JAST, Vol. 13, No. 1, pp18-25

JAST
Journal of Aerospace Science and Technology

Scientific-Research Article

Numerical Study of Changes in Length-to-Diameter Ratio of a Cylindrical Diffuser, Used in a Vacuum Test Stand

Alireza Naderi [1]*, Hamid Reza Shidvash [2]

1 , 2 - Aerospace Faculty, Malek-Ashtar University of Technology
Lavizan, Tehran.
Email: *naderi@mut.ac.ir

The vacuum test stand simulates the space systems' engines with a high expansion ratio at high altitudes and vacuum pressure for static tests. This article investigates the flow stability in the diffuser to use in a vacuum stand. Several variables are essential in the operation of this system, including the diffuser length, the location of the nozzle relative to the diffuser, the dimensions of the vacuum chamber, and the diffuser length-to-diameter ratio. In this numerical study, the diffuser length-to-diameter ratio is investigated applied at different pressures by the rocket engine to the stand. These results are performed in three length-to-diameter ratios of 6, 8, and 10, and the applied pressure varies from 30 to 50 bar. With an increase in the geometric ratio of diffuser length-to-diameter, stable conditions can be created in the diffuser at lower applied pressures.

Keywords: *Vacuum Test Stand, Stable Pressure Ratio, Diffusion Length, Vacuum Chamber*

Introduction

Performing a static test process for each aerial structure is required since the designs performed for each structure are based solely on analytical and numerical methods. In other words, the accuracy of the results that have been used to design these structures will be determined by performing static tests. Therefore, static tests performed on the ground confirm the performance of aircraft.

It is important to note that the flight conditions of the space system - such as engines with high expansion ratios - are different from the conditions to be tested on the ground. Vacuum conditions must be created to test these structures on the ground, which is very costly. On the other hand, these motors are designed for combustion in high altitude flight conditions, with the pressure close to vacuum or complete vacuum. Therefore, if they are tested in conditions other than the designed conditions (such as the ground surface), the flow will be separated in the divergent part of the nozzle. In addition to causing errors in calculating the engine thrust, the separated flow will break the nozzle during engine operation. It also can cause the nozzle's burn due to the shock wave at the separation point, the nozzle's damage due to the asymmetric pressure distribution, and excessive vibration due to the irregular movement of the separation point in the nozzle. Such a significant error in the ground tests for engines with high expansion ratios has led space scientists to build equipment that can create the flight conditions for the engines. Therefore, they have always sought to bring ambient pressure (ground pressure) close to vacuum pressure. Finally,

1 Assistant professor (corresponding author)
2 Holder of Master of science

designers have proposed two ways to simulate the flight conditions of high-expansion engines [1].
The Testing nozzles are the first way to simulate height at vacuum pressures. The engines of space systems can be simulated with a testing nozzle without any engineering equipment. In static tests by testing nozzles, first, the exact location of the separation point is determined. Then, that point of the main nozzle is cutting, and static tests are performed with this nozzle, called a testing nozzle. Of course, it should be noted that by performing a static test with a testing nozzle, the obtained trust is for the same testing nozzle due to the reduction of the expansion ratio, which should be taken into account in the calculations.
The second suggestion of the designers is to use static test equipment called a vacuum testing stand. This equipment, which includes a vacuum chamber, diffuser, cooling spray, and ejector, can model vacuum conditions for space system engines exactly like flight conditions. Figure 1 shows a test example of a PS-3 system [1]

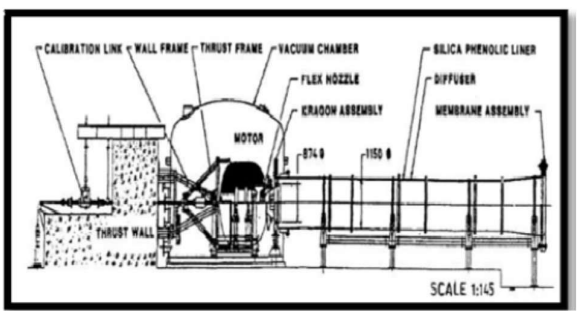

Figure 1: Vacuum test stand for PS-3 system

Many experimental, numerical, and analytical studies have been performed on supersonic flow. Annamalai et al. (2000) investigated the flow stability inside the diffuser to reduce the diffuser length and stable pressure ratio by performing experimental tests (cold test). In this study, the effect of diffuser length on stability pressure ratio has been studied by selecting three different lengths to select the optimal one [2]. Visvanathan et al. (1998) performed experimental tests (cold and hot gas) to examine the design and performance parameters. In that study, different parameters were studied, such as diffuser length-to-diameter ratio, the ratio of diffuser area to the nozzle throat area, the ratio of diffuser area to nozzle outlet area, and specific heat ratio on the ratio of diffuser stable pressure. Also, in this work, the diffuser stable pressure ratio is calculated using vertical shock relations and then compared using experimental tests [3]. Park et al. (2008) numerically analyzed the diffuser stable and the vacuum pressure in the vacuum chamber in a transient state for different lengths. They also analyzed the configuration of the vacuum conditions before starting the engine using numerical methods [4]. Ahmadabadi et al. (2010) investigated the effect of grid size and solution accuracy on the numerical solution and the inlet stagnation pressure on the vacuum creation [5]. Yeom et al. (2009) numerically studied the instability of the flow structure and vacuum pressure changes in a supersonic diffuser equipped with a high altitude simulator engine test. In that study, the emphasis was on examining the flow changes in the diffuser near the diffuser stable pressure [6]. Sung et al. (2010) investigated self-propelled diffusers' design and performance parameters to simulate high altitudes for rocket engines at the ground level using theoretical, numerical, and experimental analyses. The details of the flow structure in the diffuser, the pressure changes in the vacuum chamber, and the diffuser are evaluated to estimate the minimum stable pressure ratio of the diffuser. The design and performance parameters include the diffuser area to the throat area ratio, vacuum chamber dimensions, and engine pressure.
In the present work, the optimization of the diffuser length-to-diameter ratio is numerically studied with different rocket inlet pressures in the vacuum stand. For this purpose, Fluent commercial software is used, and validation is performed first. This validation of the numerical method approves the Roe density method and k-w-SST turbulence model. It should be noted that the flow field is discretized using the structured grid.

Problem theory

In order to identify the subsystems used in the vacuum stand, the details of a vacuum stand is shown in figure 2.

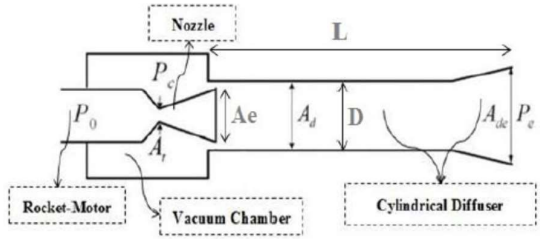

Figure 2: Vacuum test stand

Figure 3 also shows the changes in stand chamber pressure (PC) relative to rocket inlet pressure

changes (P_0). In zone A of the performance curve, both the nozzle and the diffuser are not stable. The details are shown in figure 4. If the inlet pressure increases in zone B, the flow passes entirely through the nozzle without separation, but the diffuser is still unstable. Figure 5 also accurately shows these unstable shock conditions. In general, the instability zone consists of two phases. In the first phase, the flow does not entirely pass through the nozzle and separates in the divergent part of the nozzle. In the second phase, flow separation occurs at the output edge of the nozzle. In both cases, the flow flowing out of the nozzle adapts to the dominant pressure of the vacuum chamber. In the second phase, the flow at the nozzle edge can pass through one of these two paths, either with a robust oblique shock as shown in figure 5 or through a series of expansion waves as shown in figure 6. Either way, the output flow from the nozzle is broken and decomposed by a complex and hybrid shock wave system. Furthermore, the supersonic flow does not prevail in any place or section along the entire cross-sectional area of the diffuser, which is due to breaking by hybrid shock wave system and the ambient pressure on the vacuum chamber pressure. If the rocket inlet pressure (P_0) also increases, the flow will pass entirely through the diffuser, and the shock system will be fully deployed in the diffuser. In this case, the supersonic flow inside the diffuser, as in figure 7, strikes the diffuser wall with a series of shock waves. Finally, the diffuser is stable. This is the minimum and, of course, optimum pressure required for stability. This pressure is shown in figure 3 at the beginning of region C. After this, any increase in inlet pressure slightly changes the pattern and shape of the shock system, and the vacuum chamber pressure changes linearly in region C with an increase in P_0. Due to the shock pressure gradient in the opposite direction of the passing flow, which is due to the rotation and torsion of the flow, part of the mass flow inside the vacuum chamber returns, and the air inside the vacuum chamber moves into the diffuser with the output flow from the nozzle. The nozzle then acts as an ejector. The pressure in the test chamber decreases until it reaches equilibrium. This equilibrium occurs when the nozzle's mass output is equal to the amount of mass flow from the outside into the vacuum chamber.

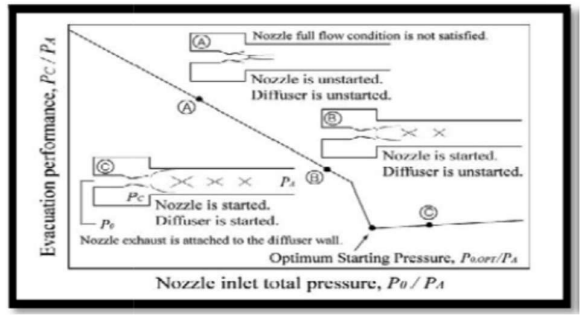

Figure 3: Diffuser stability characteristic curve

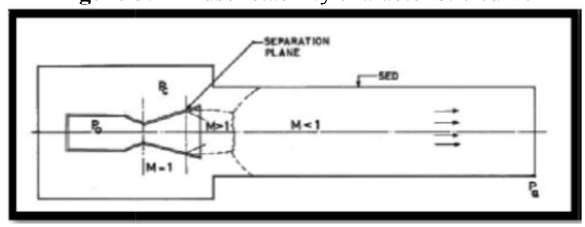

Figure 4: Instability of the flow inside the nozzle and diffuser in zone A.

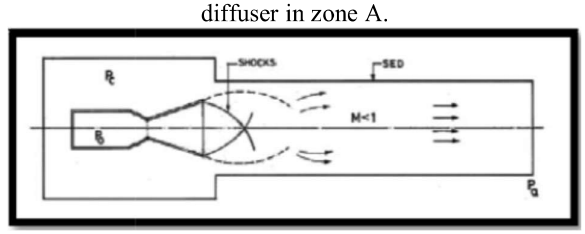

Figure 5: Instability inside the nozzle with strong shock in zone B.

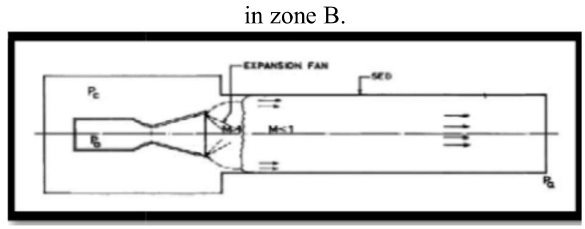

Figure 6: Instability inside the nozzle with expansion shock in zone B

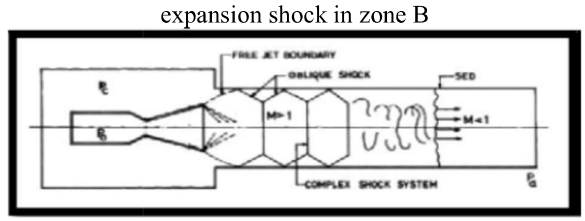

Figure 7: Stable phase, supersonic flow without separation,

Configuration and geometry production

The geometric model considered for the vacuum test stand is based on sung and Yeom (2010), shown in figure 8. In this figure, A_t represents the throat width, A_e is the nozzle outlet width, A_d is the

diffuser width, and L is the diffuser length. The vacuum chamber is shown in figure 8.

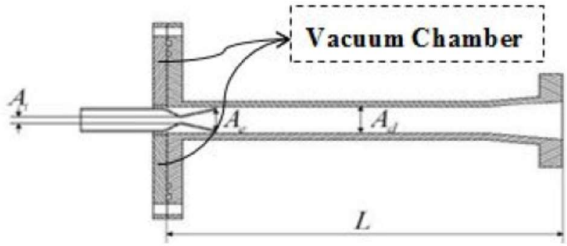

Figure 8: The case study model

Based on the geometric symmetry of the desired model, only one-half of this model is numerically analyzed to reduce the time of numerical solution. The dimensions of the case study model are shown in figure 9. Dimensions are represented in millimeters. We used a structured grid, as it can increase the speed of convergence and sometimes even increase the accuracy of numerical solutions. In sensitive areas, such as the throat and nozzles of the network, the grid has become finer. Figure 10 shows this structured grid and the used boundary conditions of the problem. It should be noted pressure P_0 is applied at the input of the flow field, and ambient pressure p_a is applied at the output.

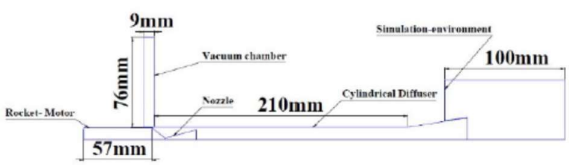

Figure 9: Geometric dimensions of the studied model

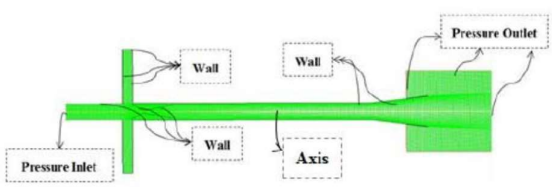

Figure 10: Boundary conditions of the model

Validation

Sung et al. (2010) did not present accurate information on the initial pressure used in numerical analysis. Based on equation 1, the ratio of the inlet to the outlet pressure should be such that the inlet Mach value to the nozzle is approximately 0.1. With a Mach value of 0.1, the flow in the nozzle throat becomes 1, and finally, it reaches the supersonic value in the nozzle outlet.

$$\left(\frac{p_0}{p_a}\right) = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \tag{1}$$

Figure 11 compares the static pressure distribution of this numerical analysis with the experimental results along the diffuser wall. Note that the unit of the longitudinal axis is centimeters, and this diagram is presented for the length-to-diameter ratio of 10. It is observed that the numerical analysis of the present study has a relatively good agreement with the experimental results. However, the pressure at the first point of contact of the outlet flow from the nozzle to the diffuser wall (approximately at point X = 2) is not entirely consistent with the experimental results. As shown in figure 11, the inlet pressures are not perfectly matched. However, the inlet pressure to the diffuser, the simulated pressure (vacuum), depends only on the problem. It may be necessary to reconsider the problem and examine the rocket engine operation at certain vacuum pressure. Therefore, the designer determines the diffuser inlet pressure (vacuum chamber pressure) in the present problem.

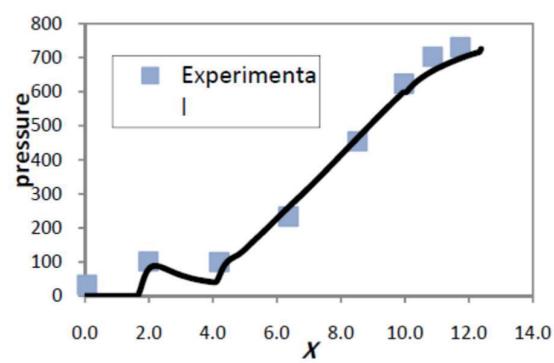

Figure 11: Static pressure distribution on the diffuser wall of the experimental test in comparison with the numerical simulation in geometric ratio of 10

Numerical study of geometric changes ratio of diffuser length-to-diameter

The geometric ratio of diffuser length-to-diameter A_d/L at different inlet pressures is investigated. These studies aim to optimize the diffuser length-to-diameter ratio and the minimum stability pressure ratio of the vacuum test stand. Therefore, numerical analysis has been performed in three ratios of length-to-diameter and different inlet pressures to achieve this optimization. Optimizing the diffuser length-to-diameter ratio and the minimum stability pressure ratio means that the vacuum test stand

performs well at the lowest value of these ratios. It also means that a stable flow is created in the diffuser, and the required vacuum pressure is created in the vacuum chamber at the lowest value of these ratios.

The diffuser length-to-diameter ratio has been optimized on the diffuser of the experimental model. It should be noted that the geometric ratio of length-to-diameter of the experimental model is 10. If the flow in the diffuser is stable at a lower ratio, it is concluded that the lower ratio can also satisfy the vacuum test stand. Therefore, it cannot be the optimal ratio for the diffuser to be used in the vacuum test stand.

Numerical study of length-to-diameter ratio equal to 8

In this numerical analysis, the inlet pressure to the diffuser has been selected as the convergence criterion. Therefore, numerical analysis has been evaluated from the beginning to determine the changes in this pressure. The diagram of changes in the inlet pressure to the diffuser is shown in figure 12. As can be seen in this figure, the inlet pressure to the diffuser is constant after about 100,000 repetitions, and the present numerical analysis converges. Therefore, according to figure 12, which validates the numerical analysis of the present work, the results can be examined.

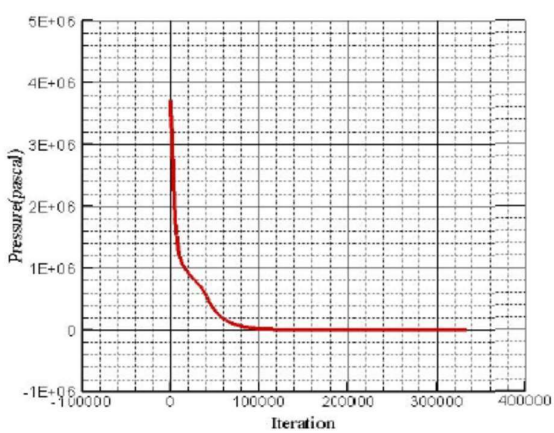

Figure 12: Convergence diagram of numerical study of length-to-diameter ratio equal to 8.

The simulation of the static pressure distribution on the diffuser wall is the most important result of the ratio equal to 8. This pressure distribution can be seen in figure 13. According to figure 13, the flow is stable in the diffuser, and the static pressure on the diffuser wall is recovered from low to high. The output pressure obtained from the numerical analysis of the present work is approximately equal to the atmospheric pressure. The approximate equality of the diffuser output pressure with the atmospheric pressure indicates that the diffuser length is suitable to use in the vacuum test stand. However, it should be noted that the mentioned condition is necessary for the proper performance of the vacuum test stand with modeled ratio. However, in addition to the above condition, the output flow from the nozzle must be subsonic and collide with the diffuser wall. Figure 13 also shows the first point of contact of the output flow from the nozzle to the diffuser wall. Eventually, a vacuum pressure will be created in the vacuum chamber when these two conditions are met. Therefore, a ratio of 8 has a good performance to use in a vacuum test stand.

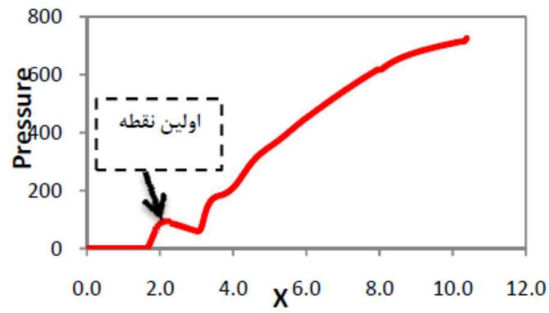

Figure 13: Static pressure distribution on the diffuser wall with a geometric ratio of 8

Also, diffusers with a ratio of 8 at different inlet pressures have been numerically investigated. This study was performed to analyze the diffuser's flow dynamics and the effect of reducing the diffuser length-to-diameter ratio for different inlet pressures. Also, the question of "what inlet pressure is suitable for the ratio of 8?" is answered. In other words, it was investigated how many space engines this ratio of the diffuser can support. Numerical analysis has been performed for a pressure range of 50-30 bar. The assumptions made for each of these analyzes are the same as the previous analysis.

Figure 14 shows the static pressure profiles on the diffuser wall for a ratio of 8 and an inlet pressure range of 50-30 bar. According to figure 14, the diffuser outlet pressure for each inlet pressure is equal to the atmospheric pressure. This figure shows that the vacuum test stand does not have the required momentum to create a vacuum pressure in the vacuum chamber for inlet pressures less than 45 bar. Therefore, after reducing the inlet pressure to less than 45 bar, the vacuum chamber pressure approaches atmospheric pressure. Therefore, the

vacuum stand is not supprted for pressures less than 45 bar.

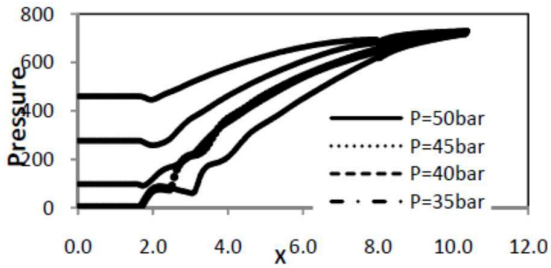

Figure 14: Static pressure profiles on the diffuser wall for different inlet pressures where geometric ratio is 8.

Next, the Mach number contour for the pressure range of 30-50 bar is shown in figure 15. As shown in figure 15, the output momentum of the nozzle decreases for lower inlet pressures. Due to the reduction of the nozzle's output momentum, the diffuser is not able to create the necessary vacuum pressure in the vacuum test stand. In other words, for inlet pressures of less than 45 bar, the outlet flow from the nozzle is not subsonic. However, the output flow from the nozzle cannot create a vacuum pressure in the vacuum chamber due to a lack of expansion of the flow or insufficient power of the output momentum. In the presented diagram, the extension length of the output flow from the nozzle is obtained for inlet pressures of 30-50 bar.

Also, the extension length of the output momentum in terms of different input pressures is shown in figure 16 to understand input pressure's effect on the output momentum of the nozzle. As shown in figure 16, as the inlet pressure (chamber pressure) increases, the extension length increases, too.

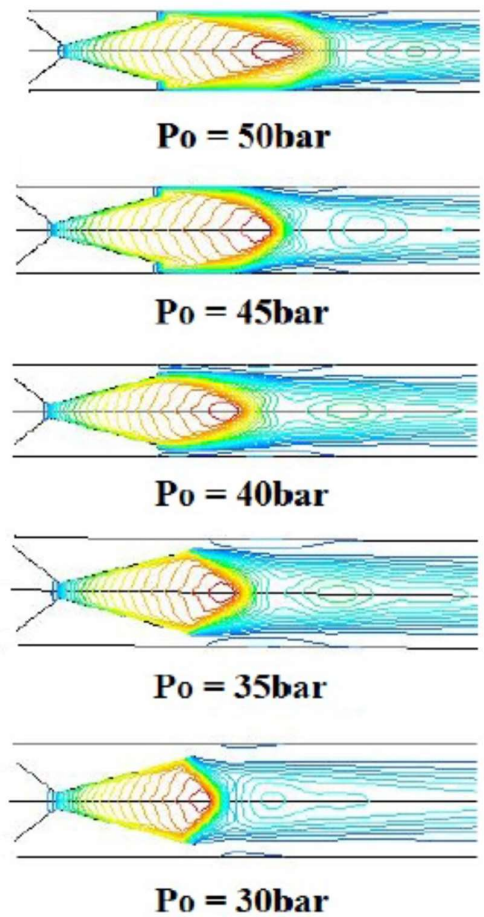

Figure 15: Mach number contour for different inlet pressures and geometric ratios of 8

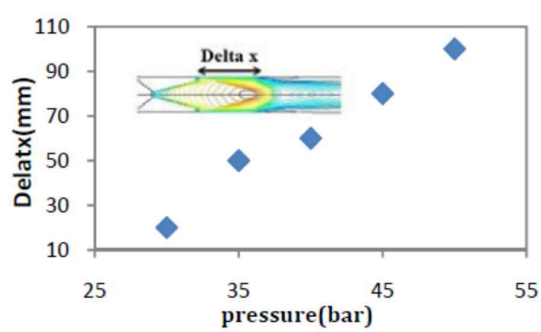

Figure 16: The extension length of the output flow from the nozzle for different inlet pressures and geometric ratio of 8

Numerical study of length-to-diameter ratio equal to 6

In this part, Length-to-diameter ratio of 6 for inlet pressures of 50-45 bar is investigated. Figure 17 shows the change in pressure on the diffuser wall by

changing the rocket inlet pressure. Based on this figure, the diffuser flow is stable with a ratio of 6 and at the inlet pressure of 50 bar. Then, the necessary vacuum pressure is created in the vacuum chamber. In other words, the vacuum test stand has a good performance with this ratio and inlet pressure. However, the required vacuum pressure has not been simulated at the ratio and pressure of 45 bar. Also, the output flow from the nozzle did not hit the diffuser wall. Therefore, a diffuser with a ratio of 6 at an inlet pressure of 45 bar was simulated for a nozzle. However, it is shown that it cannot satisfy the vacuum test stand.

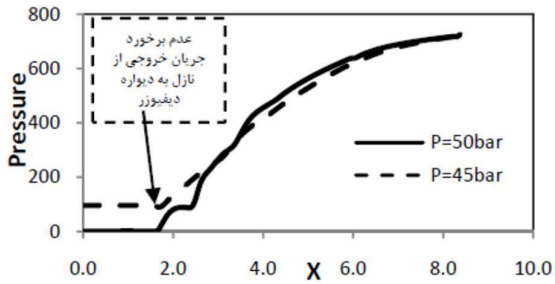

Figure 17: Static pressure profiles for different inlet pressures and geometric ratio of 6

As shown in figure 18, by reducing the pressure from 50 bar to 45 bar, the output momentum of the nozzle decreases, and finally, the expansion flow from the nozzle does not hit the diffuser wall. Therefore, due to the lack of contact of the output flow from the nozzle to the diffuser, the flow in the diffuser is unstable, and the required vacuum pressure is not simulated.

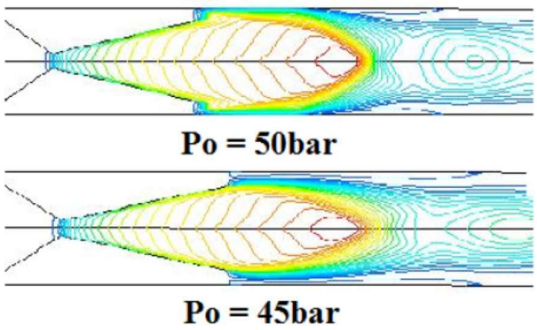

Figure 18: Mach number contour for different inlet pressures at geometric ratio of 6

Conclusion

The effect of the geometric ratio of diffuser length-to-diameter on the flow stability inside the diffuser is numerically investigated. These studies have been performed at different applied pressures by the rocket nozzle. The density base method and Fluent commercial software were used for these numerical analysis. The appropriate basis for the applied pressure in different geometric ratios is that the shock outlet of the nozzle strikes the wall of the diffuser to maintain stable. The results show that in the higher geometric ratio of length-to-diameter, a lower applied pressure can stabilize the diffuser and thus create a vacuum condition. Therefore, in the geometric ratio of 8, stable conditions can be created with a pressure of 45 bar.

References:

[1] RGM. Kumaran, 2009, Analysis of Diffuser and Ejector Performance in a High Altitude Test Facility, Indian Institute of Technology Madras, AIAA, 1-10, 2009.

[2] K.Annamalai and T.N.V.Satyanarayana, Development of design methods for short cylindrical supersonic exhaust diffuser, Experiment in fluid 29(2000) 305-308.

[3] K.Annamalai and K.Visvanthan, Evaluation of the performance of supersonic exhaust diffuser using scaled down Models, Experimental Thermal and Fluid since 17(1998)217-229.

[4] BH.Park and J. Hyung, Studies on the starting transient of the straight cylindrical supersonic exhaustdiffuser: Effects of diffuser length and pre-evacuation state,International journal ofheat and fluid flow 29(2008) 1369-1379.

[5] M. N. Ahmadabadi and H. Korabi, Numerical and Experimental Study of Ultrasonic Flow in Laboratory Vacuum Simulator, 10th Conference on Aerospace Association, (2010).

[6] HW.Yeom and S.Yoon ,Flow dynamics at the minimum starting condition of a supersonic diffuser. Mechanical since and technology, Mechanical since and technology 23(2009)254-261.

[7] Hy.sung and H.yeom, Investigation of rocket exhaust diffuser for altitude simulation, Propulsion and power 26 (2010)