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Influence of Expansion Level on Base Pressure and Reattachment Length

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ABSTRACT

In high speed projectiles like rocket, the thrust is created by the convergent divergent nozzle. The flow from the nozzle is exhausted in the enlarged duct of larger diameter to maximize the thrust. When the flow from the nozzle is exhausted in the enlarged duct, the base pressure gets reduced and hence increases base drag. This paper numerically simulates and investigates the flow field and the effectiveness of the Nozzle Pressure Ratio (NPR) on the base pressure, development of the flow field in the enlarged duct, the location of reattachment point, and the reattachment length. The supersonic flow was generated by the C-D nozzle, and the same is exited in the enlarged duct of area ratio 4.84 (ratio of enlarged duct area to nozzle exit area). The base pressure and the wall pressure distribution along the enlarged duct length have been studied. The Mach numbers considered for CFD analysis are 1.5, 2.0 and 2.5. NPR and the L/D ratios of the study are from 2, 5, and 8. Based on the results it is concluded that with enhancement in NPR, the nozzle becomes under-expanded, the reattachment length is reduced and the base pressure tends to get reduced at all the parameters of the present investigation.

Keywords:
Base pressure, Nozzle pressure ratio, Mach number, Supersonic flow

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1. Introduction

In high-speed projectiles, the base flow happens in several aerospace applications, such as rocket, missile, space shuttle, bomb, and has been the subject of many investigations from several years. It is well understood that the high-speed aerodynamic flow introduces many unwanted separation characteristics, such as very unsteady pressure fluctuations, a vital thrust loss due to flow entrainment, and so on. These flow-induced influences can mainly decrease the performance of the aerospace vehicle. Efforts to develop more efficient aerodynamic vehicles have been correlated by similar attempts to understand and to reduce these unwanted effects of base flow aerodynamics.

Flow field of sudden expansion is a complicated appearance described by flow detachment, recirculation, and reattachment. The boundary layer will form a shear layer may separate such a flow field into two principal regions, one being the flow recirculation region and the other the

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central/main flow region. The location where the dividing streamline hits the duct wall is known as the reattachment point, and the corresponding length from the nozzle exit is termed as reattachment length. In the case of high-speed aerodynamics, the base pressure is quite low due to the sudden expansion and hence relief available to the flow [1].

Due to the sudden increase in the area and the base being blunt the resistance offered by such aerospace vehicles at the high-speed projectiles can be as high as 50% of the total drag of a missile in jet OFF position [2]. An investigation in the literature shows that the oscillatory characteristics of the flow field in the rectangular duct is different from that for circular cross-section at the same flow conditions [3]. The base pressure increases with an increase in Mach number as well as an increase in area ratio [4-9].

Several scholars have investigated the effectiveness of microjets to control base pressure. The results show that the microjets are useful to increase the base pressure [10-26]. The flow fields for internal and external suddenly expanded flows are principally the same [27]. The various parameters affecting suddenly expanded flows have been analyzed using CFD and experimentation [14-20]. The area ratio and L/D ratios have been optimized to minimize base drag [21]. With increase in the nozzle pressure ratio, the nozzle becomes correctly expanded and the under expanded [14].

When the flow from the nozzle is exhausted in the enlarged duct of larger diameter to maximize the thrust, the base pressure gets reduced and hence increases base drag. This paper numerically investigates the effectiveness of the Nozzle Pressure Ratio (NPR) on the base pressure the reattachment length. The wide range of supersonic Mach numbers, length to diameter ratios and nozzle pressure ratios are considered in this research work. The pressure contours are studied in details for all the combinations of the parameters which will be very useful for better understanding of the pressure variations in the nozzle and enlarged duct. This is an advantage of this research work over the existing literature.

2. Methodology

2.1 CFD Analysis

The CFD analysis is based on the fundamental governing equations of fluid dynamics – the continuity, the momentum, and the energy equations.

The volume flow rate is even at each cross-section of a stream tube for incompressible flow.

$$\dot{Q} = AV \quad (1)$$

The mass flow rate is constant at any cross-section of a stream tube for compressible flow.

$$\dot{m} = \rho AV \quad (2)$$

Where,

V and *ρ* are velocity and density of fluid respectively at that cross-section,

A is cross-sectional area if stream tube.

For three dimensional compressible flow

$div(\rho V) = 0$, i.e.

$$\frac{\partial(\rho U_x)}{\partial x}+\frac{\partial(\rho U_y)}{\partial y}+\frac{\partial(\rho U_z)}{\partial z}=0 \tag{3}$$

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0 \tag{4}$$

The momentum equation and energy equations are given in Eq. (5) - (6).

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_i}=\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_i}\tau_{ij} \tag{5}$$

$$\frac{\partial}{\partial t}\left[\rho\left(e+\frac{V^2}{2}\right)\right]+\frac{\partial}{\partial x_j}\left[\rho u_j\left(e+\frac{V^2}{2}\right)+P+q_j-u_i\tau_{ij}\right]=0 \tag{6}$$

where

τ_{ij} is viscous stress tensor.
P is gas pressure,
ρ is gas density,
V is velocity modulus,
q_j is heat flux and
u is instantaneous velocity,

Academic licensed ANSYS software is used for the CFD analysis. CFD analysis has numerous assumptions and the flow considerations that need to be considered for better accuracy of the results.

Sutherland's equation to compute the stickiness of air at a different temperature is given in Eq. (7) [14, 16].

$$\frac{\mu}{\mu_0}=\frac{T_0+T_S}{T_0+T}\left(\frac{T}{T_0}\right)^{\frac{2}{3}} \tag{7}$$

The flow field was numerically simulated by initializing the proper boundary conditions. The element count is reduced using hexahedral mesh elements instead of tetrahedral elements. The well-known turbulence model k-ε is used for the simulation of the flow field. The k-ε turbulence model satisfactorily explains the viscous characteristics of the flow. Also, the qualitative characteristics of the flow are well prophesied in the form of shock waves, expansion fans, and recirculation zone [28-34].

2.2 Modelling, Meshing, and Boundary Conditions

The various geometries are modeled for all the possible combinations of Mach numbers, NPR and L/D ratios. The 2D axisymmetric geometries are modeled for the CFD analysis. Figure 1 shows 2D axisymmetric model for area ratio = 4.84, Mach number = 2.5 and L/D ratio = 8. The boundary conditions, inlet, outlet, axis and base edge are defined in geometries as shown in Figure 1. The edge at the base of the enlarged duct is named as a base edge, and it is defined as a wall in the Fluent during the CFD analysis. The duct wall is divided into many parts, and each part is used to calculate an average pressure during post-processing. After getting the pressure at each part, the combined wall pressure distribution is plotted for all the cases. The base edge is used to calculate an average base pressure during post-processing.

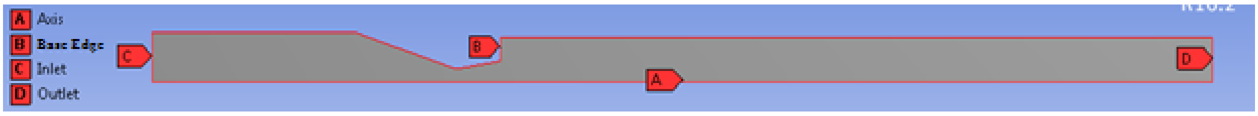

Fig. 1. 2D axisymmetric model for AR = 4.84, M = 2.5 and L/D = 8

The entire structured mesh is generated by dividing the geometry into a few segments, and each segment has meshed separately with structured meshing scheme. Figure 2 shows an entirely structured meshed model, and the skewness mesh metric for area ratio = 4.84, Mach number = 2.5 and L/D ratio = 8. The total 11144 numbers of mesh elements are generated for the geometry shown, out of which 10592 elements are having the skewness of less than 0.05 as shown in elements metrics in Figure 2.

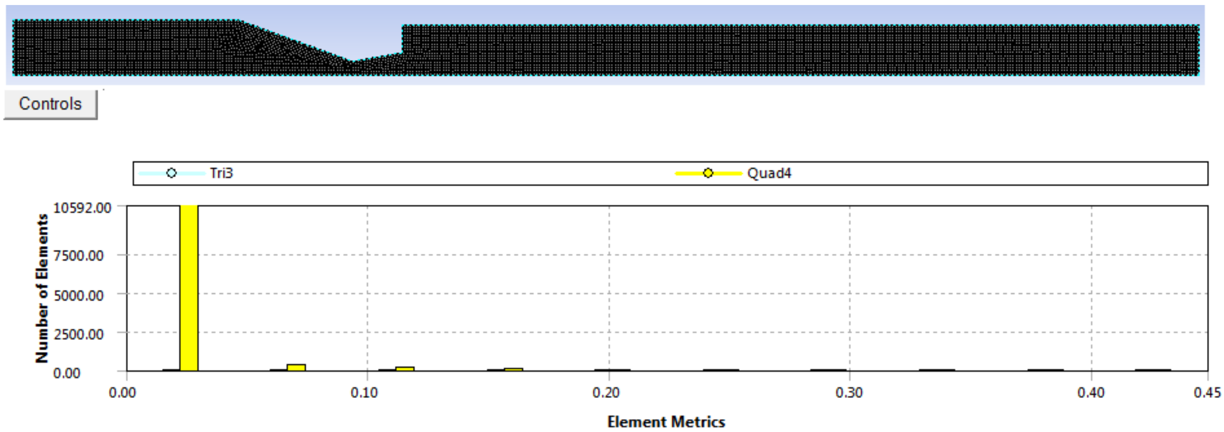

Fig. 2. Structured meshed model and skewness mesh metric for L/D = 8

The Table 1 shows the grid independence test for the model. From Table 1 it is clear that the mesh element size 1 mm is sufficient to get good quality results.

Table 1
Grid independence test for various mesh sizes

Mesh Max Size (mm)	Mesh Elements	Static Pressure at Base Edge	Total Pressure at Base Edge
5	56	0.982321125	0.983963473
4	92	0.924344944	0.92464879
3	162	0.860645547	0.862173393
2	352	0.878006385	0.881550664
1	1310	0.885458179	0.886654320
0.8	2030	0.883369159	0.884080365
0.6	3609	0.885199250	0.886767540

3. CFD Analysis and Results

The CFD analysis was carried out for a total of 27 different combinations of factors. CFD analysis settings are the same as discussed in previous sections. The responses in the form of the total base pressure in the recirculation zone of the duct and wall pressure distribution along the length of the enlarged duct are recorded. All the base pressure and wall pressure values are converted into dimensionless pressure.

3.1 Effect of NPR on Base Pressure

The average base pressure is calculated on the base edge with the help of ANSYS Fluent post-processor. The plots for dimensionless base pressure vs. nozzle pressure ratio at various Mach numbers and L/D ratios are plotted in Figure 3.

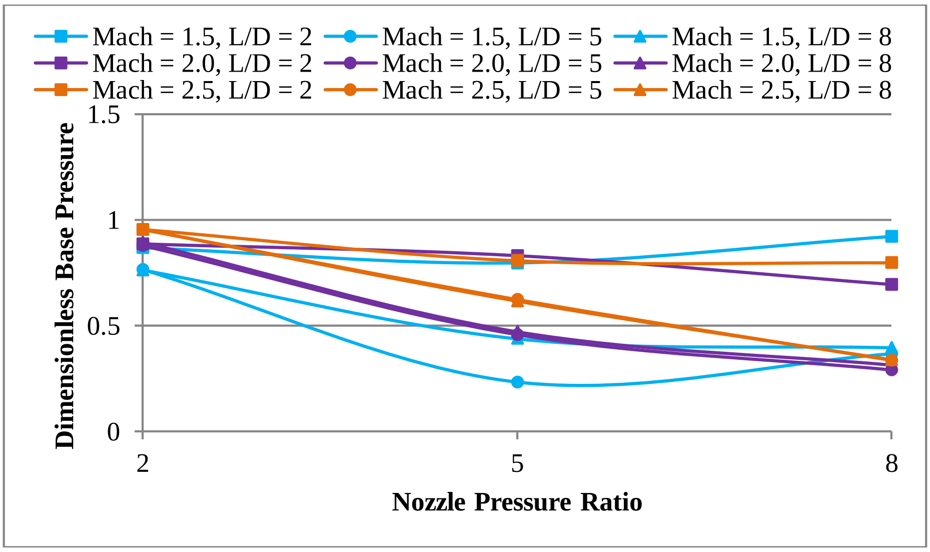

Fig. 3. Dimensionless base pressure vs Nozzle pressure ratio at various Mach numbers and L/D ratios

From Figure 3 it is noticed that as the nozzle pressure ratio increases from 2 to 5, the base pressure dropped for all the cases. With the increase in NPR from 5 to 8, the case to case observations is as follows.

I. At Mach number = 1.5 and L/D = 2 and 5, the base pressure increases. At Mach number 1.5, the nozzle is under-expanded in both the cases of NPR = 5 and 8. However, at NPR = 8, because of a very high level of expansion, the base pressure is relatively higher.
II. At Mach number = 2.0 and L/D = 2, the base pressure reduced. Since at NPR = 8, the nozzle becomes under-expanded and the flow partially reattached to the enlarged duct and the base pressure relatively reduced.
III. At Mach number = 2.5 and L/D = 2, there is no variation in the base pressure. As the nozzle is highly over-expanded and the flow does not expand and does not reattach to the enlarged duct.
IV. At Mach number = 2.0 and L/D = 5 and 8, the base pressure reduced. At Mach number 2.0, the nozzle becomes under-expanded at NPR = 8. When the nozzle becomes under-expanded, the flow completely reattached to the enlarged duct; hence the base pressure reduced.
V. At Mach number = 2.5 and L/D = 5 and 8, the base pressure reduced. At Mach number 2.5, the nozzle is over-expanded at NPR = 8. Due to an increase in NPR, the flow gets reattached to the enlarged duct, and the base pressure reduced.
VI. At Mach number = 1.5 and L/D = 8, the variation in the base pressure is negligible.

3.2 Effect of NPR on Reattachment Length for L/D = 2

The contours plots are extracted from the simulated results of Fluent post-processor. The pressure contours for area ratio = 4.84 at length to diameter (L/D) = 2 and various Mach numbers NPR's are shown in Figure 4 to 12.

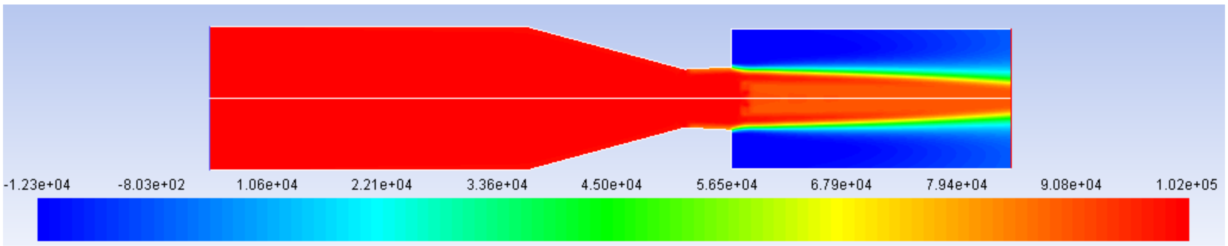

Fig. 4. Pressure contour (in Pascal) for L/D = 2, M = 1.5 and NPR = 2

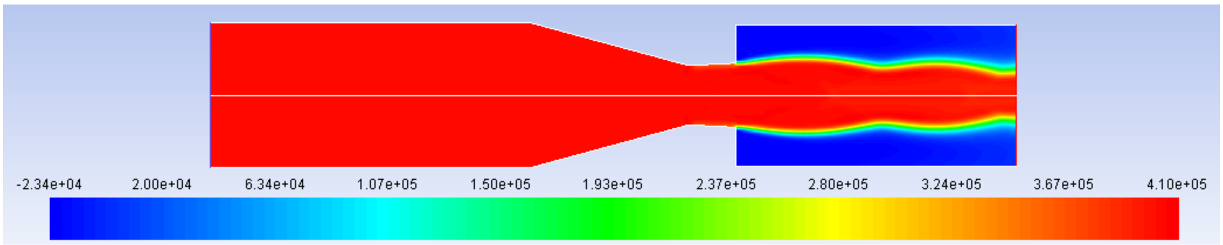

Fig. 5. Pressure contour (in Pascal) for L/D = 2, M = 1.5 and NPR = 5

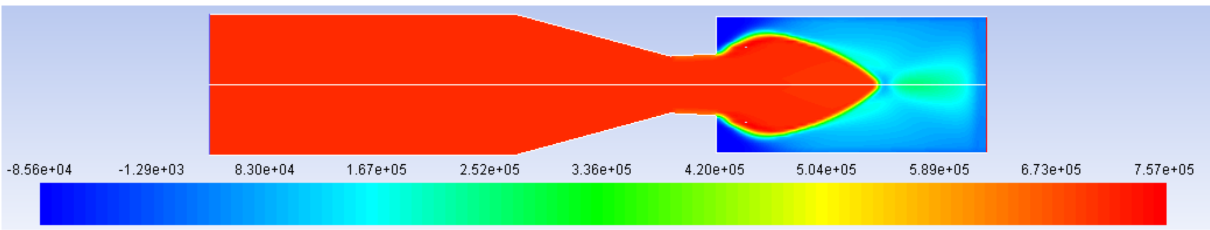

Fig. 6. Pressure contour (in Pascal) for L/D = 2, M = 1.5 and NPR = 8

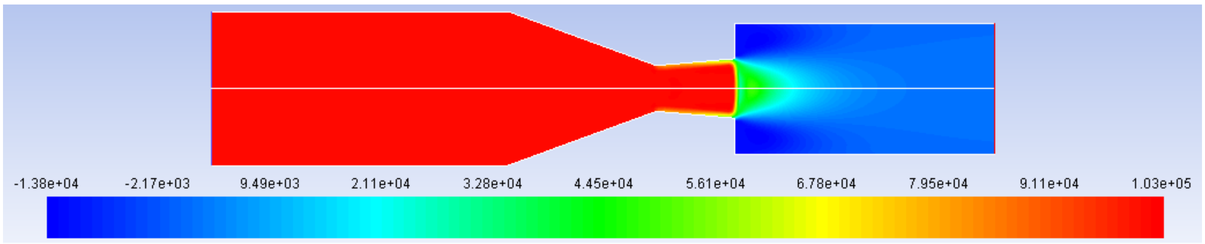

Fig. 7. Pressure contour (in Pascal) for L/D = 2, M = 2.0 and NPR = 2

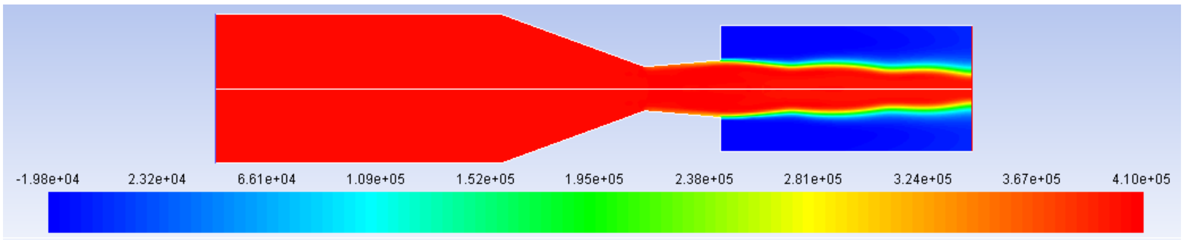

Fig. 8. Pressure contour (in Pascal) for L/D = 2, M = 2.0 and NPR = 5

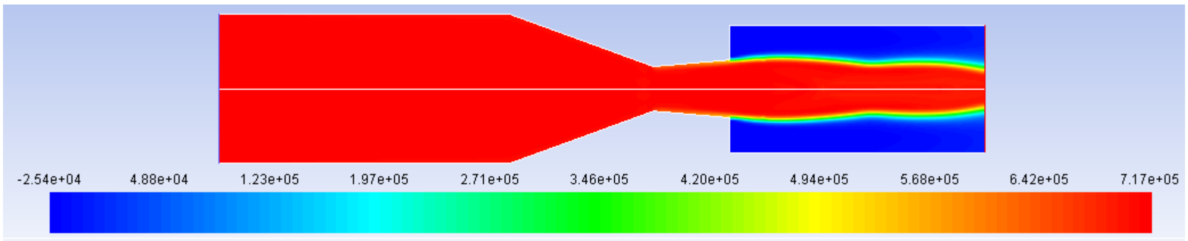

Fig. 9. Pressure contour (in Pascal) for L/D = 2, M = 2.0 and NPR = 8

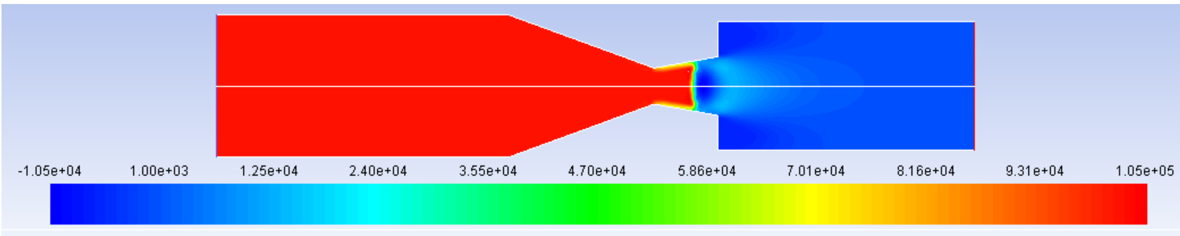

Fig. 10. Pressure contour (in Pascal) for L/D = 2, M = 2.5 and NPR = 2

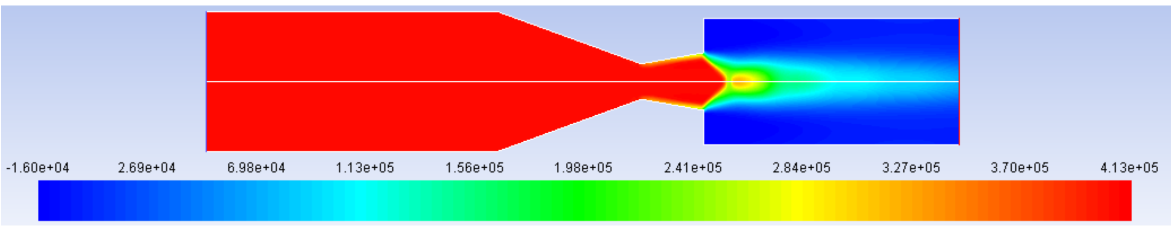

Fig. 11. Pressure contour (in Pascal) for L/D = 2, M = 2.5 and NPR = 5

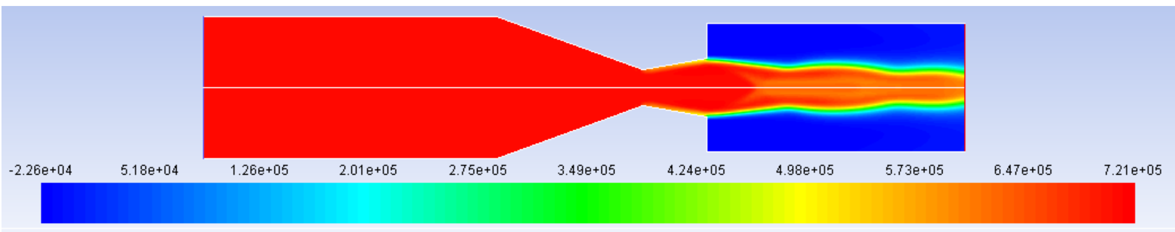

Fig. 12. Pressure contour (in Pascal) for L/D = 2, M = 2.5 and NPR = 8

From Figure 4 to 12 it is observed that the value of the pressure at the blunt base in the base corner of the pipe is almost same as the atmospheric pressure at L/D ratio = 2, except the case of Mach number = 1.5 and NPR = 8 as shown in Figure 6. At lower L/D ratio, the flow does not reattach to the enlarged duct except highly under-expanded cases. At Mach number = 1.5 and NPR = 8, the nozzle becomes highly under-expanded, and the flow is reattached to the enlarged duct; hence the base pressure reduced.

Figure 13 shows the wall pressure distribution along the enlarged duct length for L/D ratio = 2. From Figure 13 it is observed that at Mach 1.5 and nozzle pressure ratio of 8, the pressure in the base region is considerably lower. A sudden peak is observed in the pressure value at a distance of 1D, which means that the jet has become highly under-expanded, and the flow is reattached to the enlarged duct at a distance of x/D = 1. For remaining all the cases, the flow does not reattach to the enlarged duct due to the shorter length of the enlarged duct.

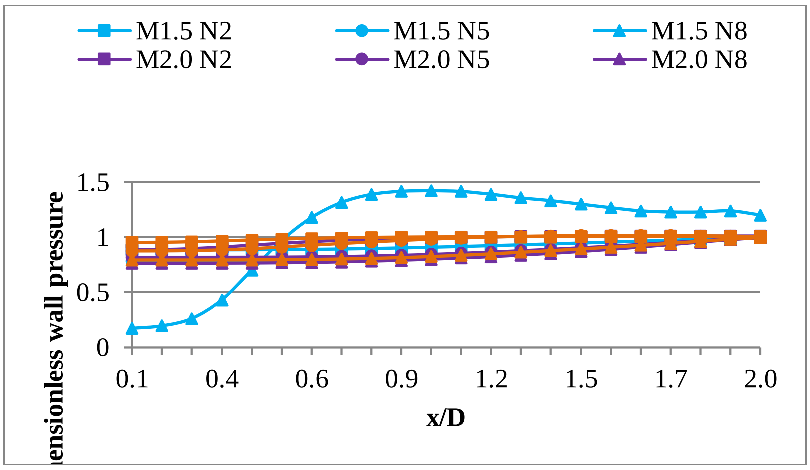

Fig. 13. Wall pressure distribution along the enlarged duct length for L/D = 2

3.3 Effect of NPR on Reattachment Length for L/D = 5

The pressure contours for area ratio = 4.84 at length to diameter (L/D) = 5, Mach number 1.5, 2.0 and 2.5 and nozzle pressure ratios 2, 5 and 8 are shown in Figure 14 to 22.

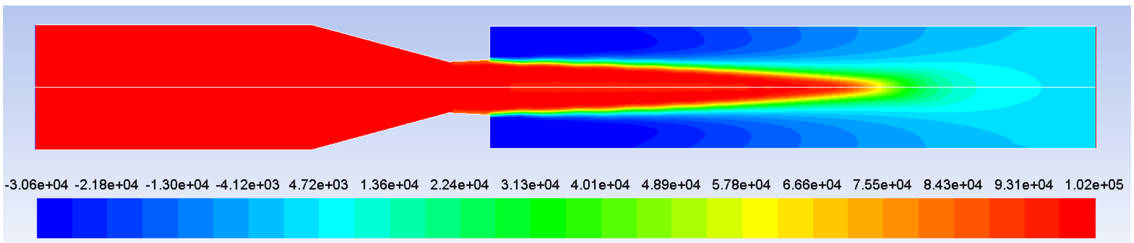

Fig. 14. Pressure contour (in Pascal) for L/D = 5, M = 1.5 and NPR = 2

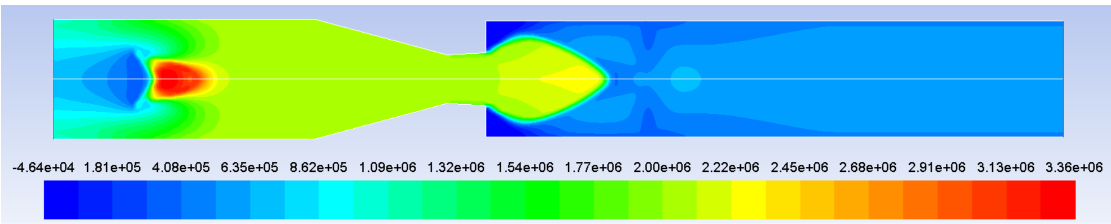

Fig. 15. Pressure contour (in Pascal) for L/D = 5, M = 1.5 and NPR = 5

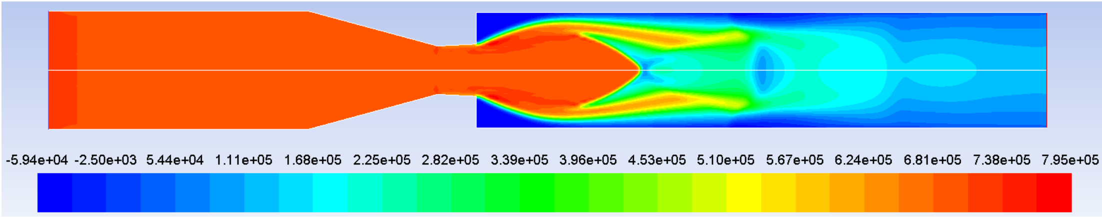

Fig. 16. Pressure contour (in Pascal) for L/D = 5, M = 1.5 and NPR = 8

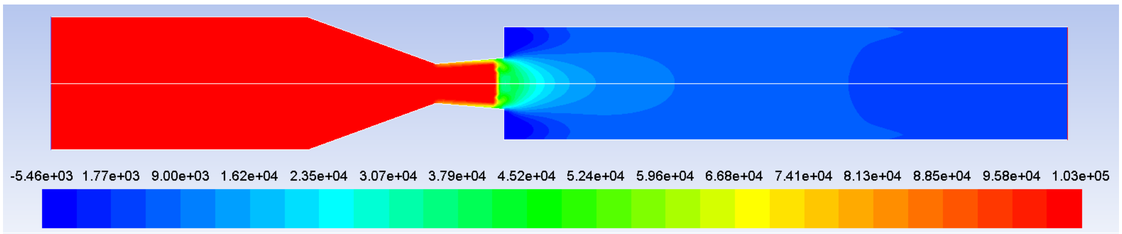

Fig. 17. Pressure contour (in Pascal) for L/D = 5, M = 2.0 and NPR = 2

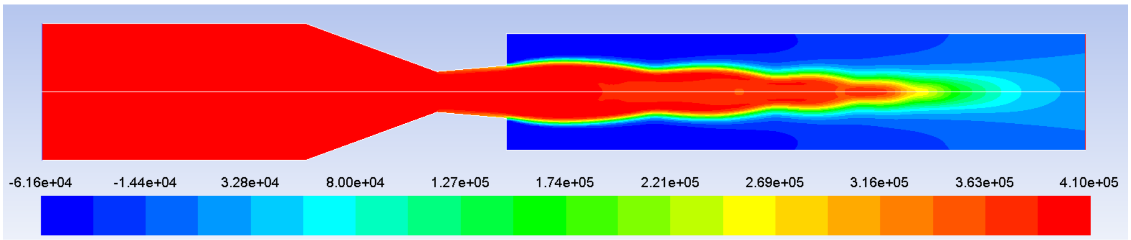

Fig. 18. Pressure contour (in Pascal) for L/D = 5, M = 2.0 and NPR = 5

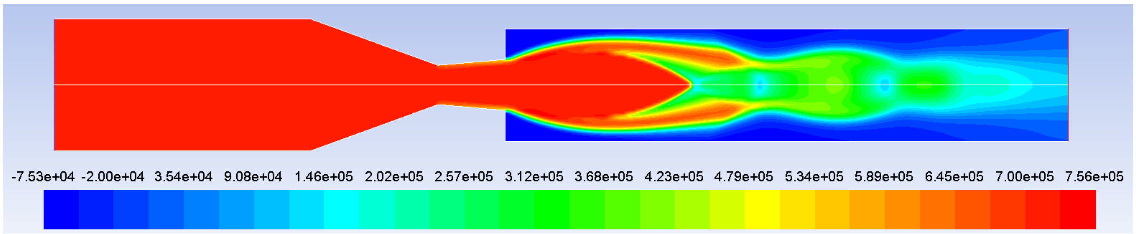

Fig. 19. Pressure contour (in Pascal) for L/D = 5, M = 2.0 and NPR = 8

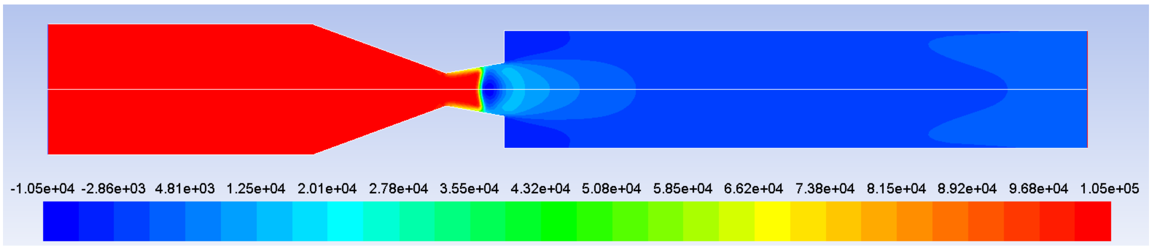

Fig. 20. Pressure contour (in Pascal) for L/D = 5, M = 2.5 and NPR = 2

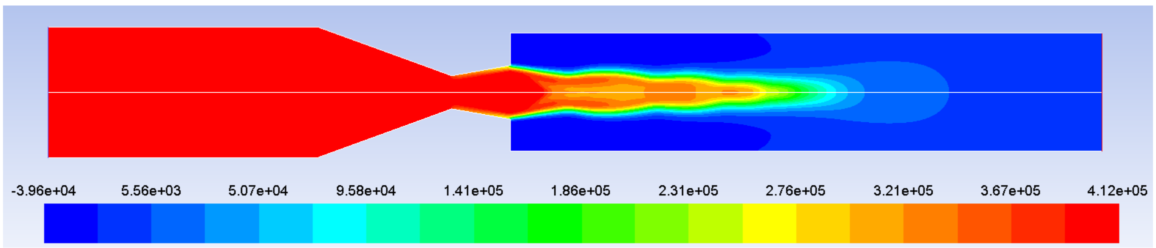

Fig. 21. Pressure contour (in Pascal) for L/D = 5, M = 2.5 and NPR = 5

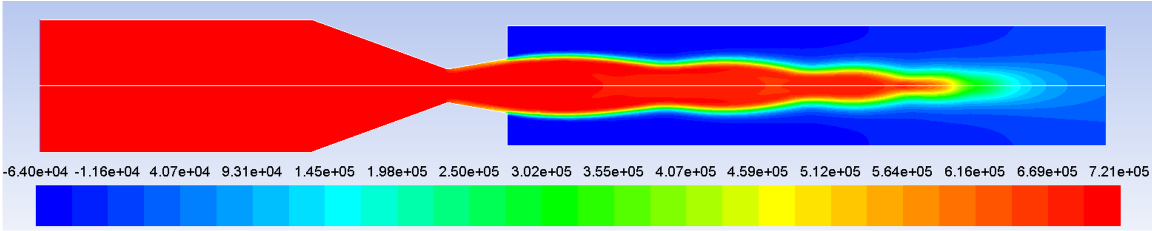

Fig. 22. Pressure contour (in Pascal) for L/D = 5, M = 2.5 and NPR = 8

Figure 14 to 22, indicate that at the blunt base the pressure at the recirculation of the duct is lower than the atmospheric pressure at L/D ratio = 5 except the cases of lower NPR, i.e., NPR = 2 at higher Mach numbers, i.e., Mach number = 2.0 and 2.5. At lower nozzle pressure ratio and higher Mach number due to low NPR and high inertia level, the nozzle becomes highly over-expanded, and the flow does not reattach to the enlarged duct.

From the pressure contours, it can be seen that with an increase in NPR, the nozzle becomes under-expanded for Mach numbers 1.5 and 2.0, and the stress at the blunt base of the pipe is considerably decreased. For Mach number 2.5, all the cases of the study are over-expanded as the NPR required to expand the jet is 17.09 correctly. Figure 15, 16 and 19 show the under-expanded conditions while Figure 14, 17, 18, 20, 21 and 22 show the over-expanded conditions.

Figure 23 shows the wall pressure distribution along the enlarged duct length for L/D ratio = 5. From Figure 23 the following observations are drawn.

I. At M = 1.5 and NPR = 2, the nozzle is over-expanded, the flow exiting from the nozzle has remarkably high reattachment length. Since the flow is reattached to the enlarged duct, the base pressure is reduced near the base region.
II. At high Mach numbers, i.e., 2.0 and 2.5 and lower nozzle pressure ratio, i.e., NPR = 2, the nozzle becomes highly over-expanded and the flow exiting from the nozzle does not reattach to the enlarged duct. Hence the base pressure and wall pressure along duct length are almost the same as atmospheric pressure.
III. At Mach number = 1.5 and nozzle pressure ratio = 5 and 8, the nozzle becomes under-expanded and high peaks are observed in the pressure value at a distance of 1.2D from nozzle exit, which means that the flow is reattached to the enlarged duct at a distance of x/D = 1.2. This behavior of the flow can also be observed in Figure 15 and 16.
IV. At Mach number = 2.0 and NPR = 5, the flow reattached to the enlarged duct at a considerable length as compared to the case when the flow is under-expanded at NPR = 8.
V. At Mach number = 2.0 and NPR = 8, the nozzle becomes under-expanded, and flow gets reattached with the enlarged duct at a distance of x/D = 1.8.
VI. At Mach number = 2.5, the flow from the nozzle is over-expanded at all nozzle pressure ratios. The more duct length is required to reattach the flow with the enlarged duct wall.

3.4 Effect of NPR on Reattachment Length for L/D = 8

The total pressure contours were plotted from the results obtained with the help of Fluent post-processor. The pressure contours for area ratio = 4.84 at length to diameter (L/D) = 8, Mach number 1.5, 2.0 and 2.5 and nozzle pressure ratios 2, 5 and 8 are shown in Figure 24 to 32.

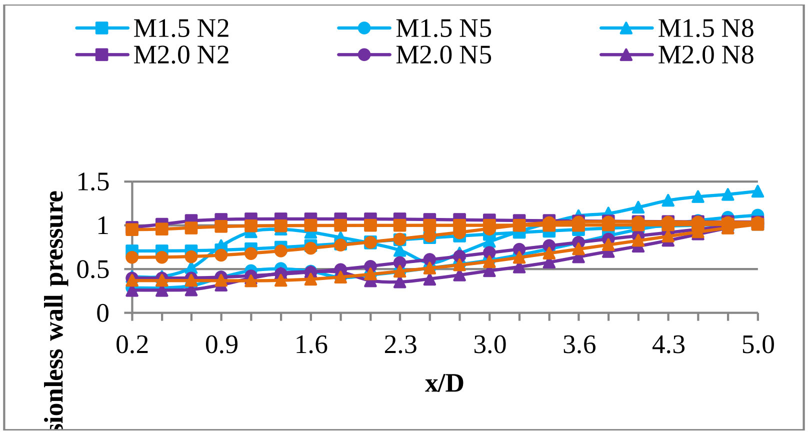

Fig. 23. Wall pressure distribution along the enlarged duct length for L/D = 5

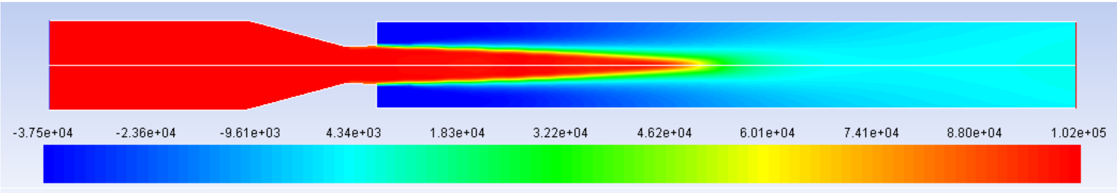

Fig. 24. Pressure contour (in Pascal) for L/D = 8, M = 1.5 and NPR = 2

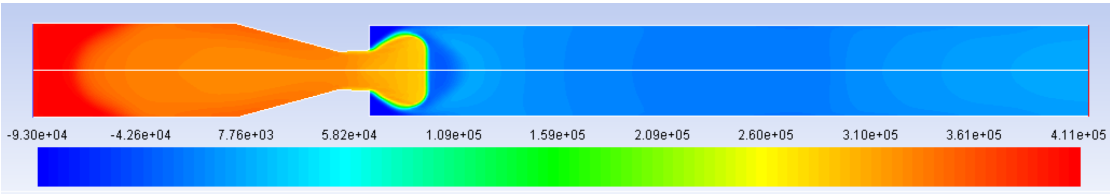

Fig. 25. Pressure contour (in Pascal) for L/D = 8, M = 1.5 and NPR = 5

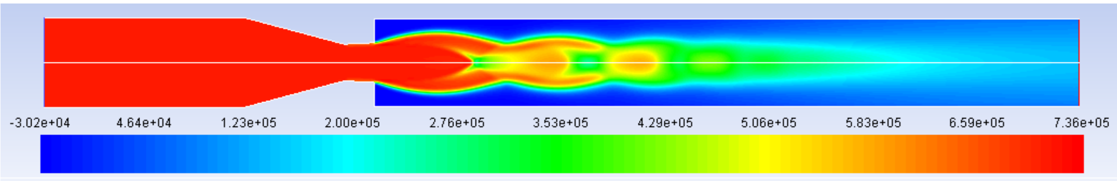

Fig. 26. Pressure contour (in Pascal) for L/D = 8, M = 1.5 and NPR = 8

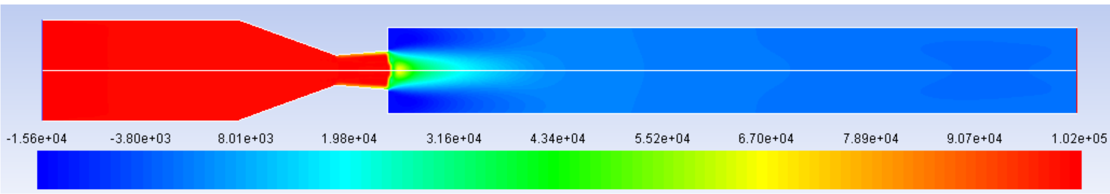

Fig. 27. Pressure contour (in Pascal) for L/D = 8, M = 2.0 and NPR = 2

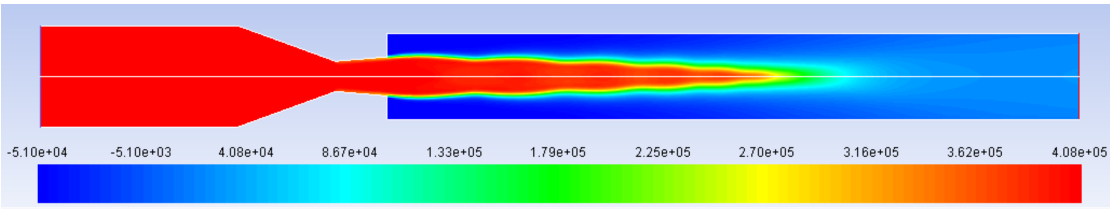

Fig. 28. Pressure contour (in Pascal) for L/D = 8, M = 2.0 and NPR = 5

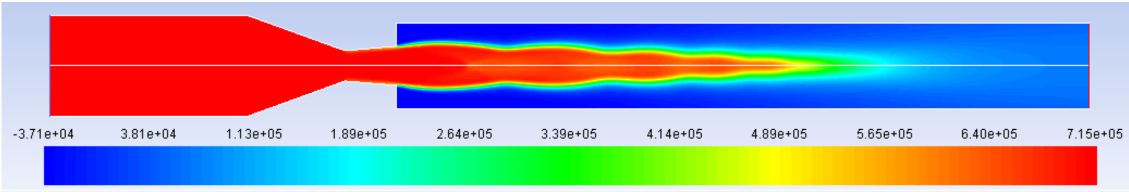

Fig. 29. Pressure contour (in Pascal) for L/D = 8, M = 2.0 and NPR = 8

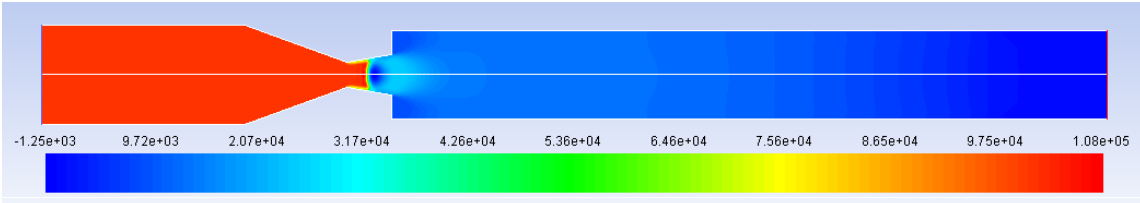

Fig. 30. Pressure contour (in Pascal) for L/D = 8, M = 2.5 and NPR = 2

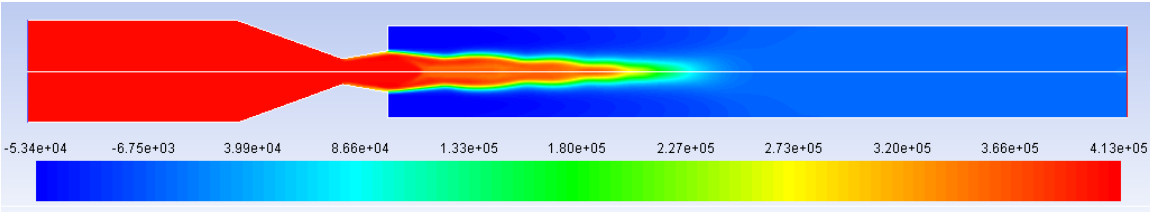

Fig. 31. Pressure contour (in Pascal) for L/D = 8, M = 2.5 and NPR = 5

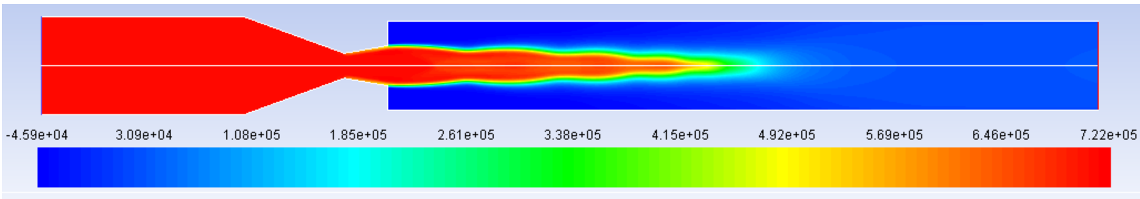

Fig. 32. Pressure contour (in Pascal) for L/D = 8, M = 2.5 and NPR = 8

Figure 24 to 32 show wall pressure results, which is lower than the ambient pressure at L/D ratio = 8 except the cases of lower NPR, i.e., NPR = 2 at higher Mach numbers, i.e., Mach number = 2.0 and 2.5. At lower nozzle pressure ratio and higher Mach number, the nozzle becomes highly over-expanded, and the flow appears not to reattach to the enlarged duct.

From the pressure contours, it can be seen that with an increase in NPR, the nozzle becomes under-expanded for Mach numbers 1.5 and 2.0, and the stress at the blunt base corner in the pipe is reduced. For Mach number 2.5, all the cases of the study are over-expanded.

Figure 33 shows the wall pressure distribution along the enlarged duct length for L/D ratio = 8. From Figure 33 the following observations are drawn.

I. At Mach = 1.5 and nozzle pressure ratio = 2, the nozzle is over-expanded, the flow exiting from the nozzle has considerable reattachment length. As the flow is reattached to the enlarged duct, the base pressure is reduced near the base region.

II. At high Mach numbers, i.e., 2.0 and 2.5 and lower nozzle pressure ratio, i.e., NPR = 2, the nozzle becomes highly over-expanded and the flow exiting from the nozzle does not reattach to the enlarged duct. The base region is open to the atmosphere. Hence the base pressure and wall pressure distribution are almost the same as atmospheric pressure.

III. At M = 1.5, and NPR = 5, the nozzle becomes under-expanded, and a sudden rise is seen in the pressure at a distance of 1.5D, which means that the flow is reattached to the enlarged duct at a length of 1.5 times the diameter of the enlarged duct.
IV. At M = 1.5, and NPR = 8, the nozzle is highly under-expanded. Because of high nozzle pressure ratio and more considerable duct length, the pressure is stretched over the length of the duct, and a sudden peak in the pressure value disappear as it appears in case of L/D = 5.
V. At Mach number = 2.0 and NPR = 5 and 8, the flow reattached to the enlarged duct near the duct exit. At Mach number = 2.5, the flow from the nozzle is over-expanded at all nozzle pressure ratios. The substantial duct portion is needed to reattach the flow with the enlarged duct surface.

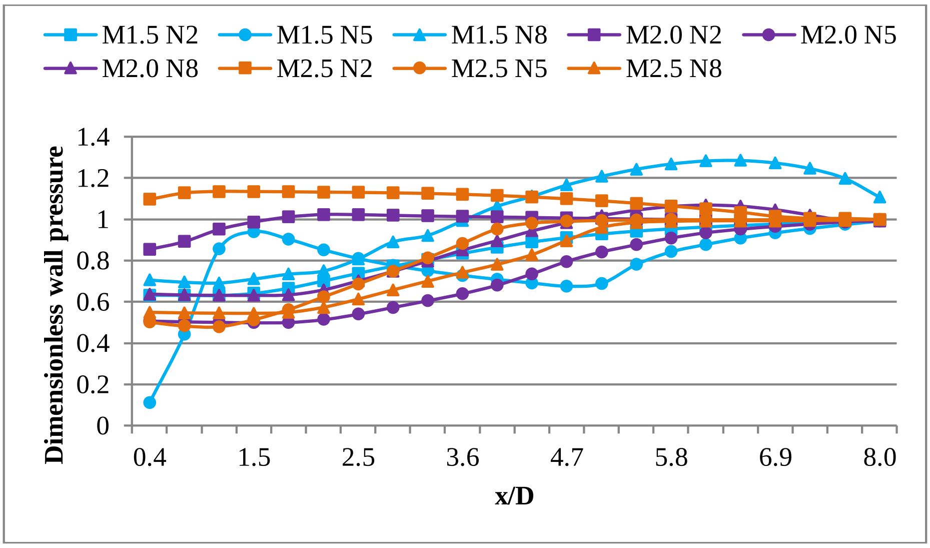

Fig. 33. Wall pressure distribution along the enlarged duct length for L/D = 8

4. Conclusions

Based on the discussion of the results, it is concluded that the nozzle pressure ratio is a critical variable which impacts the base pressure and reattachment length the most. With the increase in NPR, the nozzle flow results in the decrease of the level of over-expansion and ultimately becoming correctly expanded jets, and then later the jets become under-expanded. It may be concluded that with an increase in NPR, the base pressure tends to decrease for all the values of NPR at each parameter of the existing study. It can be concluded that with increase in Mach number the base pressure as well as the reattachment length increases.

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