, India
[3] School of Aerospace Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

ARTICLE INFO

Article history:
Received 20 January 2024
Received in revised form 16 March 2024
Accepted 30 March 2024
Available online 30 May 2024

Keywords:
Base pressure; passive control; Computational Fluid Dynamics (CFD)

ABSTRACT

The primary goal of this study is to use CFD analysis to investigate the impact that a cavity has on the pressure at the base of a structure. In this analysis, we considered the NPR, the cavity aspect ratio, and the cavity position. In this case, the area ratio is 3.24, and the Mach number is 2.0. Simulations were run with L/D ratios between 1 and 6 and NPRs of 3, 5, 7.8, 9, and 12. The 2-dimensional model was developed using ANSYS Fluent's Design Modeler. The nozzle is operating at Mach 2.0. Base pressure and wall pressure in the duct were the primary research foci. The C-D nozzle was created for this research. ANSYS Fluent was used to verify the CFD findings. When the nozzles are under-expanded and the cavity is at 0.5D, passive control as a cavity is shown to be effective. It appears that 1D is the bare minimum for duct length. Because the shear layer gets reattached to the duct wall at 1D and the boundary layer grows after reattachment, passive control is not observed in the flow process, regardless of whether the cavity is located at 1D, 1.5D, 2D, or 3D. An oscillating base pressure is seen at shorter duct lengths. This phenomenon does not occur at longer duct lengths. Whether or not there are cavities in the duct, the flow field is the same.

1. Introduction

Presently, engineers and scholars are placing considerable emphasis on the investigation of high-velocity aerodynamic flow. The practical utility of understanding high-speed aerodynamics can be found in various aspects of everyday technological advancements, notably in the domains of vehicles and aircraft. One of the paramount hurdles encountered in aerodynamic vehicles pertains to reducing drag. Specifically, when the Mach Number exceeds one, augmenting the surface area leads to a proportionately amplified velocity, and conversely, diminishing the surface area results in a corresponding reduction in velocity.

* *Corresponding author.*
E-mail address: sakhan@iium.edu.my

https://doi.org/10.37934/aram.117.1.121

In a divergent duct, the velocity experiences an increase, whereas in a converging duct, the velocity undergoes a decrease. This behavior contradicts what is observed in subsonic flow within divergent and convergent ducts. The flow field in an abrupt axisymmetric expansion is an intricate phenomenon marked by flow separation, recirculation, and subsequent reattachment [1]. A shear layer can partition a flow field into a recirculation and primary flow regions [2]. When the dividing streamline reaches the wall, the reattachment line is formed. Due to a quick shift in the rear geometry, a massive division of the shear layer arises at the base of baseflow. Split flow in the base area causes two distinct issues: base instability and more significant drag. In this study, the base pressure is the parameter affected by the recirculation zone at the base region. This research aims to manage the base pressure to reduce base drag. Active and passive control are the two methods for optimizing the base pressure [3]. These two methods are critical because controlling the low pressure in the base region and bringing it closer to air pressure is critical for achieving near-zero base drag.

The endeavor to enhance the aerodynamic efficiency of flight vehicles by mitigating different forms of drag has garnered significant attention from numerous researchers. In real-world scenarios, an increase in drag has an undesirable impact on the range of missiles, rockets, etc. Flow separation can be managed through two approaches: active control and passive control. Passive control involves manipulating the geometric characteristics of structures, employing methods such as ribs, cavities, boattails, splitter plates, and locked vortex devices to regulate the base pressure. The differentiation between active and passive control can be briefly summarized as follows: dynamic control necessitates an external energy source, whereas passive control operates without such a requirement.

Passive control methods find diverse applications across various domains, encompassing the study of flow over blunt projectiles, missiles, jet engines, vernier rockets, internal combustion engine ports, and numerous other areas. These passive flow control techniques hold promise for directly influencing the structure of the boundary layer, vortices, and wake flows. The research aims to investigate the aerodynamic effectiveness of various passive and active flow control techniques in aerodynamic flows, specifically emphasizing reducing drag, managing flow separation, and controlling wake patterns. According to the previous study [3], various passive control techniques, such as cavities, ribs, dimples, static cylinders, spikes, and others, focus on managing the base pressure and controlling the drag force. A higher or lower base drag could result from a change in the base pressure, which he found the passive control device could affect. Furthermore, passive control is effective when a positive pressure gradient exists close to the nozzle exit.

Under transonic speeds, how effective various base modifications or passive devices reduce base and overall afterbody drag is investigated. This study examines several changes to the base, including cavities, ventilated cavities featuring a variety of ventilation geometries, and two vortex suppression devices. The impact of these devices on boattailed and flared bases is also examined [4]. The semi-circular rib in the form of passive control was introduced [5] at sonic and supersonic Mach numbers and was further predicted by the artificial neural network. The author in [6] reveals that passive control in the form of rib plays a critical role when placed at a 3D/4D location. However, when placed at 1D, the base pressure is reduced. Here, the rib of width 3mm is used with various heights from 1mm to 4mm.

Khan *et al.* [7] did a numerical simulation at sonic Mach number for duct diameter 20 mm with a rib of height 1mm to 3mm and width of 3 mm at locations 1D, 2D, 3D, and 4D. It can be observed that the rib placed near the reattachment point increases the base pressure when compared to no rib case, irrespective of height. Khan *et al.* [8] did an experimental study with convolutional neural network predictions and found that if the area ratio is high, the rib cannot show its influence. The wall pressure is studied [9] at Mach 1.5 with active control employed. It was found that there is no adverse effect on the flowfield when the tiny jets are employed as active controls. Through Computational Fluid Dynamics (CFD) software, the simulation was done for the active control at supersonic Mach number[10]. Based on the findings, it's safe to say that micro-jets are a helpful tool for lowering overall drag with minimal efficiency loss by regulating the base pressure. Micro-jets are used for active control in experimental studies of convergent-divergent nozzles [11]. During this study, it was found that micro-jets do not aggravate the flowfield. In the reverse direction, dimples [12] are used to control the base pressure and reduce drag. It is discovered that the optimum L/D can be found for a given nozzle-pressure ratio and that dimples can be used as a passive control to manage drag effectively. Multiple cavities [13] are experimentally investigated and found to reduce overall drag effectively. Micro-jets as active control are studied [14] using the design of experiments and computational fluid dynamics. The results of this analysis indicate that the L/D ratio plays a crucial role in regulating the system as a whole. Researchers [15] study the flow around the non-circular cylinder to learn how it affects drag. Pressure is low at the back and sides but high and positive at the front—only bluff bodies with extreme corners experience such a high drag coefficient. Computational fluid dynamics is used to investigate suddenly expanded flows internally and externally at Mach numbers between 0.3 and 3[16]. Internal and external suddenly expanded flows have nearly identical fields in the foundational region. The nozzle-pressure ratio is investigated through both experimental and computational fluid dynamics analysis. Microjets have been shown to increase the base pressure by 160–400% at a nozzle pressure ratio of 8 [17]. The experimental investigation of 2.56, 3.24, 4.84, and 6.25 area ratios at Mach numbers of 1.6 to 2.0 [18] demonstrated that the micro-jets effect at lower Mach numbers and area ratios is only marginal. Still, the micro-jets result in an increase of base pressure at all the Mach numbers. Research on convergent-divergent nozzles using microjets at Mach 2.1[19] determined that, for nozzle pressure ratios greater than 5, the minimum duct length for the flow to remain attached is 2D. The flow separation in the sudden expansion will affect the flow field, as determined by experimental and numerical research on an area ratio of 7.84 using passive control as a rib at sonic Mach number [20]. Azami *et al.* [21] conducted an experimental study to assess supersonic flow in a CD nozzle with a suddenly expanded duct. L/D tests were performed from 10 to 1, and wall pressure data acquisition tests were conducted at levels 3, 5, 7, 9, and 11. The results show that the control deployment did not aggravate the flow field. The Mach number was 1.87, and the area ratio of 3.24 was used in the study by Khan *et al.* [22]. The duct's L/D was set to 10, and the nozzle pressure ratio (NPR) used for simulation ranged between 3, 5, 7, 9, and 11. The results showed that microjets could control the base pressure, pressure loss, and drag reduction. An experimental study on passive control in the form of multiple cavities has been done. From the results, it is seen that the numerous cavity has a significant effect on reducing base drag by decreasing base suction and, thus, increasing base pressure [23]. Using dimples as passive controls proved to be highly effective, and at higher NPR, the wall pressure distribution remained remarkably stable. The fact that the geometric parameter influences the base pressure for a given NPR was also found in this study [24]. Research by Pathan *et al.* [25, 26] examined the differences in base pressure caused by internal and external flows. To design effective aerodynamic systems, it is crucial to understand how base pressure behaves in various flow configurations. Their findings shed light on the variables that affect base pressure and the opportunities for optimization in different settings [27].

2. Methodology

2.1 Convergent-Divergent Nozzle:

The converging-diverging (CD) nozzle accelerates compressible flows to supersonic velocities. It finds widespread application in rocket and jet engine propulsion systems. The CD nozzle consists of three distinct sections: a converging section, a throat (with the smallest cross-sectional area), and a diverging section. Depending on the specific geometry of the nozzle and the pressure ratios at the inlet and outlet, the flow at the nozzle exit can be subsonic or supersonic. Here, we'll simulate to solve the compressible flow inside a two-dimensional axisymmetric CD nozzle, then look at how that flow behaves under different parameters.

2.2 Flow Chart of Present Work

Figure 1 shows the flowchart of the present work.

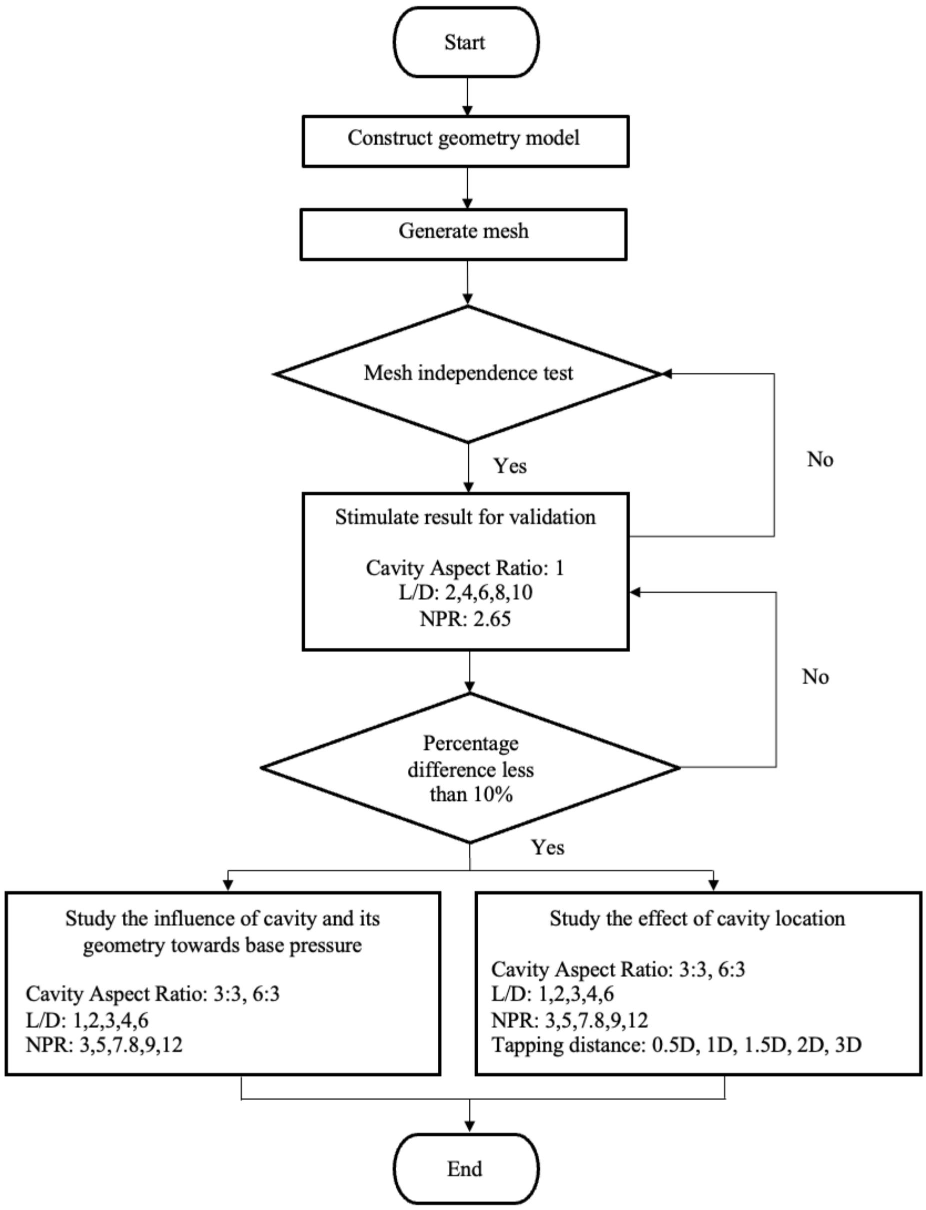


Fig. 1. Flowchart of present work

2.3 Geometry of Convergent-Divergent Nozzle

Figure 2 shows the schematic of an experimental model for the validation part, and Table 1 shows the Parameters of the present work.

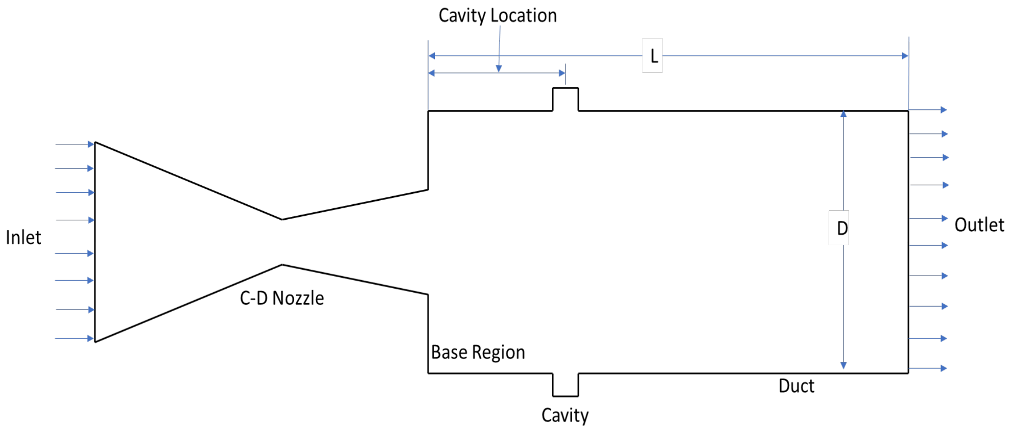


Fig. 1. Schematic of an experimental model for validation part

Table 1
Parameters of present work

Mach Number	2.0
Area Ratio	3.24
Convergent angle	20^{o}
Divergent angle	5^{o}
Inlet diameter	25.9 mm
Outlet diameter	10 mm
Throat diameter	7.7 mm
Convergent length	25 mm
Divergent length	13.2 mm
Duct diameter	18 mm
Duct length	Depends on the L/D ratio

2.4 Cavity Dimensions and Locations

This study examines the impact of cavity geometry and its location on base pressure. The research utilizes two distinct cavity geometries, and Table 2 illustrates comprehensive information on each cavity's dimensions and specific locations.

Table 2
The cavity dimension based on the aspect ratio

Cavity Aspect Ratio, ASR	Width (mm)	Height (mm)
1	3	3
2	6	3

In this work, the cavity locations from the base pressure wall varied to 0.5D, 1D, 1.5D, 2D, and 3D (Table 3). Furthermore, the cavity locations were calculated using:

$$Cavity\ location, CL = D - \frac{w}{2} \tag{1}$$

Table 3
The cavity location from the base pressure wall

D	Cavity Width (mm)	CL (mm)
0.5D	3	7.5
1D	3	16.5
1.5D	3	25.5
2D	3	34.5
3D	3	52.5
0.5D	6	6
1D	6	15
1.5D	6	24
2D	6	33
3D	6	51

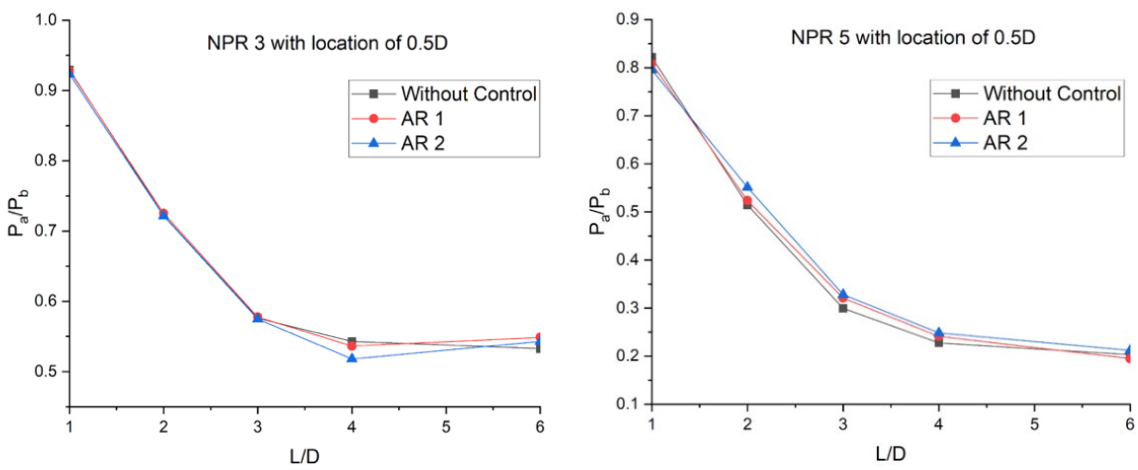
2.5 Nozzle Pressure Ratio (NPR)

According to Appendix B, the pressure ratio for Mach number 2.0 is 7.8 (Oosthuizen & Carscallen, 1997). The design condition for the model was set at this value. The values selected were lower than the design condition for the overexpanded cases, which were 3 and 5. On the other hand, the values chosen for the under-expanded situations were higher than the design conditions, which were 9 and 12.

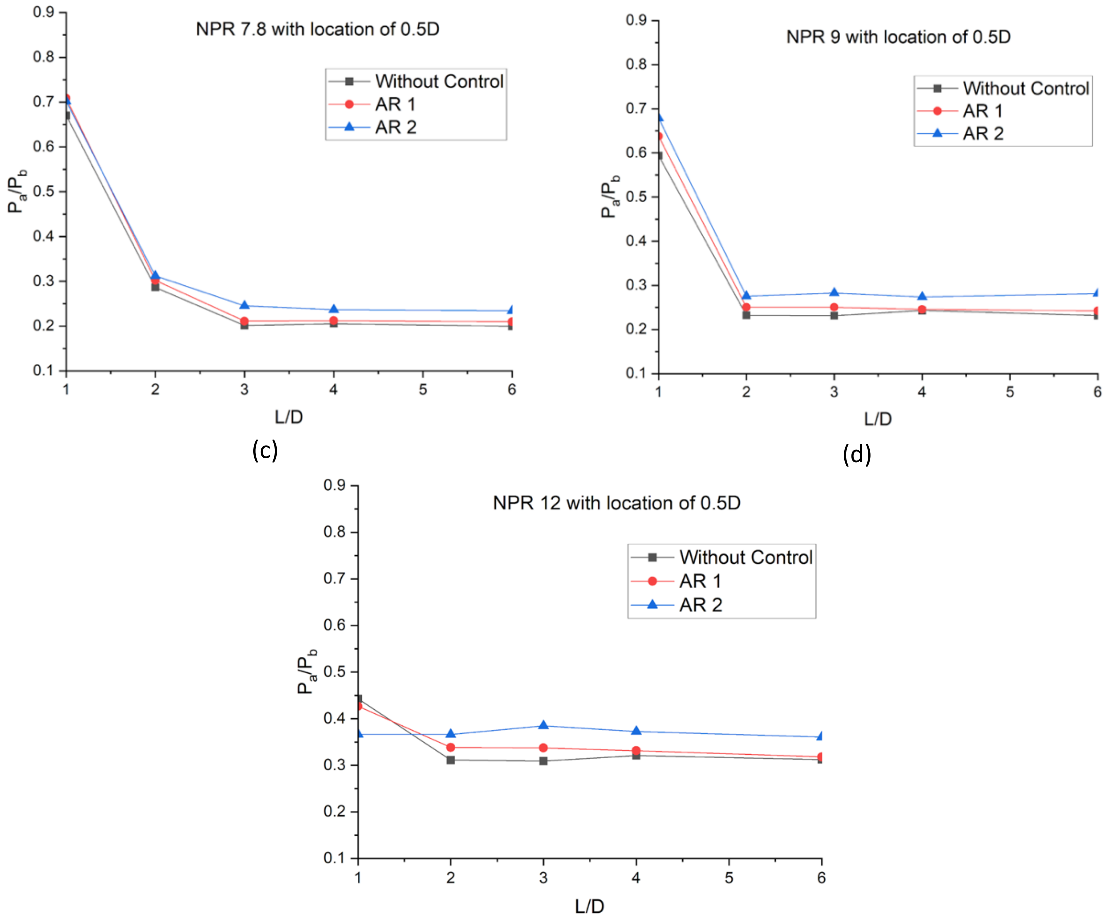
3. Results

3.1 The Influence of the Cavity and its Geometry Towards its Base Pressure

For a specific NPR with passive control located at 0.5D, the variation in base pressure ratio with L/D is depicted in Figure 3. As seen above, the base pressure of NPR 3 (a) increases from L/D 4. There is a gradual drop in base pressure from L/D 1 to L/D 3. However, starting at L/D 4, the difference between the base pressure with control and without control is negligible, and it remains so until L/D 6. In contrast, the NPR 5 case shows a steady decrease in base pressure throughout controlled and uncontrolled scenarios until L/D 6. The results of NPR 7.8 show that the base pressure gradually drops from L/D 3 with and without regulation. The baseline pressure then holds steady until L/D 6. Here, ASR 2 causes a rise from L/D 2 to L/D 6 in the base pressure. Base pressure drops for NPR 9 and NPR 12 cases until L/D 2, stabilizing and then rising again for L/D 6. The base pressure in NPR 9 for ASR2 rises from L/D 2, while in NPR 12 for ASR2, it rises from the beginning.



(a) (b)



(c) (d)

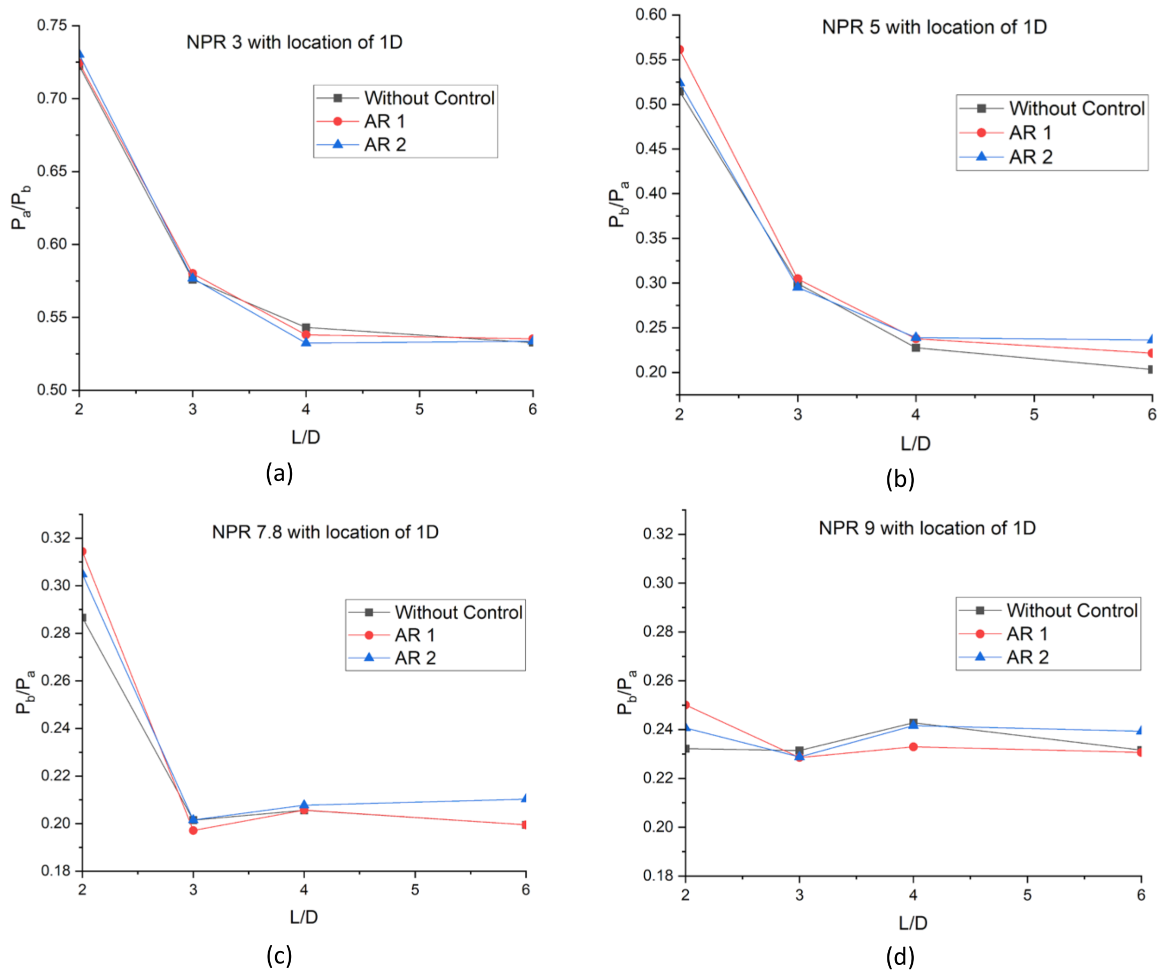
(e)

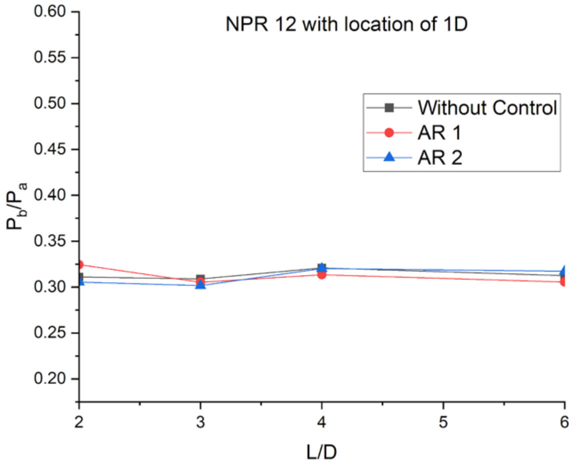
Fig. 2. Base pressure ratio variations with L/D at numerous locations of 0.5D

When NPR 7.8 is reached, the correct expansion for Mach 2 occurs. As a result, if we compare the ASR2 to the ASR1 and remove the control case, we find that the ASR2 results in a higher base pressure. When the nozzle is not adequately expanded, normal shock waves are generated at the nozzle's exit, travel along the duct's inner wall, and are reflected into the nozzle. The ASR2 has a width of 6 mm, compared to the ASR1, which has a width of 3 mm. The ASR 2, due to its increased width, can trap more flow when it gets incident or reflected, even for a more extended amount of time. Hence, the base pressure is increased till L/D 6 when compared to ASR1. The same ASR 2 shows a decrease in the base pressure till L/D 2 when placed at 0.5D location as L/D 1 and L/D 2 have minimal duct lengths, and the back pressure shows its presence. The oblique shock formed at the nozzle exit reduces the base pressure, making it difficult for the passive control in a rectangular cavity to have much of an effect in the over-expanded case for NPR 3 and NPR 5.

For NPR 9 and NPR 12, the maximum effect of AR2 is seen when the base pressure is increased due to the formation of an expansion fan at the nozzle exit in the under-expanded case. When the flow leaves the nozzle and enters the expansion fan, it expands and raises the base pressure even without control. When control is applied, the flow becomes trapped at the rectangular cavity's two corners and is recirculated within it. When the flow gets circulated within the cavity, it affects the main flow field, as with a high velocity, the flow gets reflected from the cavity walls and joins the main flow field. This increases the overall velocity of the flow and its speed of reflection and expansion, thus increasing the overall base pressure. This is more evident for ASR2 for NPR 12. When the cavity is placed at a 0.5D location near the base of the duct, the effect of the cavity is not prominent at this location and becomes constant at higher L/Ds.

Figure 4 shows the base pressure results when the cavity, which acts as passive control, is positioned 18 mm from the base. Figure 3(c) demonstrates that when the cavity is located at 0.5D, the result is the same as that observed in Figure 3(a). The cavity's efficiency becomes apparent at L/D = 4 for NPR = 3. As seen in Figure 4, the presence of a cavity altered NPR 5's base pressure (b). Because of this, the base pressure in the cavity is more significant than that in the plain duct. For duct lengths up to L/D = 3, the results show that a cavity with an aspect ratio of 3:3 is optimal, while for longer duct lengths, a cavity with an aspect ratio of 2 is preferable. The efficiency of the cavity is not noticeable until L/D = 4 for NPR = 3. Figure 4 demonstrates how the presence of a cavity modified the base pressure ratio for NPR 5. (b). Because of this, the base pressure in the cavity is more significant than that in the plain duct. For duct lengths up to L/D = 3, the results show that a cavity with an aspect ratio of 3:3 is optimal, while for longer duct lengths, a cavity with an aspect ratio of 2 is preferable. Figures 4(d) and (e) also show that the practical cavity geometry has a negligible impact on the underlying pressure. At 18 mm, the flow does not interact with the cavity, so the reattachment length may grow as the level of under-expansion rises.

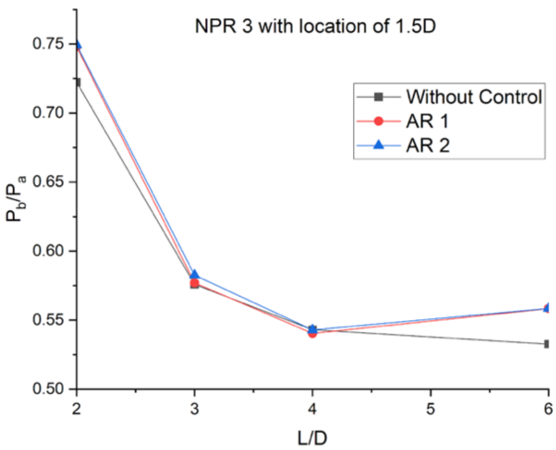




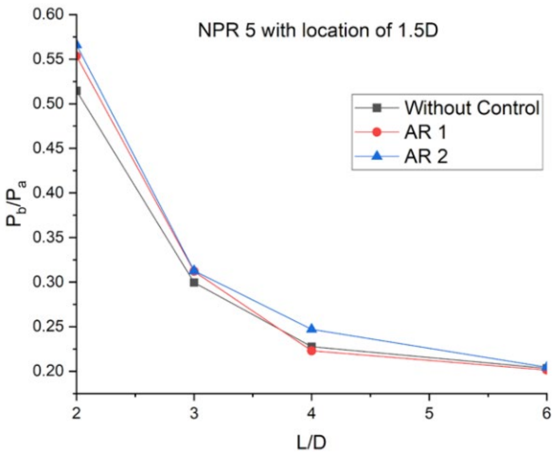
(e)

Fig. 3. Base pressure variations with L/D with control located at 1D

The above diagram displays the outcomes for many NPRs when the cavity is positioned at a distance of 1.5. The base pressure at NPR 3 is similarly affected by the cavities with AR1 and AR2, as shown in Figure 5(a). For both cavity geometries, the flow is reversed, and the base pressure is increased when L/D is greater than 3. For NPR = 5, the outcomes are consistent regardless of the degree of overexpansion or the effect of variations in ambient pressure. The only difference is a slight shift in the magnitude of the base pressure. When comparing the base pressure values at design with the results of NPR and control, the latter shows a substantial decrease, while the former shows an increase up to L/D = 3. While the base pressure in cavity AR1 decreases with increasing duct length, it rises in cavity AR2. As depicted in Figure 5, Mach waves at the nozzle exit are one possible explanation for this pattern (c). Results at NPRs 9 and 12 are shown in Figure 5 (d) and (e). The base pressure increases in a cavity with AR2 and decreases in a cavity with AR1. While the results fluctuate for shorter duct lengths, the base pressure values are relatively stable for the longest (NPR = 12). Because of the presence of expansion waves at the nozzle exit, there are distinctive patterns in the resulting base pressure.



(a)



(b)

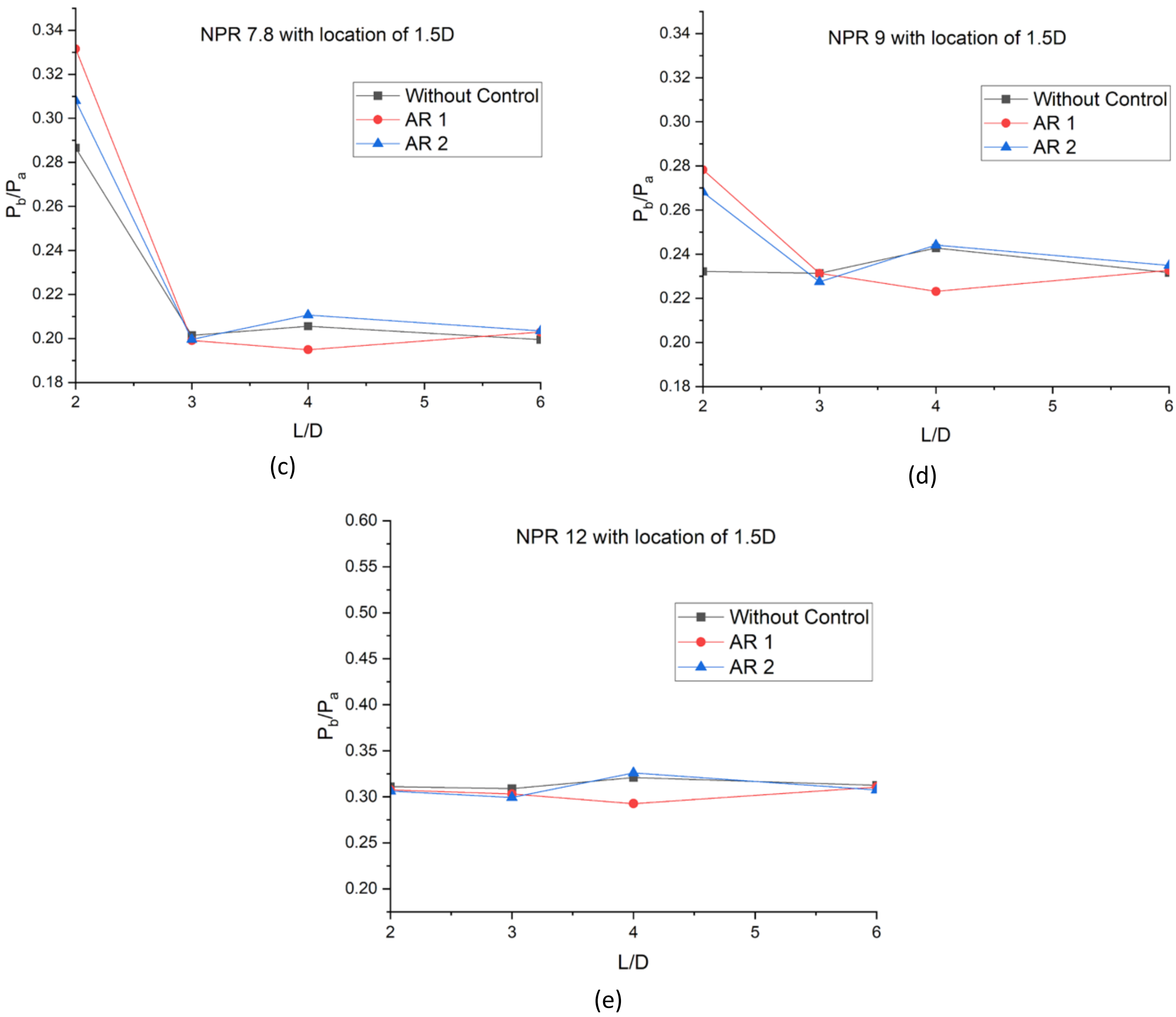


Fig. 4. Base pressure variation with L/D for both plain duct and duct with control

Base pressure results for cavity location 2D are shown in Figure 6 for various expansion and cavity geometry levels. For NPR 3, as shown in Figure 6(a), the presence of a cavity influenced the base pressure, and the cavity influenced base pressure positively. The control for cavity AR1 and AR2 are both effective in this case. It may be due to the location of the cavity and the reattachment point being nearby, resulting in excessive interactions of the shock waves and the shock reflections from the wall of the duct. Hence, the base pressure with the cavity is higher compared to the plain duct. For the remaining NPR, which are shown in Figures 6(b), (c), and (d), the cavity geometry's effectiveness has the most negligible influence on the base pressure, and the cavity with AR2 performs better than AR1.

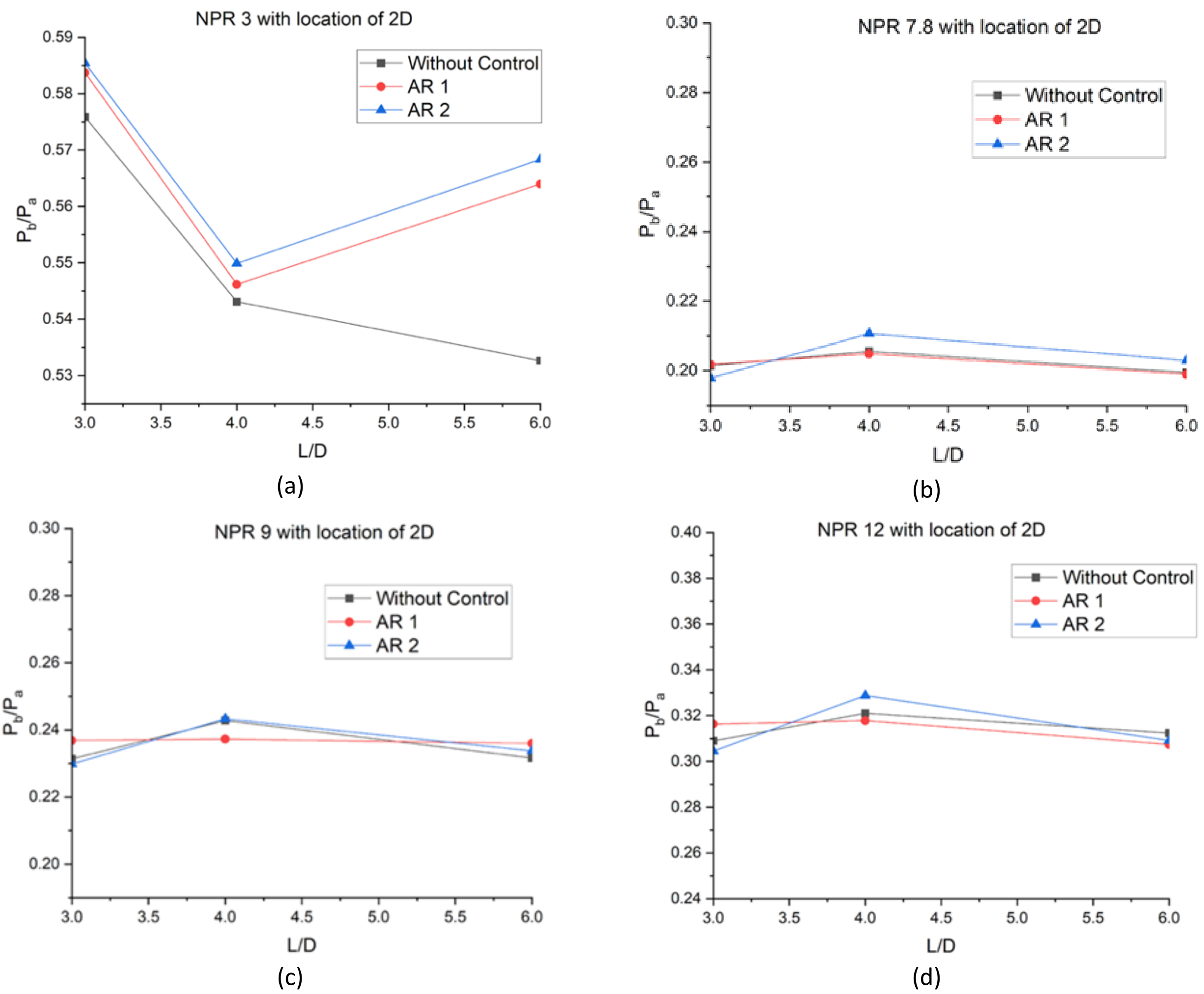
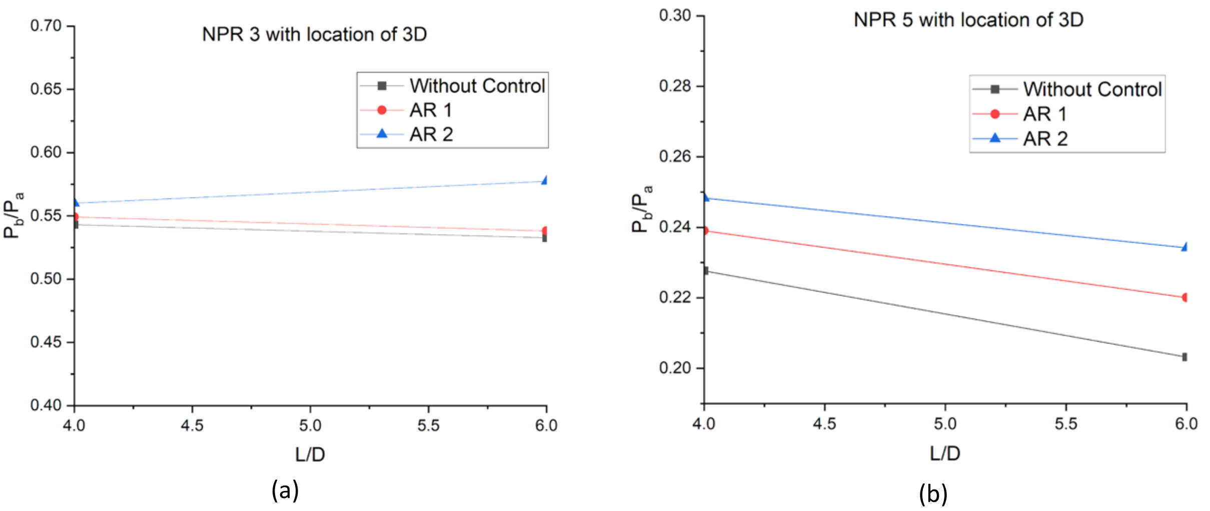
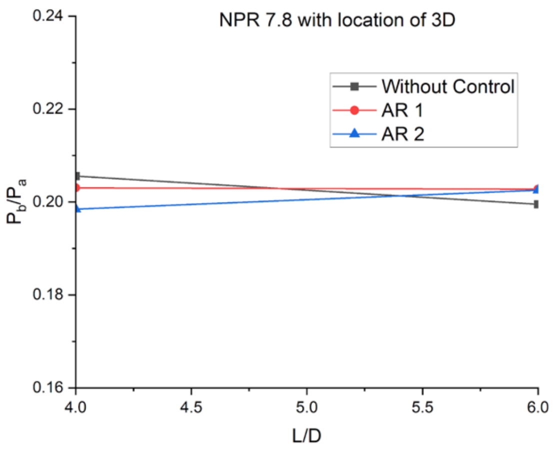


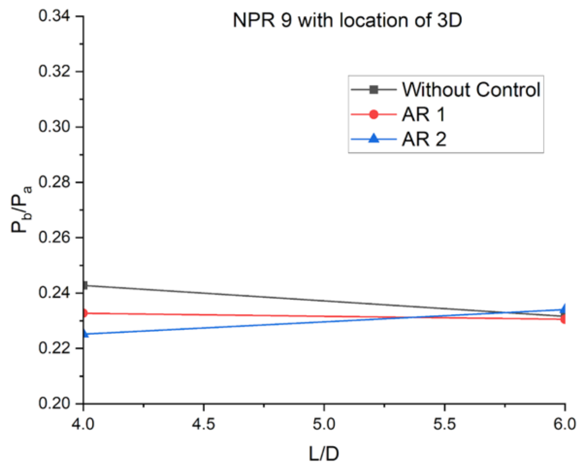
Fig. 5. Base pressure ratio varies with L/D at various locations at 2D

Figure 7 depicts the results for NPRs 3, 5, 7.8, 9, and 12 when cavities with aspect ratios AR1 and AR2 are positioned in three-dimensional space within the enlarged duct. The results show no clear pattern because the cavity is so far from the base region and because we considered duct lengths of up to 6D. It could be because the duct length has been cut to a shorter size, rendering the back pressure control ineffective. As a result, there is no way to conclude anything with certainty.

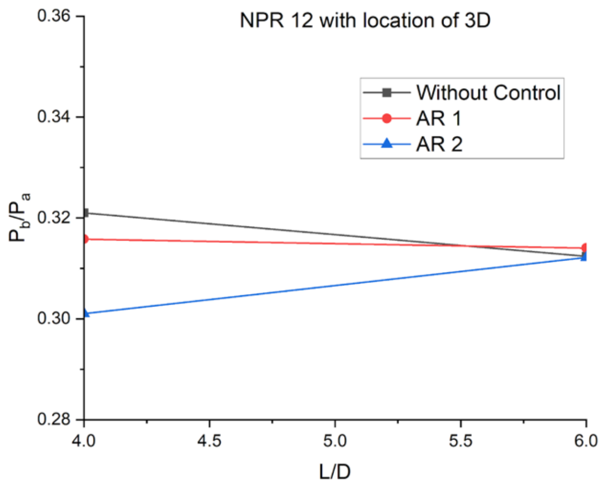




(c)



(d)



(e)

Fig. 6. At different locations of 3D, the ratio of the base pressure to the total pressure varies for both plain duct and duct with control with L/D

3.2 The Effect of the Base Wall's Location of the Cavity on the Base Pressure

Figure 8 depicts the impact of NPR on a specific L/D and at a fixed rib location, namely 0.5D. Because the duct length is so short and the backpressure strongly influences the flow field inside the duct, the L/D 1 cannot demonstrate its impact on the base pressure. As a result, in highly expanded cases, the base pressure continuously decreases. The cavity's impact is visible for L/D = 2, and the base pressure increases after NPR 9. As the flow from the nozzle is over-expanded until NPR = 9, the base pressure for L/D = 3, 4, and 6 continuously decreases until NPR 5 and then gradually increases until NPR 12. Passive control can significantly raise the base pressure once the flow is optimally expanded or under-expanded.

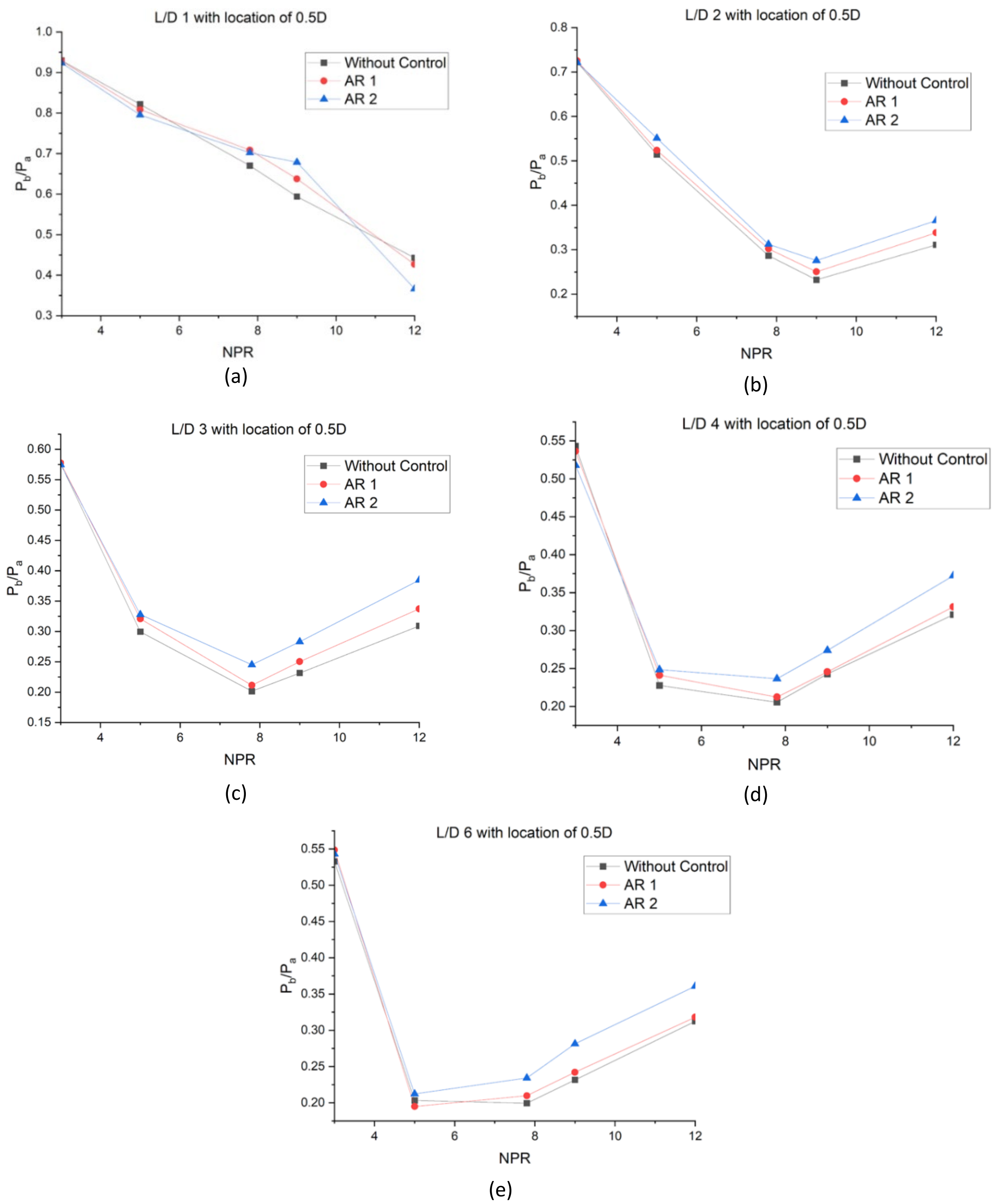


Fig. 7. Base pressure ratio variation with NPR for cavity location at 0.5D

Figure 9 shows the effect of NPR when the cavity is placed at a 1D location for various L/Ds. Here, the results of the 1D location are almost similar to the results of the 0.5D location, with ASR2 showing its effect on the base pressure values. This may be because both the cavity locations are before the reattachment point. When the cavity is placed before the reattachment point, it will show a marginal effect on the base pressure, but its impact will not be prominent. The passive control cannot affect the main flow field as the flow coming out of the nozzle passes through the cavity with a high velocity and will not be able to feel its presence and, hence, not able to increase the base pressure to a more excellent value.

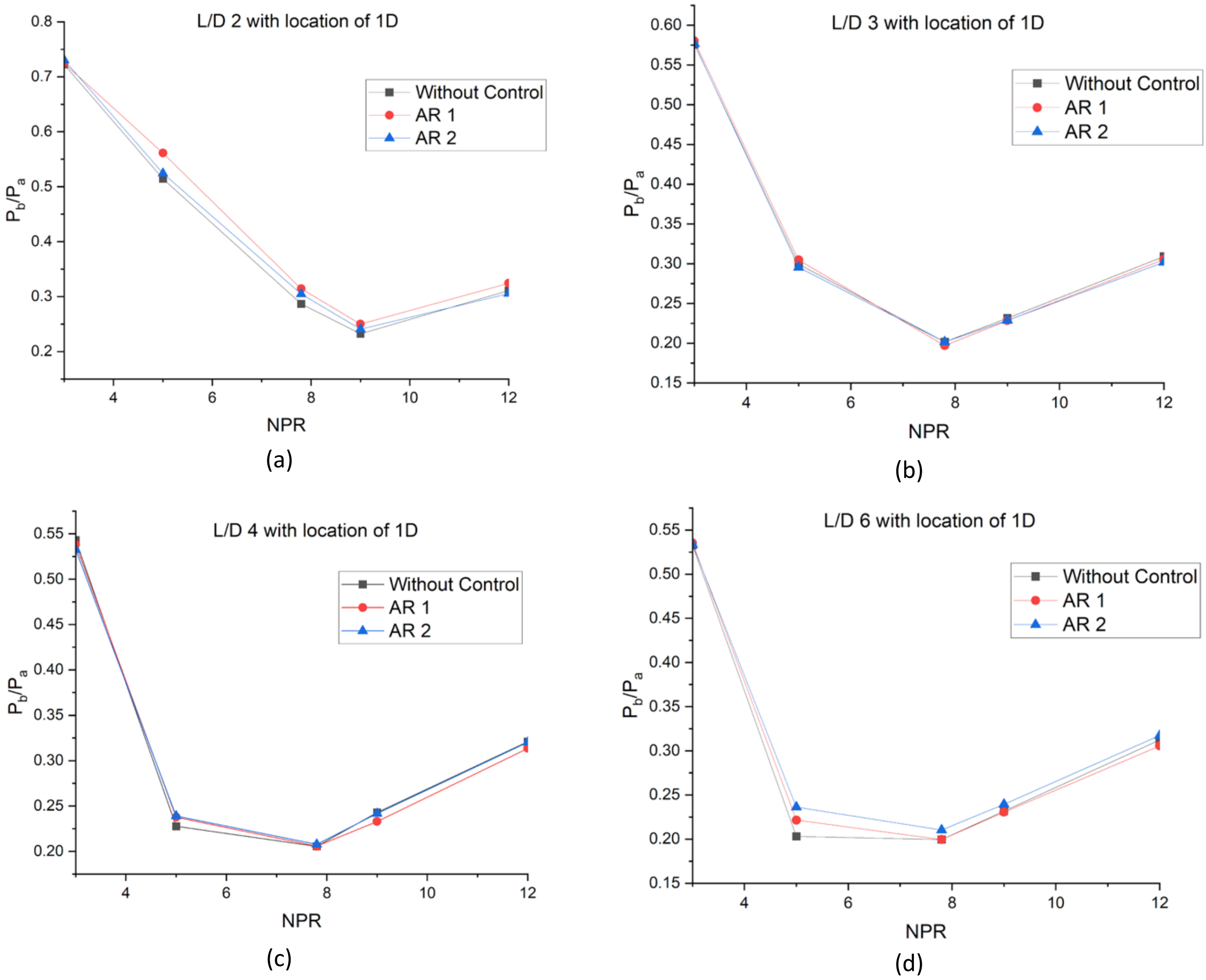
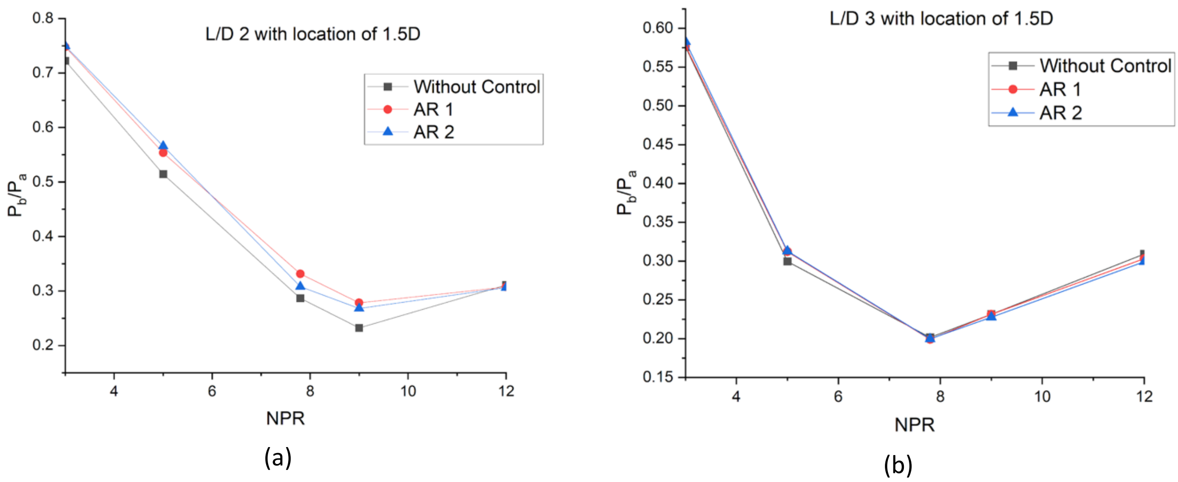
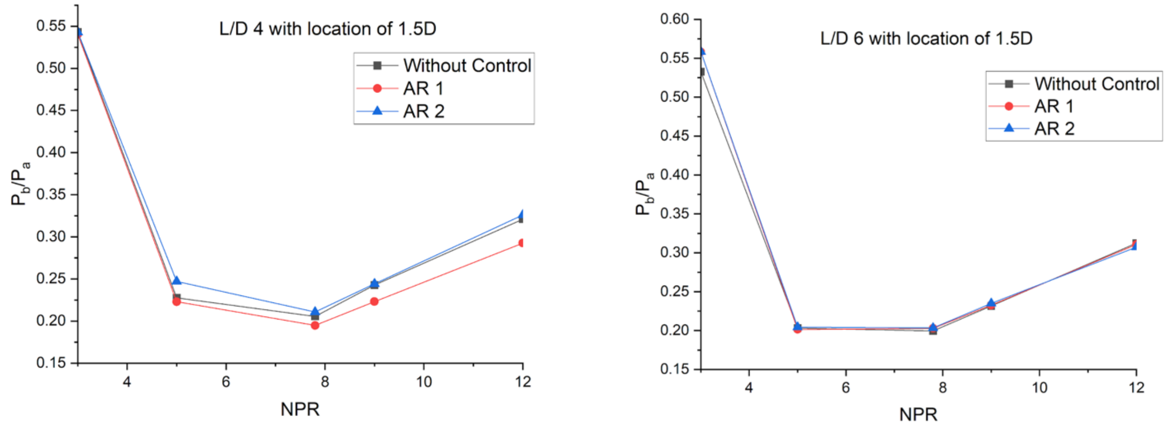


Fig. 8. Base pressure ratio varies with NPR for cavity location at 1D

Figure 10 illustrates that the base pressure ratio varies with NPR for plain and enlarged ducts with cavities at several 1.5D locations. From the graphs, it can be seen that for the location of 1.5D, the cavity is ineffective because the point of reattachment is not favorable at the location of the cavity.

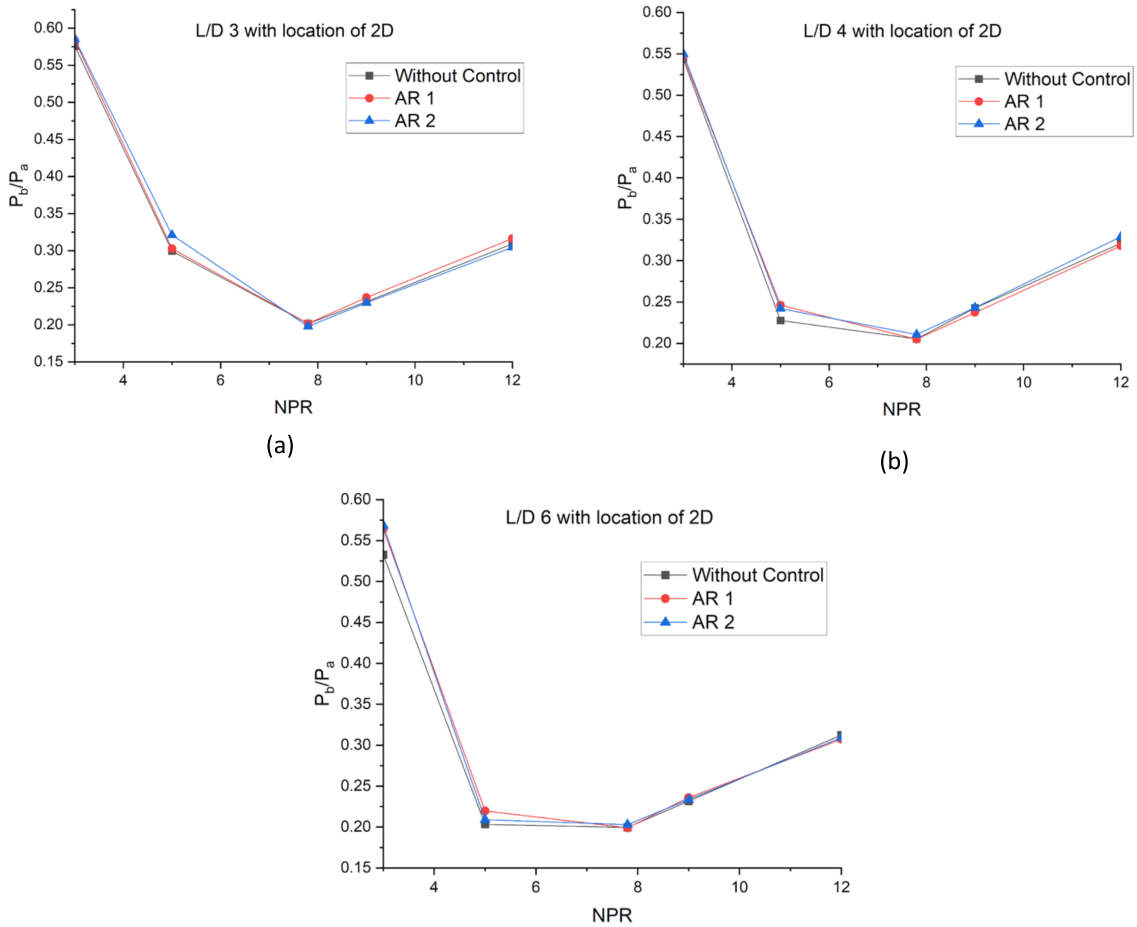




(c) (d)

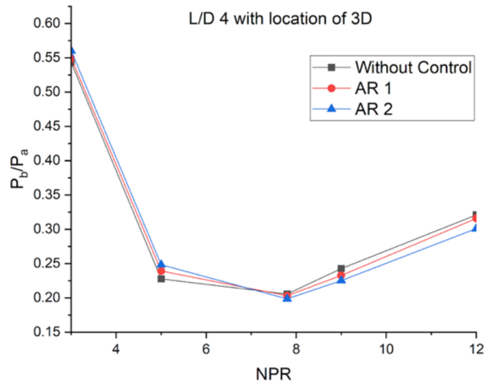
Fig. 9. Base pressure ratio varies with NPR at 1.5D cavity locations.

Figure 11 and Figure 12 show the locations of the cavity in 2D and 3D. Although these locations are close to the reattachment point, the cavity cannot demonstrate its effects to a greater extent. The primary cause of this phenomenon is that the flow becomes trapped inside when the cavity is positioned close to the reattachment point. Still, because the flow leaves the nozzle at Mach 2, it moves so quickly that the cavity is not visible in the flowfield as it simply passes through it. Once the flow has been over-expanded, the trapped flow inside the cavity may exhibit a slight effect.

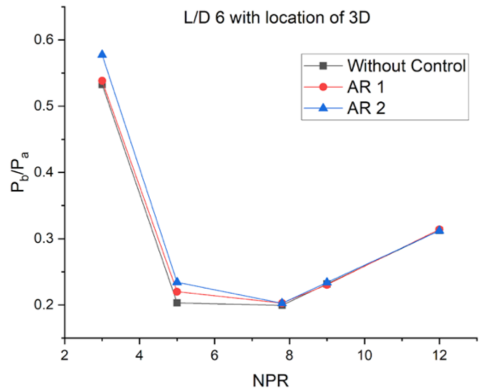


(a) (b) (c)

Fig. 10. Base pressure ratio varies with NPR for cavities located at 2D



(a)



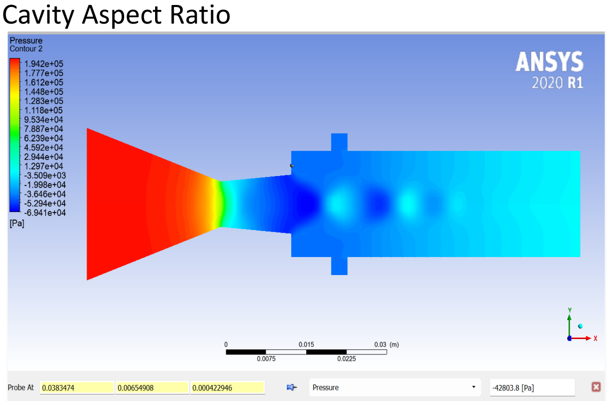
(b)

Fig. 11. Base pressure ratio varies with NPR for a cavity location 3D

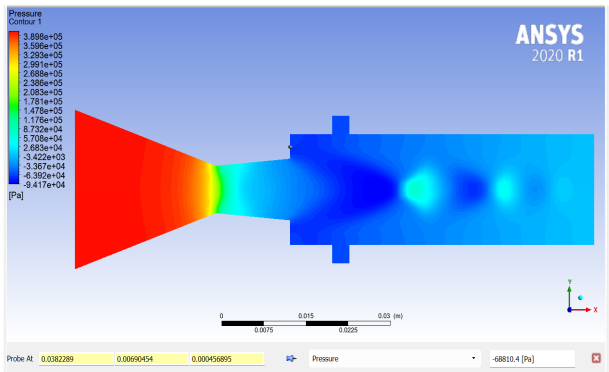
3.3 Pressure Contours
3.3.1 Condition 1 (L/D=3)

Figure 13 shows the pressure contours for the various NPRs for L/D=3. It is clear from the contours that NPR 3 and NPR 5 when the nozzle is over-expanded, form oblique shock waves at the exit of the nozzle. When the nozzle is correctly expanded, the bow shock is formed at the nozzle exit. In the case of under-expanded cases, the expansion fan is formed. In the under-expanded, the back pressure plays a role; hence, the expansion fan cannot be seen clearly and gets mixed with the ambient pressure. The role of the cavity is not apparent in all the above cases, as the L/D is small.

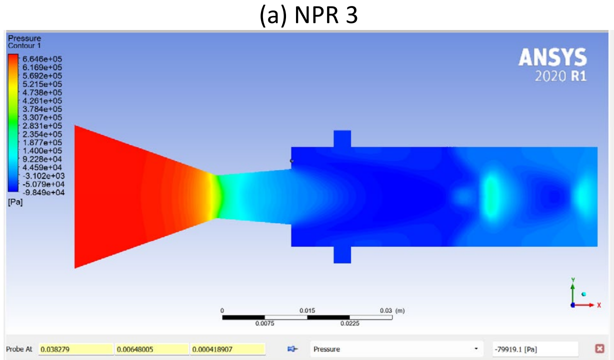
Duct Length	54mm
Cavity Location	0.5D (7.5mm)
Cavity Aspect Ratio	1



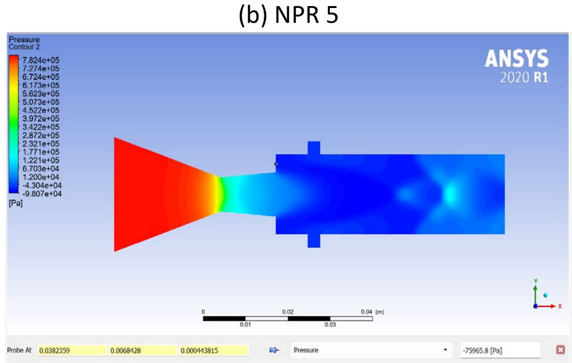
(a) NPR 3



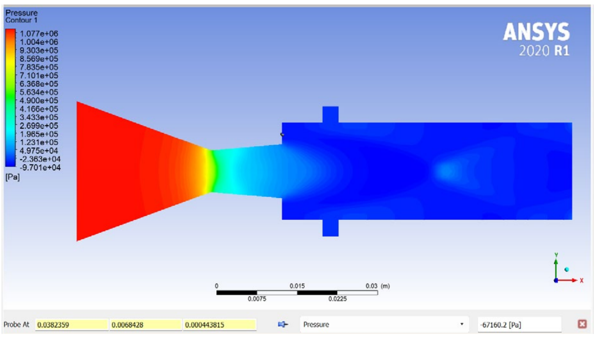
(b) NPR 5



(c) NPR 7.8



(d) NPR 9

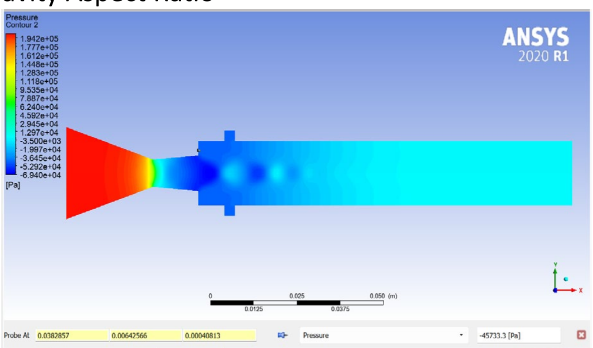


(e) NPR 12
Fig. 13. Pressure contours for Condition 1

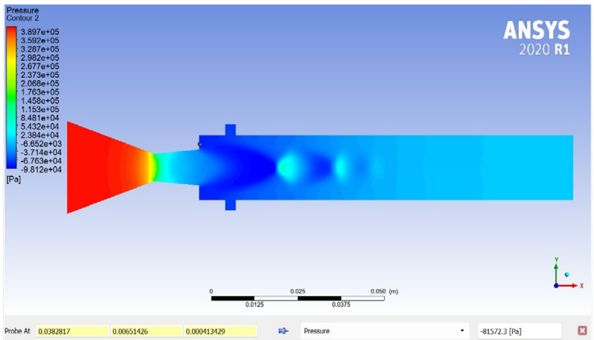
3.3.2 Condition 2 (L/D=6)

Figure 14 shows the L/D 6 case for the 0.5D cavity location. Here, it is apparent that due to the longer duct length, the waves can be developed along the duct and are more visible in correctly expanded and under-expanded cases as it get enough space to form and grow. The cavity role is not visible much as it is near the base in all NPRs.

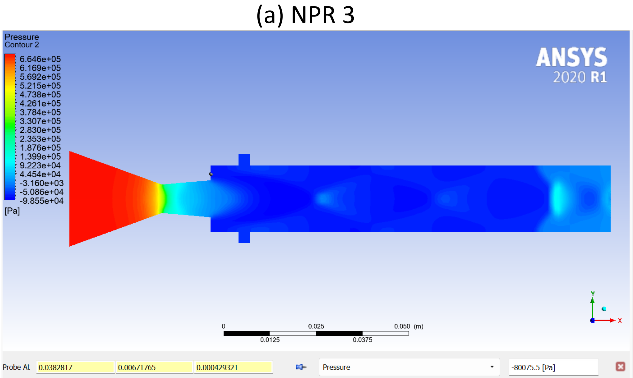
Duct Length	108mm
Cavity Location	0.5D (7.5mm)
Cavity Aspect Ratio	1



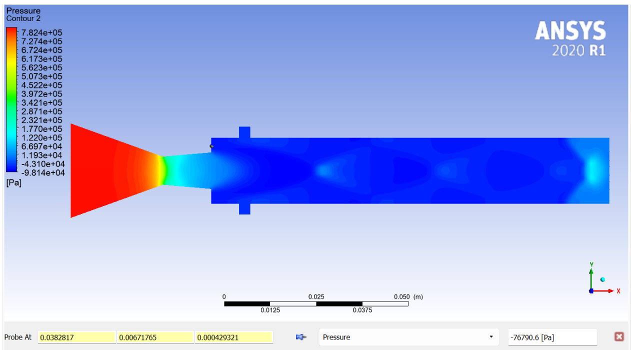
(a) NPR 3



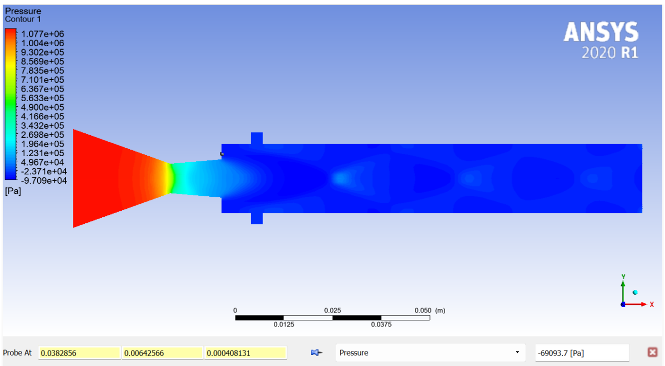
(b) NPR 5



(c) NPR 7.8



(d) NPR 9



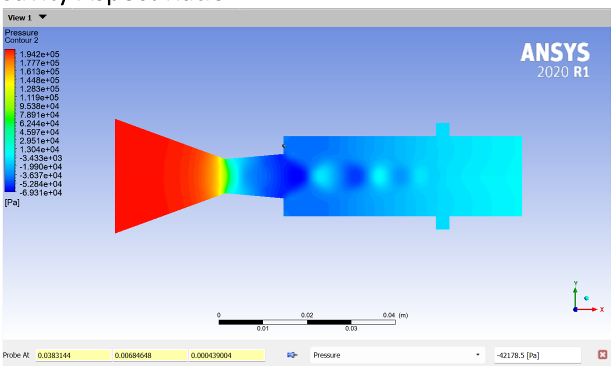
(e) NPR 12

Fig. 14. Pressure contours for Condition 2

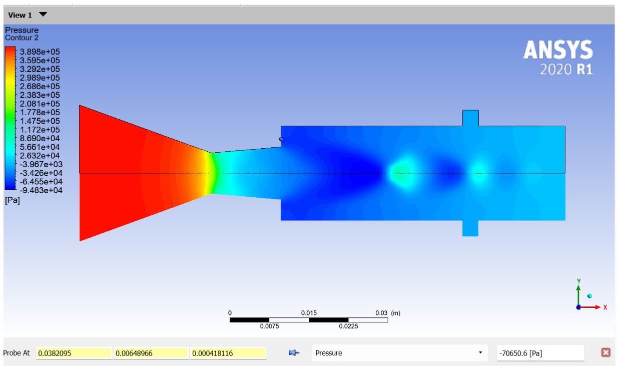
3.3.3 Condition 3 (L/D = 3)

In Figure 15, the L/D 3 case is shown for the 2D location of the cavity. It can be observed that the role of the cavity is not apparent in the over-expanded cases. But for the correctly expanded and under-expanded cases, the role of the cavity can be seen as the Mach wave formation is more apparent.

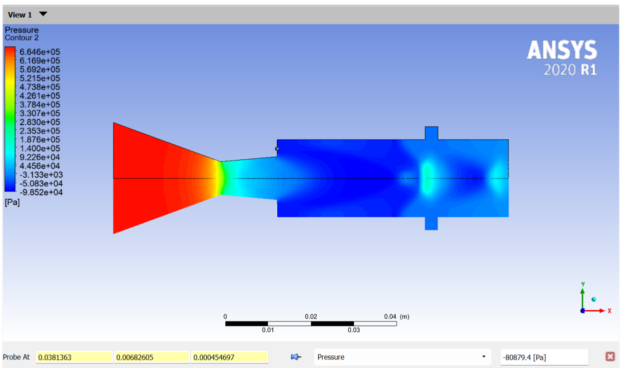
Duct Length	54mm
Cavity Location	2D (34.5mm)
Cavity Aspect Ratio	1



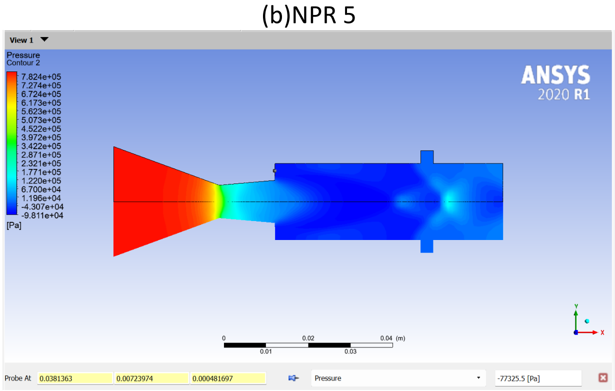
(a)NPR 3



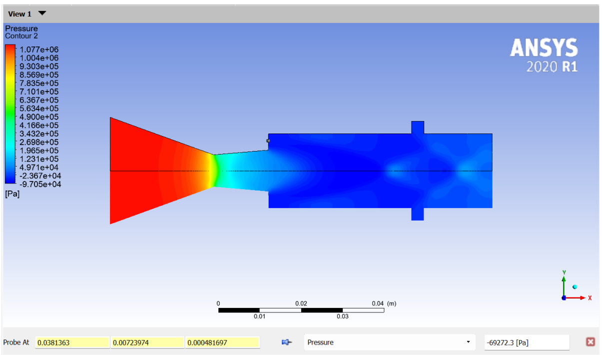
(b)NPR 5



(c) NPR 7.8



(d)NPR 9



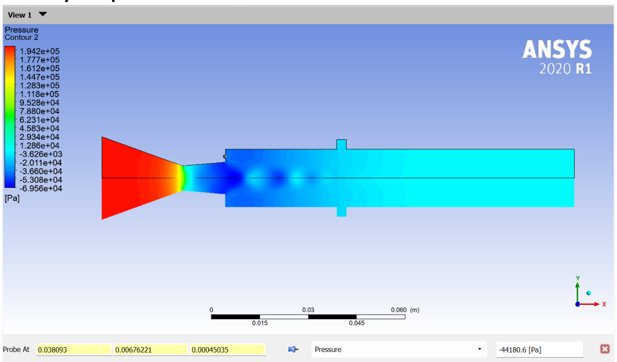
(e) NPR 12

Fig. 15. Pressure contours for Condition 3

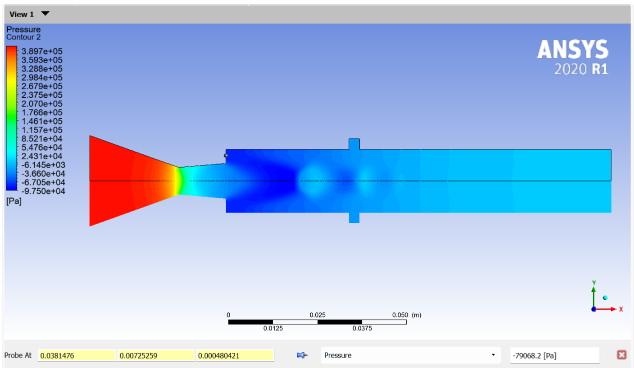
3.3.4 Condition 4 (L/D = 6)

From Figure 16, L/D 6, and cavity location placed at 2D, it can be observed that Mach waves are more apparent as this shows the presence of a cavity near the reattachment point for the cases.

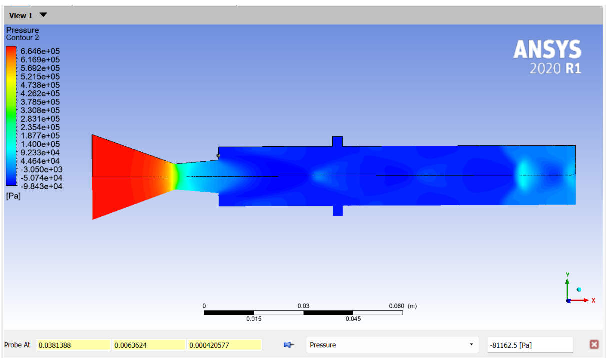
Duct Length	108mm
Cavity Location	2D (34.5mm)
Cavity Aspect Ratio	1



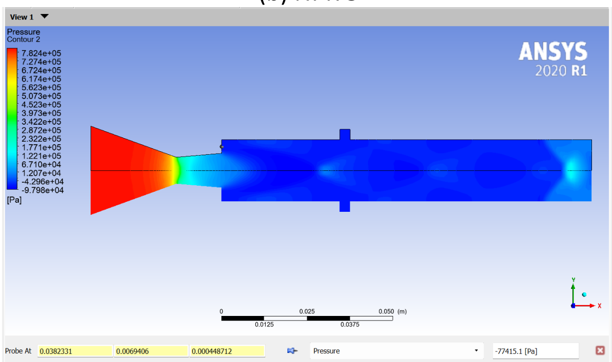
(a) NPR 3



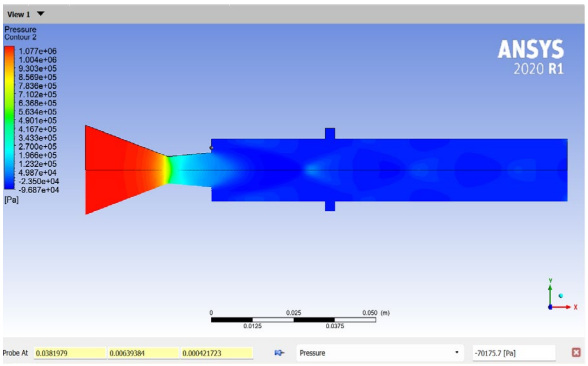
(b) NPR 5



(c) NPR 7.8



(d) NPR 9



(e) NPR 12

Fig. 16. Pressure contours for Condition 4

4. Conclusions

The cavity is a passive control device that successfully modifies the base pressure. Locations between 0.5 and 1.5 dimensions are optimal for lowering the base pressure, while locations between 2 and 3 are optimal for raising the base pressure. Backpressure is especially important in regulating the base pressure at lower L/Ds. The optimal cavity locations are found in two- and three-dimensional space for the higher L/Ds. Once properly expanded, the nozzle's presence of Mach waves significantly raises the base pressure. Although ASR2 performs better than ASR1, the latter can still demonstrate its efficacy at higher NPRs. Therefore, it is reasonable to infer that the cavity, when situated at an ideal location and L/Ds with a favorable pressure gradient, is an effective passive control method.

Acknowledgment
This research was not funded by any grant.

References

[1] Pandey, K. M., and E. Rathakrishnan. "Annular cavities for Base flow control." *International Journal of Turbo and Jet Engines* 23, no. 2 (2006): 113-128. https://doi.org/10.1515/TJJ.2006.23.2.113

[2] Wick, Robert S. "The effect of the boundary layer on sonic flow through an abrupt cross-sectional area change." *Journal of the Aeronautical Sciences* 20, no. 10 (1953): 675-682. https://doi.org/10.2514/8.2794

[3] Khan, Ambareen, Parvathy Rajendran, and Junior Sarjit Singh Sidhu. "Passive control of base pressure: a review." *Applied Sciences* 11, no. 3 (2021): 1334. https://doi.org/10.3390/app11031334

[4] Viswanath, P. R., and S. R. Patil. "Effectiveness of passive devices for axisymmetric base drag reduction at Mach 2." *Journal of Spacecraft and Rockets* 27, no. 3 (1990): 234-237. https://doi.org/10.2514/3.26130

[5] Khan, Ambareen, Parvathy Rajendran, Junior Sarjit Singh Sidhu, and Mohsen Sharifpur. "Experimental investigation of suddenly expanded flow at sonic and supersonic Mach numbers using semi-circular ribs: a comparative study between experimental, single layer, deep neural network (SLNN and DNN) models." *The European Physical Journal Plus* 138, no. 4 (2023): 314. https://doi.org/10.1140/epjp/s13360-023-03853-1

[6] Khan, Ambareen, Mohd Azmi Ismail, and Nurul Musfirah Mazlan. "Numerical Simulation of Suddenly Expanded Flow from Converging Nozzle at Sonic Mach Number." In *Proceedings of International Conference of Aerospace and Mechanical Engineering 2019: AeroMech 2019, 20–21 November 2019, Universiti Sains Malaysia, Malaysia*, pp. 349-359. Springer Singapore, 2020.. https://doi.org/10.1007/978-981-15-4756-0_29

[7] Khan, Ambareen, Nurul Musfirah Mazlan, and Mohd Azmi Ismail. "Analysis of flow through a convergent nozzle at Sonic Mach Number for Area Ratio 4." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 62, no. 1 (2019): 66-79.

[8] Khan, Ambareen, Parvathy Rajendran, Junior Sarjit Singh Sidhu, S. Thanigaiarasu, Vijayanandh Raja, and Qasem Al-Mdallal. "Convolutional neural network modeling and response surface analysis of compressible flow at sonic and supersonic Mach numbers." *Alexandria Engineering Journal* 65 (2023): 997-1029. https://doi.org/10.1016/j.aej.2022.10.006

[9] Azami, Muhammed Hanafi, Mohammed Faheem, Abdul Aabid, Imran Mokashi, and Sher Afghan Khan. "Experimental research of wall pressure distribution and effect of micro jet at Mach." *International Journal of Recent Technology and Engineering* 8, no. 2S3 (2019): 1000-1003. https://doi.org/10.35940/ijrte.B1187.0782S319

[10] Khan, Sher Afghan, Abdul Aabid, and Ahamed Saleel Chandu Veetil. "Influence of micro-jets on the flow development in the enlarged duct at supersonic Mach number." *International Journal of Mechanical and Mechatronics Engineering* 19, no. 1 (2019): 70-82.

[11] Azami, Muhammed Hanafi, Mohammed Faheem, Abdul Aabid, Imran Mokashi, and Sher Afghan Khan. "Inspection of supersonic flows in a CD nozzle using experimental method." *International Journal of Recent Technology and Engineering* 8, no. 2S3 (2019): 996-999. https://doi.org/10.35940/ijrte.B1186.0782S319

[12] Khan, Sher Afghan, Mohammed Asadullah, and Jafar Sadhiq. "Passive control of base drag employing dimple in subsonic suddenly expanded flow." *Int. J. Mech. Mechatron. Eng. IJMME-IJENS* 18, no. 03 (2018): 69-74.

[13] Khan, Sher Afghan, Mohammed Asadullah, G. M. Fharukh Ahmed, Ahmed Jalaluddeen, and Maughal Ahmed Ali Baig. "Passive control of base drag in compressible subsonic flow using multiple cavities." *Int. J. Mech. Prod. Eng. Res. Dev* 8, no. 4 (2018): 39-44. https://doi.org/10.24247/ijmperdaug20185

[14] Aabid, Abdul, and Sher Afghan Khan. "Investigation of high-speed flow control from CD nozzle using design of experiments and CFD methods." *Arabian Journal for Science and Engineering* 46, no. 3 (2021): 2201-2230. https://doi.org/10.1007/s13369-020-05042-z

[15] Sajali, Muhammad Fahmi Mohd, Abdul Aabid, Sher Afghan Khan, Fharukh Ahmed Ghasi Mehaboobali, and Erwin Sulaeman. "Numerical investigation of the flow field of a non-circular cylinder." (2021).

[16] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Investigation of base pressure variations in internal and external suddenly expanded flows using CFD analysis." *CFD Letters* 11, no. 4 (2019): 32-40.

[17] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Effect of nozzle pressure ratio and control jet location to control base pressure in suddenly expanded flows." *Journal of Applied Fluid Mechanics* 12, no. 4 (2019): 1127-1135. https://doi.org/10.29252/jafm.12.04.29495

[18] Fharukh, Ahmed GM, Mohammad Asad Ullah, and Sher Afghan Khan. "Experimental study of suddenly expanded flow from correctly expanded nozzles." *ARPN Journal of Engineering and Applied Sciences* 11, no. 16 (2016): 10041-10047.

[19] Akhtar, Mohammad Nishat, Elmi Abu Bakar, Abdul Aabid, and Sher Afghan Khan. "Control of CD nozzle flow using microjets at Mach 2.1." *International Journal of Innovative Technology and Exploring Engineering (IJITEE)* 8, no. 9S2 (2019): 631-635. https://doi.org/10.35940/ijitee.I1128.0789S219

[20] Khan, Ambareen, Nurul Musfirah Mazlan, Mohd Azmi Ismail, and Mohammad Nishat Akhtar. "Experimental and numerical simulations at sonic and supersonic Mach numbers for area ratio 7.84." *CFD Letters* 11, no. 5 (2019): 50-60.

[21] Azami, Muhammed Hanafi, Mohammed Faheem, Abdul Aabid, Imran Mokashi, and Sher Afghan Khan. "Inspection of supersonic flows in a CD nozzle using experimental method." *International Journal of Recent Technology and Engineering* 8, no. 2S3 (2019): 996-999. https://doi.org/10.35940/ijrte.B1186.0782S319

[22] Khan, Sher Afghan, Abdul Aabid, and Ahamed Saleel Chandu Veetil. "Influence of micro-jets on the flow development in the enlarged duct at supersonic Mach number." *International Journal of Mechanical and Mechatronics Engineering* 19, no. 1 (2019): 70-82.

[23] Khan, Sher Afghan, Mohammed Asadullah, G. M. Fharukh Ahmed, Ahmed Jalaluddeen, and Maughal Ahmed Ali Baig. "Passive control of base drag in compressible subsonic flow using multiple cavities." *Int. J. Mech. Prod. Eng. Res. Dev* 8, no. 4 (2018): 39-44.

[24] Khan, Sher Afghan, Mohammed Asadullah, and Jafar Sadhiq. "Passive control of base drag employing dimple in subsonic suddenly expanded flow." *Int. J. Mech. Mechatron. Eng. IJMME-IJENS* 18, no. 03 (2018): 69-74.

[25] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Investigation of base pressure variations in internal and external suddenly expanded flows using CFD analysis." *CFD Letters* 11, no. 4 (2019): 32-40.

[26] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Influence of expansion level on base pressure and reattachment length." *CFD Letters* 11, no. 5 (2019): 22-36.

[27] Khan, Sher Afghan, Abdul Aabid, Fharukh Ahmed Mehaboobali Ghasi, Abdulrahman Abdullah Al-Robaian, and Ali Sulaiman Alsagri. "Analysis of area ratio in a CD nozzle with suddenly expanded duct using CFD method." *CFD Letters* 11, no. 5 (2019): 61-71.