

Numerical Analysis for Supersonic Exhaust Diffuser with Centre-body for High Altitude Testing of Rocket Nozzle

R.C. Mehta¹⁾ and G. Natarajan²⁾

^{1), 2)} *Department of Aeronautical Engineering, Noorul Islam University,
Kumaracoil 629180, India*

¹⁾ drakhab.mehta@gmail.com

ABSTRACT

The centre body changes the flow characteristics inside the diffuser as compared to the diffuser with and without the centre body. The conical shock is formed due the presence of the centre body which helps in recovering the pressure. The performance of a centre body diffuser is a function of many of its geometrical parameters such as cone angle, diameter of the centre body etc. Hence it is pertinent to investigate the effect of the geometrical parameters on the starting characteristics of the diffuser. The axisymmetric time-dependent compressible turbulent Reynolds-Averaged Navier-Stokes (RANS) equations considered in the present analysis are in strong conservation form and are solved using the FLUENT software. The one-equation turbulence model proposed by Spalart-Allmaras is employed to compute eddy viscosity.

The centre body changes the flow characteristics inside the diffuser as compared to the diffuser with out it. The conical shock is formed due the presence of the centre body which helps in recovering the pressure. The performance of a centre body diffuser is a function of many of its geometrical parameters such as cone angle, diameter of the centre body etc. Hence it is pertinent to investigate the effect of the geometrical parameters on the starting characteristics of the diffuser. The parametric study and its results provide a good data base for the design of centre body type diffuser for High Altitude Test facilities.

1. Introduction

A constant area supersonic exhaust diffuser (SED) is generally used for testing the propulsive nozzles. The straight cylindrical SED can simulate low pressure environment for evaluating steady-state performance of a rocket nozzle. Park et al. (2008) made a small-scale HAT facility to evaluate the flowfield of various types of SED. A lab-scale high-altitude simulator (Yeom et al. 2009, Sung et al. 2010) was set-up to analyze the complex flowfield of the SED performance in conjunction with the experimental and the numerical methods. Sivo, Meyer and Peters (1960) describe the use of the various types of SED for the High Altitude Test facility. The challenging task in designing such a diffuser is to keep the facility length shorter and starting pressure ratio as low as possible. Their experimental

studies have revealed that the starting stagnation pressure for a diffuser is a function of the geometrical parameters and the operating conditions of the rocket motor.

2. Numerical Analysis

The axisymmetric time-dependent compressible turbulent Reynolds-Averaged Navier-Stokes equations considered in the present analysis are in strong conservation form and are solved using the FLUENT (Spalart and Allmaras 1992) software. The one-equation turbulence model proposed by Spalart-Allmaras (Fluent 6.2 2010) is employed to compute eddy viscosity.

At the diffuser wall as well as on the centre body, a no-slip condition is enforced together with adiabatic wall condition the inflow conditions are given in Tables 1 and 2. The symmetric conditions are prescribed at the centre line of the diffuser.

Table 1 Parameters varied for center body diffuser analysis

Sl. No.	Parameter	Values
1	P_0 , bar	15, 17, 18, 19
2	p_e , bar	1.0
3	S_s / D_d	0.25, 0.50, 1.0, 1.25
4	α , deg	3.75°, 6°, 8°
5	L_t / D_d	1, 2, 3
6	A_d/A^*	23.36

Table 2 Nozzle exhaust condition during steady-state operation

Parameter	Values
Stagnation pressure, P_0 , bar	19.0
Stagnation temperature, T_0 , K	300.0
Exit Mach number, M_e	5.8
Nozzle area ratio, A_e / A^*	21.77
Fluid	GN ₂

The axial velocity is extrapolated and the radial velocity is calculated using the inlet condition. At the centre line of the axisymmetric convergent-divergent nozzle and the straight cylindrical supersonic diffuser, the symmetric conditions are prescribed. The turbulent kinematic viscosity is set to zero at the wall.

3. Diffuser Geometry and Grid Independence Test

Geometrical parameters of diffuser without and with centre body are depicted in Figure 1(a) and 1 (b). In the numerical simulation, the centre body location and dimensions are varied as given in the matrix of Table 3.

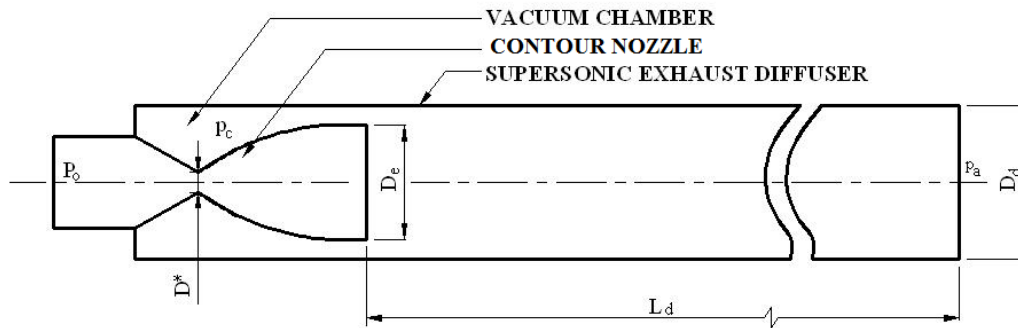


Figure 1 (a) SED without center body

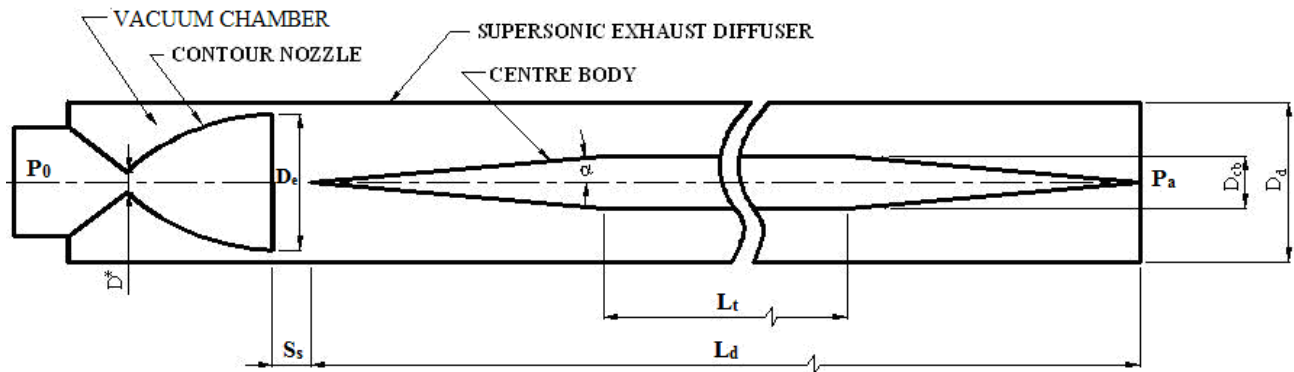


Figure 1 (b) SED with centre body

The computational grid is generated using the commercial package GAMBIT. The numerical simulations of the above mentioned equations are carried out until the residues fall below 1.0×10^6 for all the flow variables. To investigate the sensitivity of the grid in the axial and the radial directions, a numerical investigation is performed for various sizes of cells of 90000, 120000, 150000 and 180000.

Table 3 Geometrical parameters of diffuser with centre body on vacuum chamber pressure

center body			Stagnation pressure P_0 , bar			
Range of geometrical parameters			15	17	18	19
L_t / D_d	S_s / D_d	L_d / D_d	Vacuum chamber pressure, p_{vc} mbar			
			unstarted			started
1.0	0.25	6.3	0.69	0.48	.024	0.025
1.0	0.50	6.6	0.53	0.54	0.930	0.025
1.0	1.00	7.1	0.53	0.49	0.050	0.018
1.0	1.25	7.3	0.53	0.48	0.028	0.025
2.0	0.25	7.3	0.61	0.50	0.023	0.025
2.0	0.50	7.6	0.55	0.54	0.126	0.025
2.0	1.00	8.1	0.52	0.49	0.024	0.025
2.0	1.25	8.3	0.52	0.47	0.024	0.025
3.0	0.25	8.3	0.46	0.52	0.074	0.025
3.0	0.50	8.6	0.48	0.51	0.024	0.025
3.0	1.00	9.1	0.53	0.48	0.147	0.025
3.0	1.25	9.4	0.53	0.40	0.190	0.025
without center body			Vacuum chamber pressure, p_{vc} , mbar			
-	-	6.3	0.52	0.45	0.24	0.25

4 Results and Discussion

4.1 Influence of Stagnation Pressure P_0

The influence of nozzle stagnation pressure (ranging from 15 to 19 bar) on the static characteristics of the diffuser is investigated for back pressure of 1 bar. The vacuum chamber pressure decreases as the stagnation pressure increases up to a critical value of 18 bar and beyond this pressure the vacuum chamber pressure remains constant at about 25 mbar as shown in Table 3. It is also noted that the diffuser inlet attains a supersonic condition ($M > 1$) for a stagnation pressure of 18 bar. Thus the diffuser started condition achieved for stagnation pressure greater than 18 bar for most of the cases with default values of the parameters, Table 3 shows the predicted values of vacuum chamber pressure. It is seen that the diffuser attains start condition for a stagnation pressure value of 18 bar and it is unstarted for the cases with $P_0 < 18$ bar.

The mach contour shown in Figure 2 for different stagnation pressures throw more light on the phenomenon of diffuser starting. At stagnation pressure less than 18 bar, the

exhaust gases do not have the momentum for the diffuser to start. At less than the critical values of the nozzle stagnation pressure the exhaust gases do not have sufficient momentum to drive the shock train out of the nozzle; consequently the flow separates in the nozzle divergent portion. In this condition the diffuser does not flow full. Because of the reverse flow, the exhaust gases enter into the vacuum chamber through the annular space between the nozzle and the diffuser wall and reduce the vacuum. As the stagnation pressure is increased beyond the critical value, the exhaust from the nozzle covers the entire cross section of the nozzle without flow separation and the oblique shocks give rise to a series of reflected shock cells that effectively seal the vacuum chamber and help maintain the vacuum level in the test (vacuum) chamber. The oblique shock train established in the duct also facilitates a gradual recovery of pressure from the altitude pressure to the atmospheric pressure.

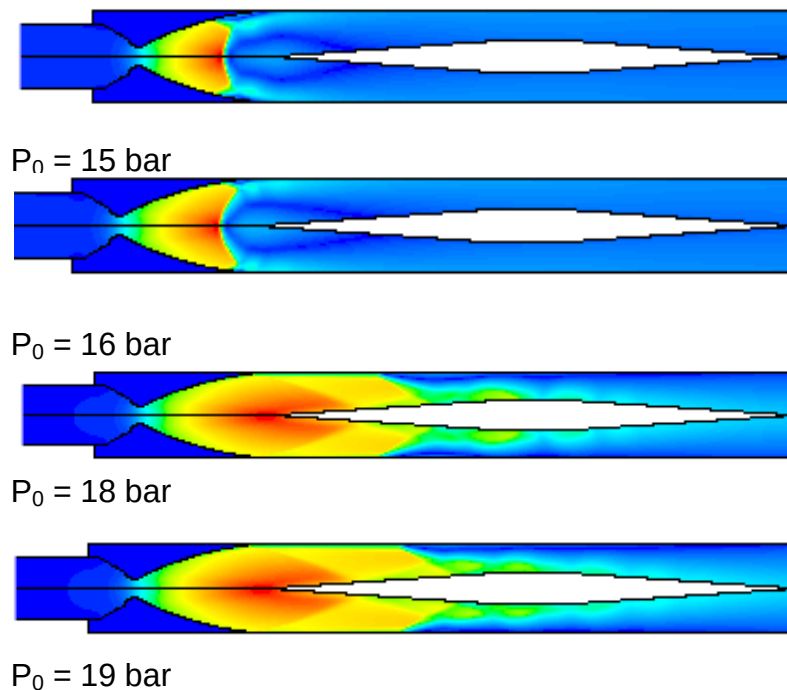


Figure 2 Mach number contour inside the diffuser with centre body
 ($L_t/D_d = 1.0$, $S_s/D_d = 0.25$, $L_d/D_d = 6.3$)

4.2 Influence of Centre Body on starting of Diffuser

The numerical simulation is carried out for the diffuser without the centre body and compared with that of a diffuser with centre body of same L/D ratio. Figure 3 shows the Mach contour inside the diffuser without the centre body for $L_d/D_d = 6.3$ for the stagnation pressure of 15, 17, 18 and 19 bar. The diffuser performance characteristics are given in Table 3. The diffuser is started at the vacuum chamber pressure of 0.25 mbar. It is interesting to observe from the contour plots that the nozzle is over-expanded at 15, 17. At the $P_0 = 18$ bar, the nozzle is started but diffuser did not start.

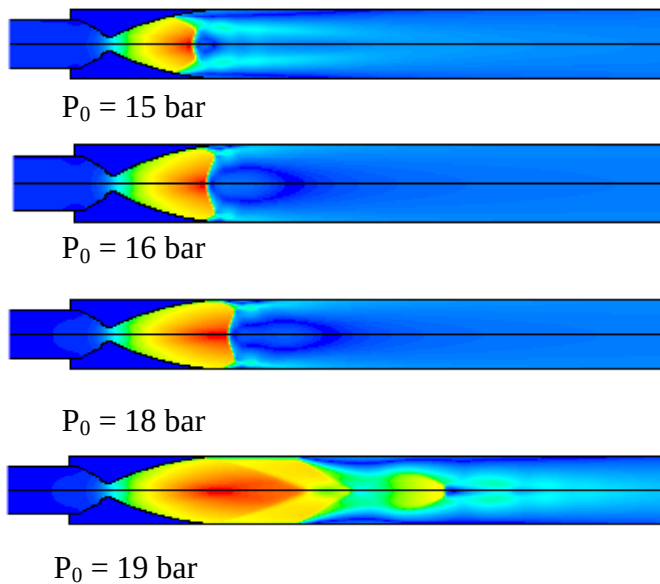


Figure 3 Mach number contours of inside of the diffuser without centre body,
 ($L_d / D_d = 6.3$)

The nozzle is fully expanded and diffuser is started at $P_0 = 19$ bar. The shock wave train is seen in the diffuser. Figure 6.58 shows the Mach contour inside the diffuser with the centre body for $L_t/D_d = 1.0$, $S_s/D_d = 0.25$, $L_d/D_d = 6.3$ for the P_0 varies from 15, 17, 18 and 19 bar. The corresponding performance characteristics can be found in Table 6.15. It is interesting to observe the effects of the centre body on the flow field as compared to without the centre body as shown in Figure 6.59. The oblique shocks have changed the flow inside the diffuser. The centre body shows the influence at $P_0 = 18$ and 19 bar, because the conical section of the centre body is immersed inside the supersonic flow.

Figures 4 and 5 show the variation of centre line Mach number in the diffuser without and with centre body respectively for $L_d / D_d = 6.3$. The normal shock location is differed in the figures. The Mach number decreased rapidly in the presence of the centre body. Figure 4 depicts that there is normal shock at about $x = 0.7$ m from the nozzle throat.

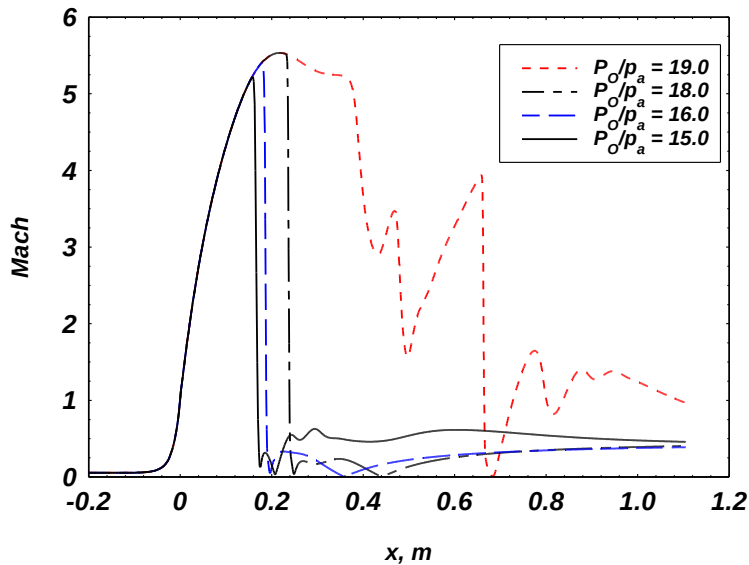


Figure 4 Variations of centre line Mach number in the diffuser without centre body ($L_d / D_d = 6.3$)

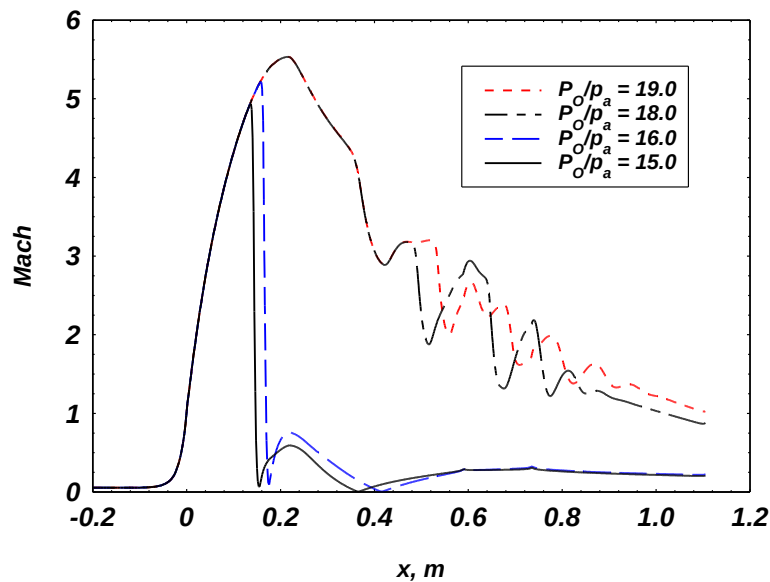


Figure 5 Variations of centre line Mach number in the diffuser with centre body, ($L_t/D_d = 1.0$, $S_s/D_d = 0.25$, $L_d / D_d = 6.3$)

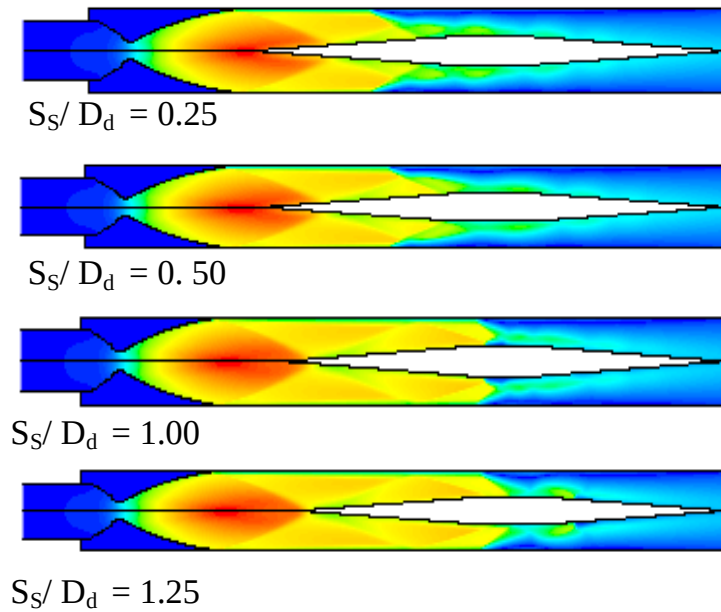


Figure 6 Mach number contours of inside of the diffuser with centre body
 ($L_t / D_d = 1.0$, $P_0 = 19$ bar, $S_S / D_d = 0.25-1.25$)

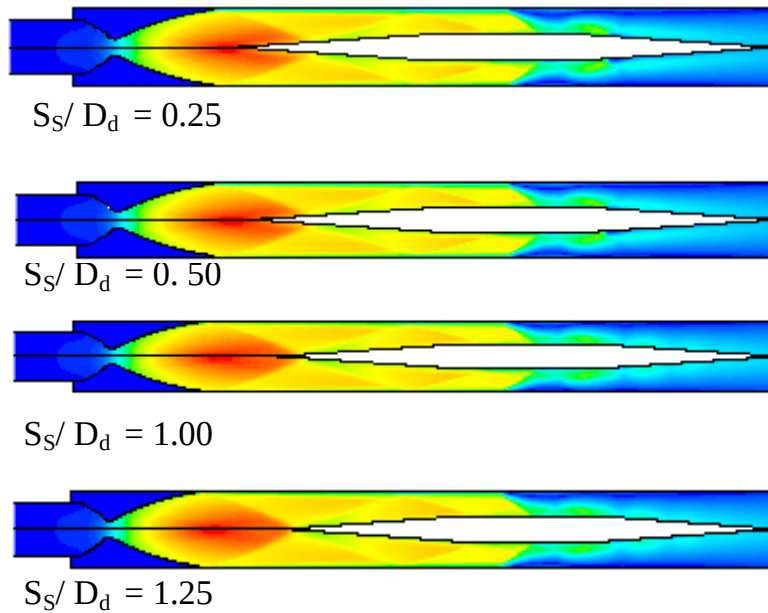


Figure 7 Mach number contours of inside of the diffuser with centre body
 ($L_t / D_d = 2.0$, $P_0 = 19$ bar, $S_S / D_d = 0.25-1.25$)

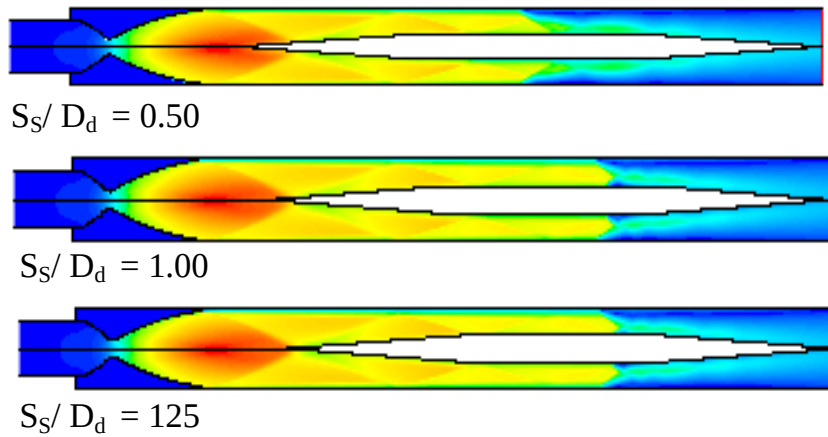


Figure 8 Mach number contours of inside of the diffuser with centre body
 ($L_t/D_d = 3.0$, $P_0 = 19$ bar, $S_s/D_d = 0.50 - 1.25$)

It is evident that from the centre line Mach number curves as shown in Figures 4 and 5, that there exists a normal shock in the case of the diffuser with out centre body, Figure 4. There are oblique shocks are observed as in the case of the diffuser with centre body as shown in Figures 5, 6, 7 and 8 show the Mach contour inside the diffuser with centre body for $L_t/D_d = 1.0$ respectively for the $P_0 = 19$ bar and $S_s/D_d = 0.25, 0.50, 1.00, 1.25$. It is important to mention here that the diffuser is started and corresponding performance characteristics are given in Table 6.15. The influence of the geometrical parameters of the centre body on the Mach contour can be observed such as the structure of the oblique shock wave, supersonic region, and flow field behaviour in side the diffuser. The flow characterises can be compared with out the centre body as shown in Figure 3.

Figures 9 and 10 show the variation of centre line pressure in the diffuser without and with centre body respectively for $L_d/D_d = 6.3$. In the case of diffuser with centre body the diffuser starts flowing full even at a stagnation pressure of 18 bar, where as the diffuser with out centre body starts only at 19 bar stagnation pressure. More over the pressure is having many sharp peaks (ranging between 2 to 1 bar) in the case of without the centre body and the peaks in the centerline pressure for the diffuser with center body ranges between 1.2 -1 bar less than the peak range of 2- 1 bar for the diffuse without centre body. Thus losses are reduced in the case of diffuser with centre body.

It is noticed that the centre body influenced the flow field due to the presence of the oblique shock. The diffuser start can be achieved earlier when the centre body is close to the nozzle. A spacing ratio of $S_s/D_d = 0.25$ was satisfactory for all configurations and was used for those evaluated in detail.

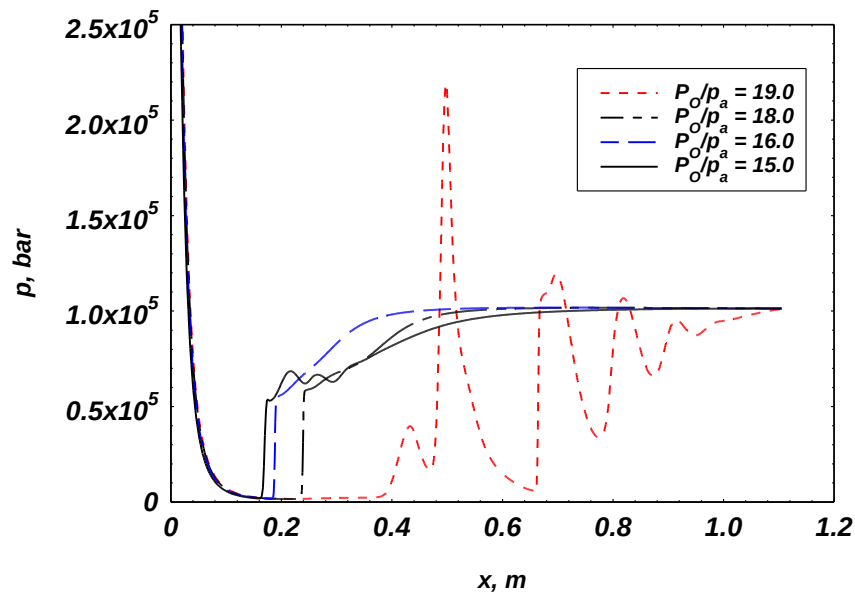


Figure 9 Variations of centre line pressure in the diffuser without centre body
 $(L_d / D_d = 6.3)$

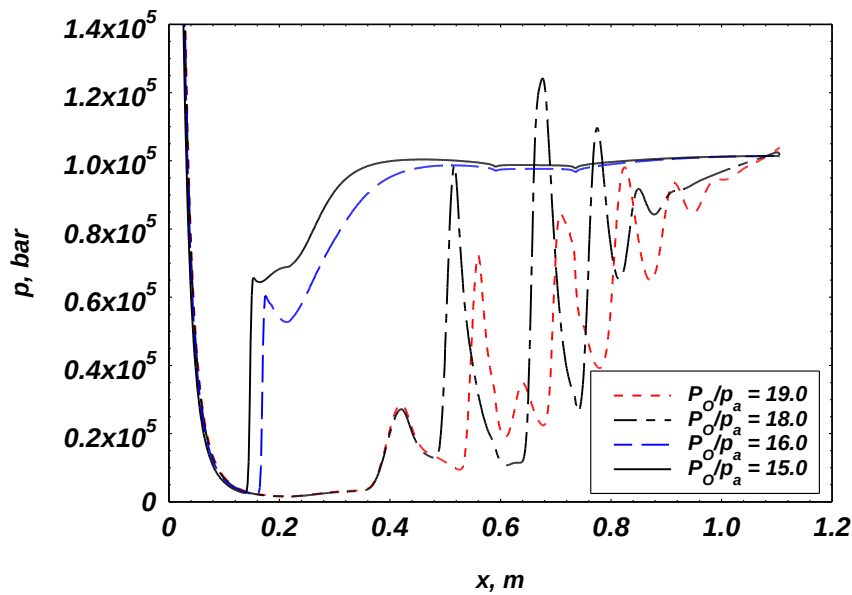


Figure 10 Variations of centre line pressure in the diffuser with centre body
 $(L_t / D_d = 1.0, S_s / D_d = 0.25, L_d / D_d = 6.3-7.3)$

6.3 Influence of Centre Body Throat Length L_t

Simulations have been carried out by varying the length of the centre body throat for L_t/D_d ratio 1, 2 and 3. In these the diffuser diameter D_d is kept constant and the throat length of the centre body alone is varied. It is observed from the Table 3 that the vacuum pressure decreases with the diffuser throat length in general, for varied stagnation pressure and fixed back pressure of 1 bar. In all the started cases of the diffuser, the terminal shock occurs at the end of the centre body throat area as seen from the Figure 11 except for the case of $L_t/D_d = 1.0$ where it is just before the start of the throat. If the second throat length is too small, even a small disturbance can make the normal shock to move back in to the nozzle divergent portion. This scenario is true even if the flow is fully developed inside the diffuser, resulting in flow separation inside the nozzle and the consequent reduction in the vacuum inside the vacuum chamber.

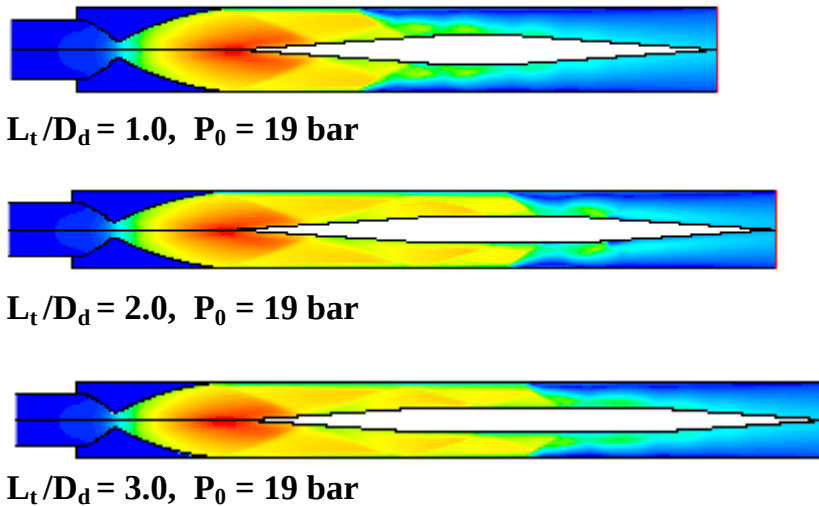


Figure 11 Mach number contours of diffuser with centre body
 $L_t/D_d = 1.0 - 3.0$ and $P_0 = 19 \text{ bar}$

If the throat length is sufficient, any disturbance related shift will not affect the performance. However, if the throat length is too large, it may result in additional capital cost and will occupy larger space. Hence, an optimum L_t/D_d seems to be between 1 and 2. Figures 12, 13 and 14 give the variation of the centre line Mach number along the diffuser in the presence of the centre body for $L_t/D_d = 1.0, 2.0$ and 3.0 , respectively, for the $P_0 = 19 \text{ bar}$ and $S_j/D_d = 0.25, 0.50, 1.00, 1.25$. The Mach number variations show significant effects due to the geometrical parameters of the centre body. The Mach variation along the centre body is in agreement with the Mach contours such as the oblique shock and reflected shock over the centre body.

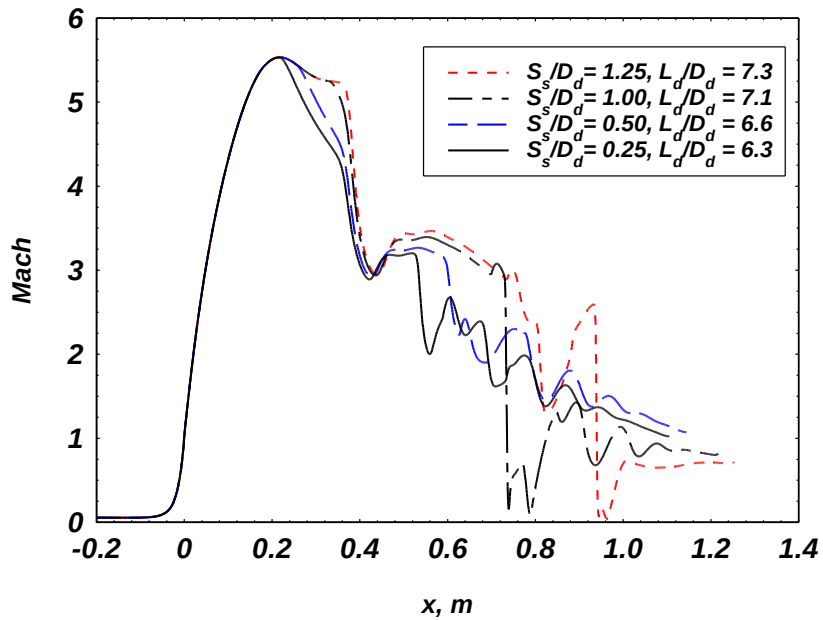


Figure 12 Variations of centre line Mach number in the diffuser with centre body, ($L_t/D_d = 1.0, P_0/p_a = 19.0$)

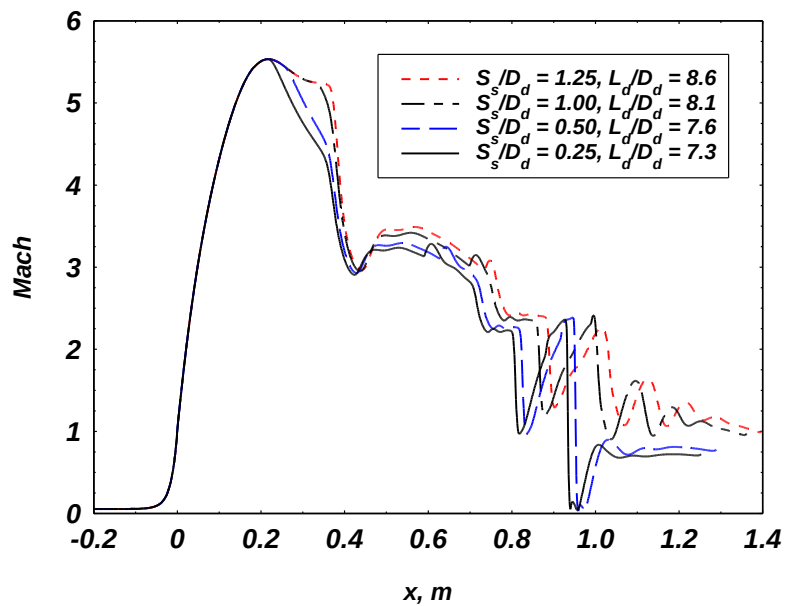


Figure 13 Variations of centre line Mach number in the diffuser with centre body, ($L_t/D_d = 2.0, P_0/p_a = 19.0$)

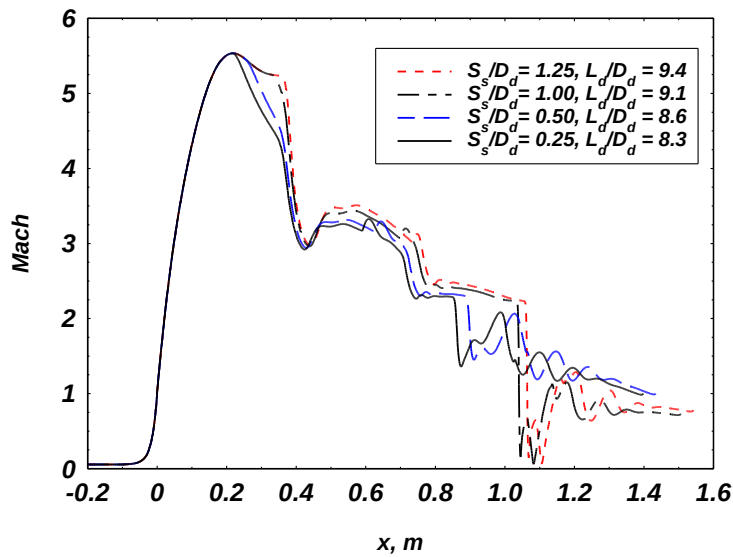


Figure 14 Variations of centre line Mach number in the diffuser with centre body,
 ($L_t/D_d = 3.0$, $P_0/p_a = 19.0$)

Figures 15, 16 and 17 show the variation of the centre line pressure along the diffuser in the presence of the centre body for $L_t/D_d = 1.0$, 2.0 and 3.0, respectively, for the $P_0 = 19$ bar and $S_s/D_d = 0.25, 0.50, 1.0, 1.25$. The pressure variation shows the behaviour of the shock structure inside the diffuser. The sharp peaks in the pressure are attributed to the shock train. The presence of the centre body can be used to get nozzle starting condition depending on the operating condition of the nozzle. Thus the centre body can be deployed depending of the nozzle expansion ratio.

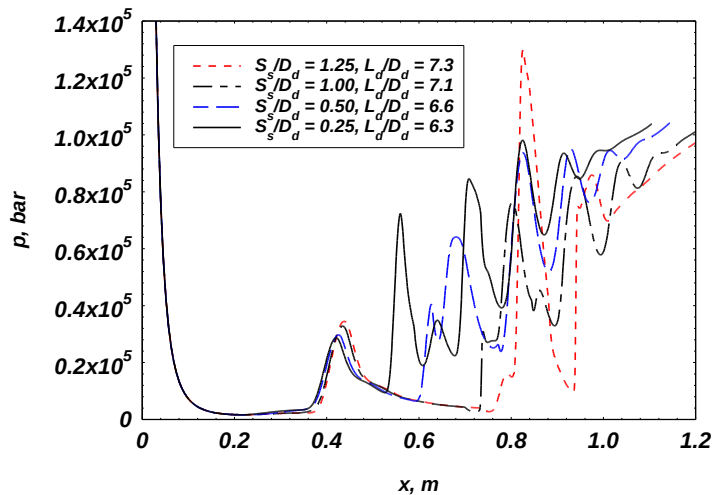


Figure 15 Variations of centre line pressure in the diffuser with centre body
 ($L_t/D_d = 1.0$, $S_s/D_d = 0.25$, $L_d/D_d = 6.3-7.3$)

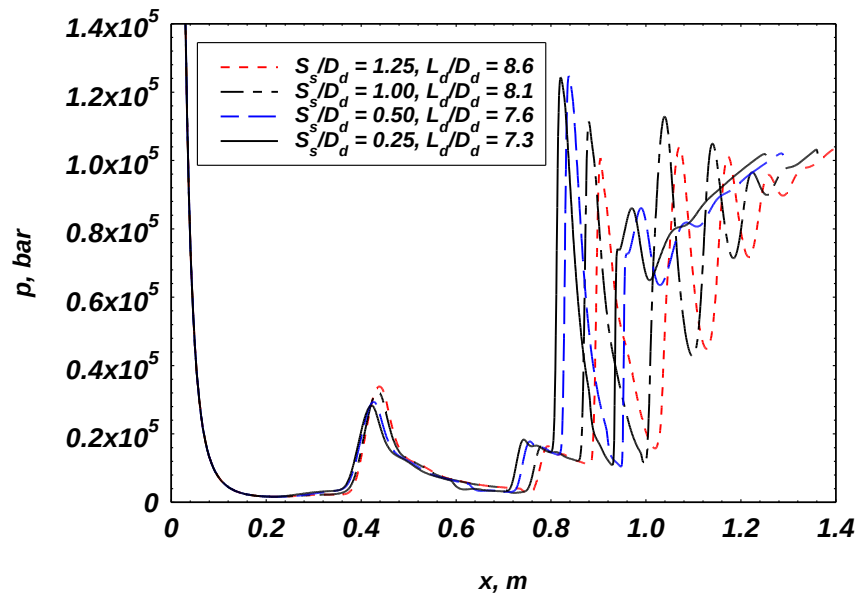


Figure 16 Variations of centre line pressure in the diffuser with centre body,
 $(L_t/D_d = 2.0, P_0/p_a = 19.0)$

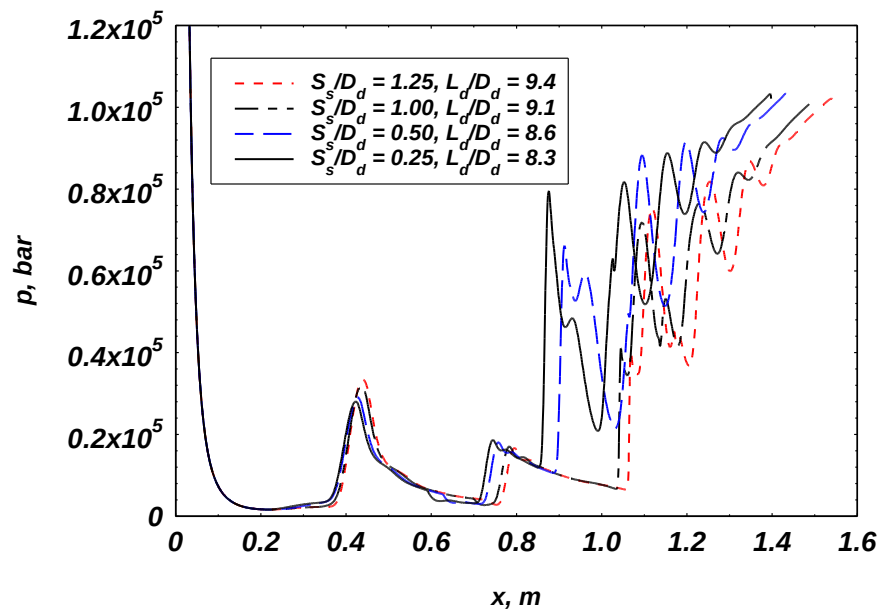


Figure 17 Variations of centre line pressure in the diffuser with centre body,
 $(L_t/D_d = 3.0, P_0/p_a = 19.0)$

6.4 Influence of half Cone angle α of the Center Body

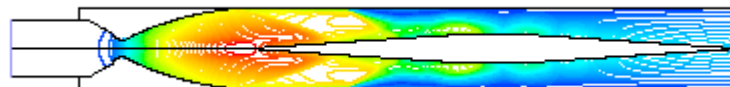
The half cone angle of the center body was varied from 3.75° to 8° and the numerical predictions illustrating the effect of variation in the vacuum chamber pressure and thus on the starting characteristics of the center body diffuser system are shown in Table 4.

Table 4 Variations of vacuum chamber pressure with variation in half one angle α of the center body

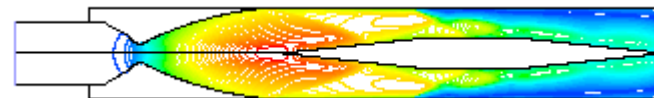
Range	Stagnation pressure P_0 in bar			
Cone angle of center body	15	17	18	19
	Vacuum chamber pressure p_{vc} in mbar			
3.75°	550	530	25	25
6°	545	540	25	25
8°	540	540	25	25

For fixed values of A_d / A^* , D_{cb} / D_d , L_t / D_d the length of the entrance cone portion decreases with increase in the half cone angle. Figure 18 shows the Mach number contour plots for the different α and Figure 19 clearly indicate that the for $\alpha = 3.75^\circ$ lesser the angle the deceleration along the entire is realized by oblique shock train, where as when the $\alpha = 6^\circ$ there is strong shock followed by oblique shocks and for $\alpha = 8^\circ$ also there is a strong shock followed by oblique shocks.

3.75°



6°



8°

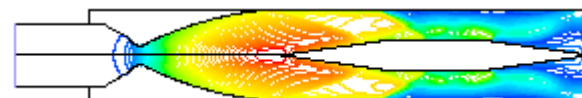


Figure 18 Mach contour plots for different half cone angle of the center body diffuser

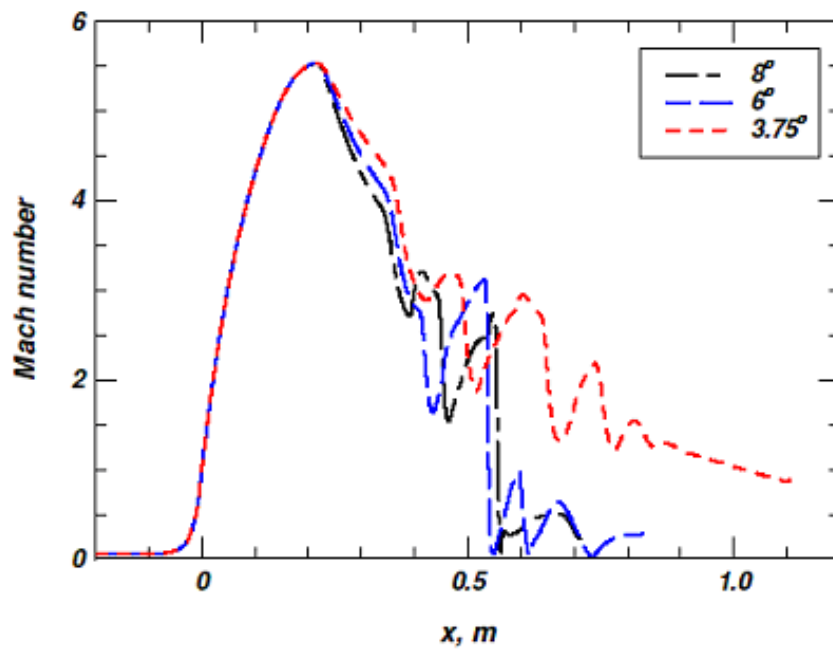


Figure 19 Centerline Mach plot for $\alpha = 3.75^\circ - 8^\circ$

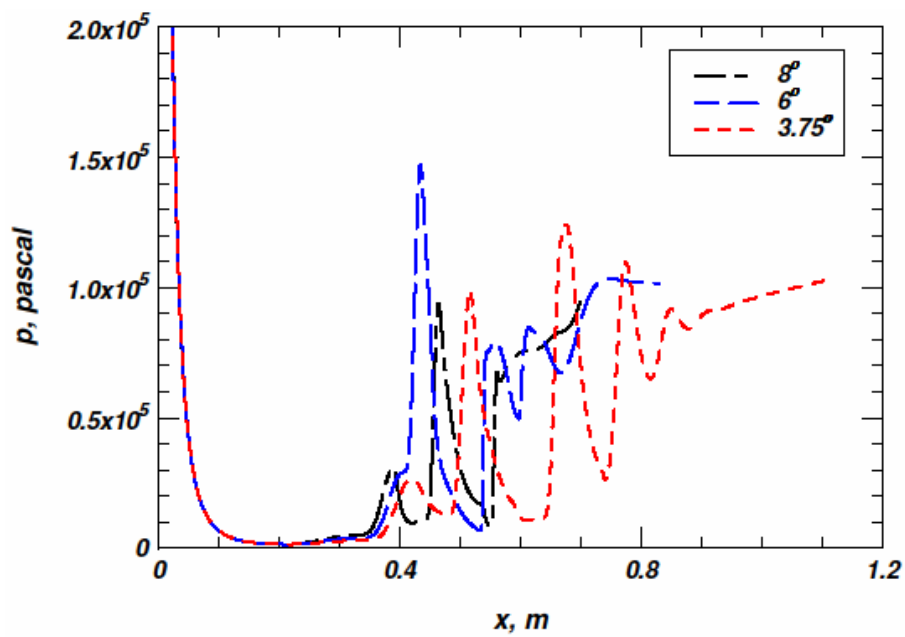


Figure 20 Centerline Pressure plot for different half cone angle of the center body

In the case of $\alpha = 8^\circ$ the flow separates from the exit cone of the center body thus affecting the performance of the diffuser. Though the Table 4 indicate that the vacuum pressure obtained are almost same, but due to the losses associated with the strong shock and subsequent flow separation obtained in $\alpha = 6^\circ$ and $\alpha = 8^\circ$ respectively the optimum cone angle for this configuration and operating conditions of the nozzle may be $\alpha = 3.75^\circ$.

6.5 Influence of ratio of center body diameter to diffuser diameter D_{cb}/D_d

Among the various parameters, the center body diameter to diffuser diameter D_{cb}/D_d has been observed to significantly influence the starting characteristics. The total possible range of variation for D_{cb}/D_d is 0.25, 0.34, and 0.41 but keeping the A_d/A^* constant at 21.36. The area at the throat of the centre body has to be larger than then the nozzle throat, since it has to accommodate the additional mass flow due to entrainment from the vacuum chamber. The effect of varying the ratio of centre body diameter to the diffuser diameter is shown in Figures 21, 22 and 23.

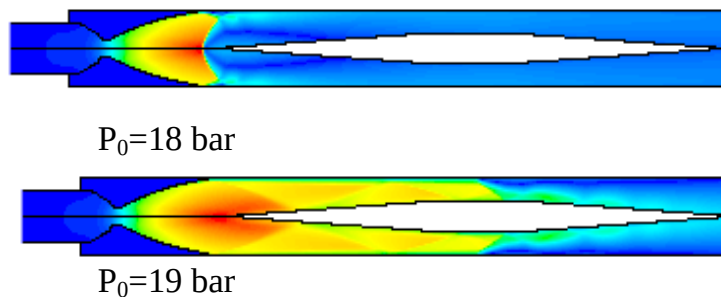


Figure 21 Mach number contour plots of diffusers with diameter of centre body to diffuser diameter $D_{cb}/D_d = 0.41$

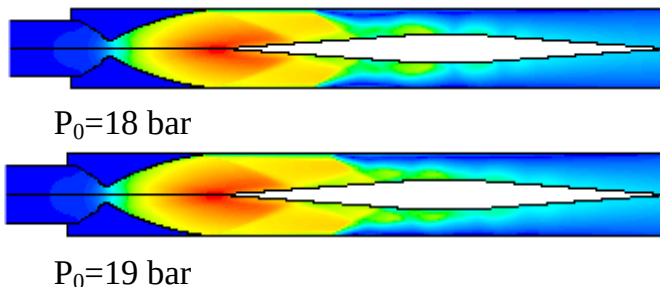


Figure 22 Mach number contour plots of diffusers with diameter of centre body to diffuser diameter $D_{cb}/D_d = 0.34$

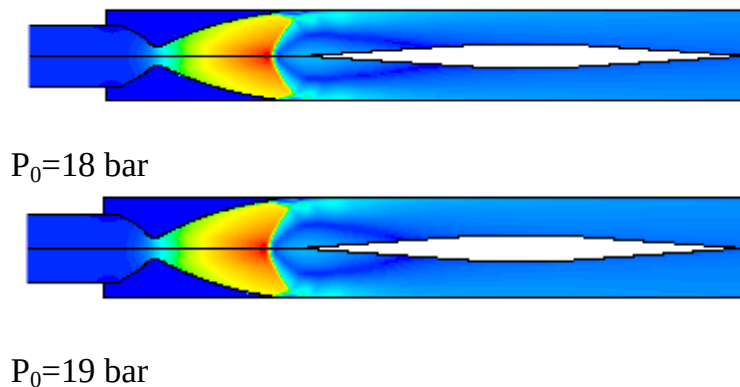


Figure 23 Mach number contour plots of diffusers with diameter of centre body to diffuser diameter $D_{cb}/D_d = 0.25$

Simulations have been carried out for a D_{cb}/D_d in the range of 0.25 – 0.41. Values which are more than 0.5 are avoided, since they will necessitate very high stagnation pressure for the diffuser starting. From the Figure 21 it is observed that the diffuser does not attain started mode for the stagnation pressure 18 bar but attains started mod for a stagnation pressure of 19 bar. It is evident from the Mach number contour plot that the area at the throat portion of the centre body is too small, the diffuser duct cannot swallow the shock cells unless the exhaust gases have very high momentum, and therefore the terminal normal shock remains inside the nozzle itself. In the case of $D_{cb}/D_d = 0.34$ the Mach number plot shown in Figure 22 clearly shows that the diffuser attains started mode attains stagnation pressure of 18 bar itself. In the case of $D_{cb}/D_d = 0.25$ the Mach number plots shown in Figure 23 indicates clearly that the diffuser does not attain started condition for the stagnation pressure of 18 bar and 19 bar. Since the centre body diameter is very small the centre body diffuser acts like an SED, which requires higher stagnation pressure for the start of the diffuser system. If the diffuser starts at a lower P_0 value, the back flow can be arrested at an earlier instant of the initial transient period for the engine, which is highly desirable. The predictions clearly indicate that there exists an optimum D_{cb}/D_d for which the stagnation pressure required for diffuser starting is minimum.

6.6 Influence of Diffuser area ratio A_d/A^*

The variation of minimum overall starting and breakdown pressure ratios P_0/p_a with diffuser area ratios A_d/A^* is presented in Figure 24 for the primary contour nozzle and center body diffuser configurations investigated with air as the working fluid. Diffuser overall length-diameter ratio L_d/D_d was greater than 6 in all cases. As expected, the minimum pressure ratios for diffuser starting increased as diffuser area ratio was

increased. The cylindrical-diffuser configurations included diffuser area ratios A_d/A^* greater than primary-nozzle area ratio A/A^* in all cases, a range of diffuser area ratios 23.6 to 54, at constant primary-nozzle area ratio with contour nozzle $A/A^* = 21.77$, from. The numerical results of Figure 4 show that the minimum pressure-ratio requirements of centre body diffuser configurations are primarily a function of diffuser area ratio A_d / A^* .

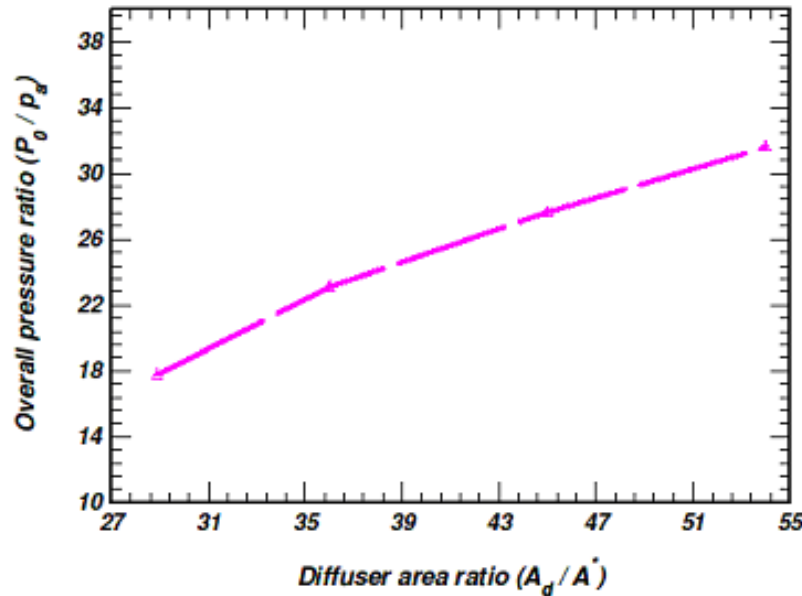


Figure 24 Diffuser area ratio vs. overall pressure ratio required for starting

The Mach number contour plots for the range of A_d / A^* is shown in Figure 25. Minimum pressure ratio requirements, however, would be obtained as diffuser area approached nozzle-exit area. The primary influence of nozzle area ratio, then, is that it approximately determines the minimum usable diffuser area ratio. It is necessary, however, that the diffuser area be somewhat greater than that of the nozzle exit to prevent nozzle-diffuser interactions.

Supersonic Exhaust Diffusers are generally used for simulating high altitude conditions on ground and for qualifying the high expansion rocket engines used as upper stages of satellite launch vehicles. In this study extensive numerical investigations have been carried out on supersonic exhaust diffusers (SED) with and without centre body and using both conical and contour nozzle driven by cold nitrogen gas. The starting characteristics of these two types of exhaust configurations were evaluated. The effects on the performance due to geometric parameter variations, such as cone angle, length, diameter of the centre body, were investigated for the centre body diffuser.

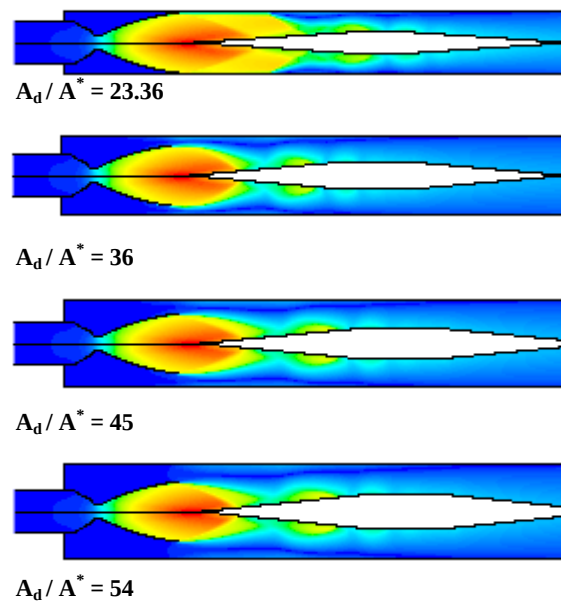


Figure 25 Mach contour plots for started diffuser for $A_d / A^* = 23.6 - 54$

CONCLUSION

The centre body influences the flow field due to the presence of the oblique shock. The diffuser can achieve earlier start when the centre body is close to the nozzle. The Mach number decreased rapidly in the presence of the centre body. The Mach number variations show significant effects due to the geometrical parameters of the centre body. The Mach number variation along the centre body is in agreement with the Mach contours such as the oblique shock and reflected shock over the centre body. The pressure is having many sharp peaks for the case without the centre body. The presence of the centre body can be used to get nozzle starting condition depending on the operating condition of the nozzle. Thus the centre body can be deployed depending on the nozzle expansion ratio.

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