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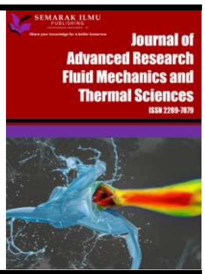

Optimization of Nozzle Design for Weight Reduction using Variable Wall Thickness

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ABSTRACT

In various fields, including rockets, turbines, and engines, the critical role played by nozzles in achieving optimal performance is underscored. Within the domain of rocketry, particular attention is given to the weight of the nozzle, where even the slightest modifications in weight can lead to a profound impact on rocket performance. In this research, an endeavor is made to comprehensively investigate the intricate interplay of nozzle pressure ratio, nozzle thickness, and Mach number, to unveil the effects of these parameters on nozzle deformation, the development of equivalent stress, and the pivotal factor of safety. Material optimization strategies for a wide array of flow and geometrical parameters are also explored within the framework of this study. With each parameter considered at four levels, an exploration is conducted across Mach numbers of 1.5, 2.0, 2.5, and 3.0, alongside Nozzle Pressure Ratios of 2, 4, 6, and 8. The meticulous analysis of nozzle thicknesses at levels of 1 mm, 2 mm, 3 mm, and 4 mm is carried out. The computational fluid dynamics (CFD) analysis is systematically executed across all cases, with resultant pressure profiles on the internal surfaces of the nozzle serving as essential boundary conditions for static structural analysis. The presentation of findings entails a comprehensive discussion of the factor of safety values for all parameter combinations. Significantly, it is observed from our results that a direct correlation exists between nozzle thickness and factor of safety, with an increase in nozzle thickness corresponding to an enhancement in factor of safety.

1. Introduction

Nozzles are recognized as fundamental components in numerous engineering applications, wherein their performance is intricately tied to parameters such as nozzle pressure ratio, thickness, and Mach number. Within the realm of rocketry, where even minute deviations in weight can exert a substantial influence on performance, the imperative of optimizing nozzle design is paramount. The

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core objective of this research is to undertake a comprehensive analysis of the impact of these parameters on nozzle behavior, encompassing both deformation and stress considerations. Furthermore, material optimization strategies are explored with a focal point on augmenting the factor of safety while preserving structural integrity.

The utility of nozzles lies in their ability to elevate the velocity of fluid passing through them at the expense of pressure, thereby enhancing fluid velocity. Nozzles manifest in various configurations, including convergent and divergent types. A notable exemplar is the Convergent Divergent nozzle (C-D nozzle), also known as a De Laval Nozzle, which commences with a convergent section and culminates in a divergent section. As the fluid enters the nozzle through the convergent section, its velocity escalates due to the narrowing of the nozzle, particularly at the throat. Subsequently, in the divergent section, the fluid attains even higher velocity before discharging from the nozzle outlet at reduced pressure.

Nozzles find applications across diverse industries commensurate with their dimensions. Their utility extends to engines, rockets, and various other domains. Extensive research has been undertaken to optimize nozzle performance, particularly within the context of rockets and missiles, where weight considerations are pivotal. Even slight variations in weight can exert a substantial impact on rocket performance. Consequently, this study focuses on reducing nozzle weight and material utilization while safeguarding the factor of safety and overall performance.

The analysis of the nozzle encompasses a comprehensive consideration of various parameters, including Mach number, Nozzle Pressure Ratio (NPR), and nozzle thickness. This investigation spans multiple conditions, elucidating their effects on equivalent stress, nozzle deformation, and the factor of safety.

Prior research by various authors has featured Computational Fluid Dynamics (CFD) analysis to explore the influence of Mach number on velocity distribution within a suddenly expanded circular duct with a larger cross-sectional area. Their findings emphasize the interplay of Mach number, area ratio, and Nozzle Pressure Ratio on the flow field in the enlarged duct [1-10]. In the broader literature, researchers have delved into optimizing area ratio and thrust in suddenly expanded flows at supersonic Mach numbers, identifying the influential roles of Mach number, NPR, and area ratio on base corner pressure. Furthermore, the analysis encompasses parameters such as Mach number, NPR, and the Pitch Circle Diameter of control jets, culminating in the conclusion that control jets can elevate base pressure [1-12]. The Suddenly expanded flow from a converging-diverging nozzle has been studied by various authors to control base pressure by passive methods and active methods [13-22]. Nowadays the requirement of studies in the field of supersonic flows increasing by various authors [23-27]. Computational Fluid Dynamics is used in various fields to study the problems associated with fluid flow [28-31].

While the existing literature has explored various aspects of nozzle behavior, the specific avenue of material optimization remains relatively uncharted. In this research, we delve into material optimization for nozzles, with a steadfast commitment to preserving the factor of safety and other critical nozzle parameters.

2. CFD Analysis

2.1 Modelling and Meshing

In contemporary times, Computational Fluid Dynamics (CFD) has found widespread utility across a multitude of applications, encompassing both internal and external flow scenarios [15-21]. In the context of this research, we focus our attention on the examination of three pivotal parameters: Mach number, Nozzle Pressure Ratio (NPR), and nozzle thickness.

Mach Number: The design specifications of the nozzles are tailored to accommodate Mach numbers spanning 1.5, 2.0, 2.5, and 3.0. Table 1 presents a comprehensive overview of the nozzle dimensions corresponding to each Mach number configuration.

Table 1
Dimensions of Nozzles

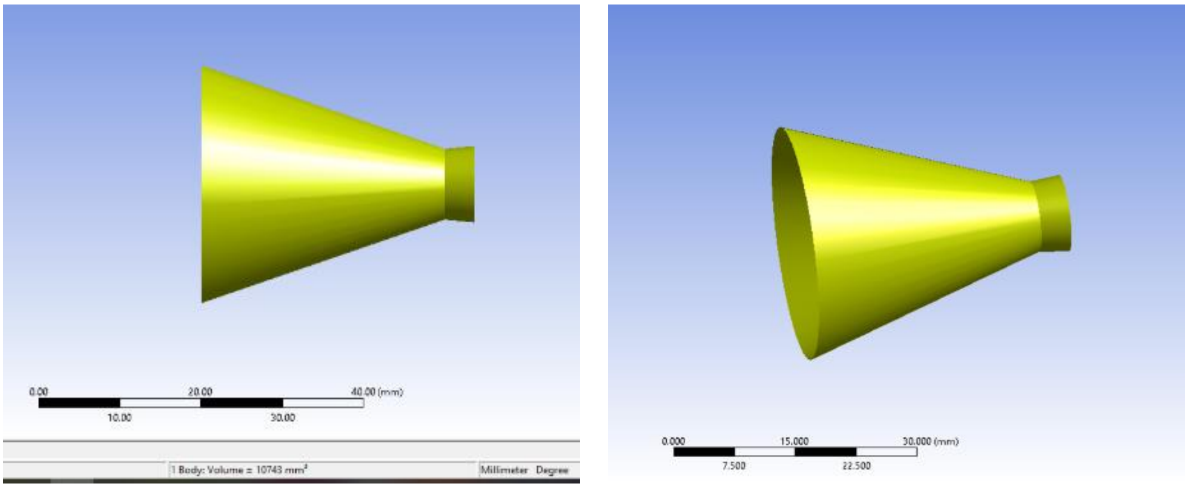
Mach Number	1.5	2	2.5	3.0
Inlet Diameter	31.059	29.536	27.996	26.698
Throat Diameter	9.221	7.698	6.158	4.859
Exit Diameter	10	10	10	10
Convergent Length	30	30	30	30
Divergent Length	3.707	10.951	18.275	24.454
Convergent Angle	20	20	20	20
Divergent Angle	6	6	6	6

Nozzle Pressure Ratio (NPR): The Nozzle Pressure Ratio (NPR) is defined as the ratio of pressure at the nozzle inlet to the pressure at the nozzle outlet. In our analytical investigation, four distinct NPR values, specifically 2, 4, 6, and 8, have been considered.

Nozzle Pressure Ratio: The ratio of pressure at the inlet to pressure at the outlet of the nozzle is called the Nozzle Pressure Ratio (NPR). For the analysis, four NPR values i.e. 2, 4, 6, and 8 are considered.

The Thickness of the Nozzle Wall: The third parameter under consideration for this research work is the thickness of the nozzle. The optimization of nozzle thickness is contemplated to reduce the weight of the nozzle and facilitate material optimization. Four thickness levels, namely 1 mm, 2 mm, 3 mm, and 4 mm, have been taken into account.

Academic-licensed ANSYS Workbench is employed for the creation and meshing of geometries. The CFD analysis is performed using ANSYS Fluent software. Figure 1(a) presents the 3D model of the nozzle from a side view, representing the fluid domain, while Figure 1(b) exhibits the solid component of the nozzle with varying nozzle thickness.



(a) (b)

Fig. 1. 3D model of nozzle for CFD analysis and static structural analysis; (a) 3D model of the nozzle (fluid domain) for CFD analysis, (b) Thickness of nozzle (Solid) for static structural analysis

In any analysis, the grid independence test is deemed the most crucial assessment for determining the optimal grid size, to minimize simulation time and ensure result accuracy. To conduct this test, various mesh conditions are considered, and the results are compared. By examining the graph in Figure 2, it can be asserted that when there are 70 divisions in each edge, the results begin to stabilize, and the disparity in results becomes negligible after this threshold.

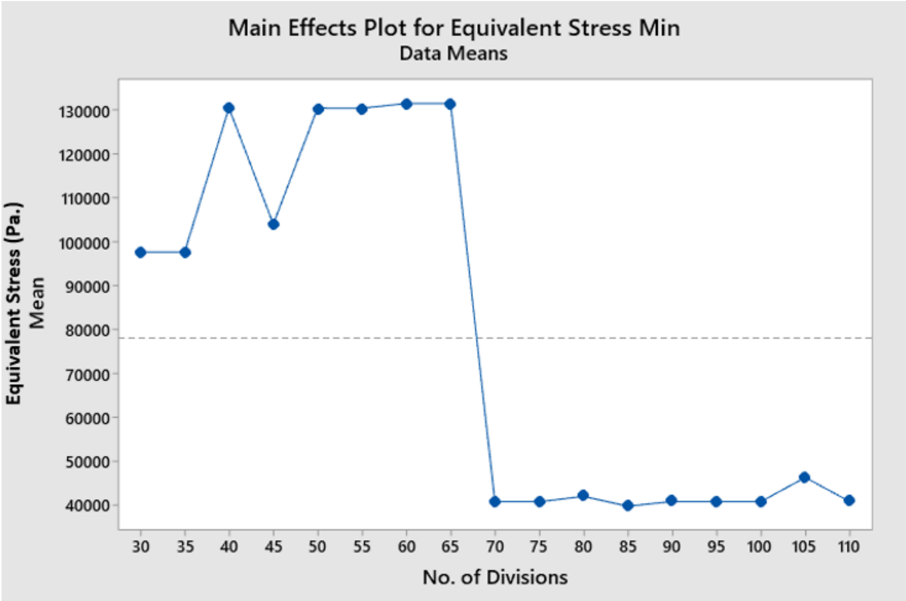


Fig. 2. Grid independence test (Deformation vs No. of Divisions)

In preparation for the CFD analysis, before meshing the model, the outer part of the nozzle, denoted by its thickness as depicted in Figure 1(b), was suppressed. Only the inner part, as illustrated in Figure 1(a), was taken into consideration. The meshing process incorporated a total of 90 divisions in each edge, alongside fine span angle settings and high levels of smoothing. Figure 3 offers a visualization of the meshed model.

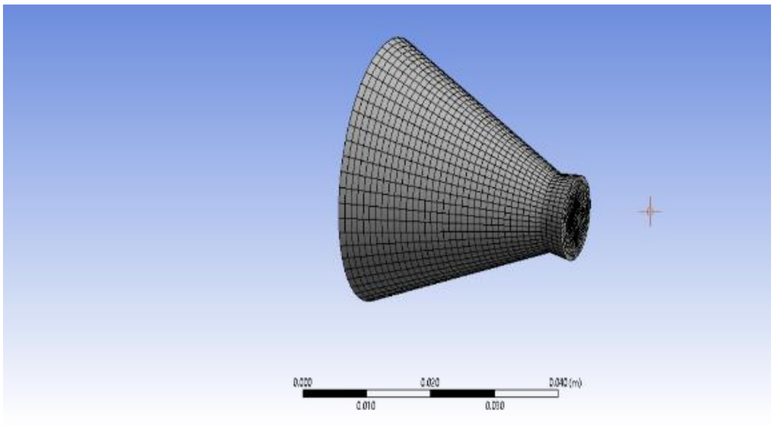


Fig. 3. Meshed model for CFD analysis

2.2 CFD Analysis Setting

This part presents a comprehensive analysis of fluid flow through a nozzle utilizing Computational Fluid Dynamics (CFD) techniques with ANSYS Fluent software. The fluid is treated as an ideal gas, and the viscosity is determined using Sutherland's law. Boundary conditions at the inlet are specified as pressure inlet, while the outlet conditions are set as pressure outlet. The analysis encompasses a range of Nozzle Pressure Ratios (NPR) including 2, 4, 6, and 8. Figure 4 displays the CFD results, illustrating the pressure distribution within the nozzle. Notably, the converging section exhibits maximum pressure, corroborating the fundamental principle that nozzles enhance fluid velocity at the expense of pressure. Subsequently, the diverging section reveals a decrease in pressure. In addition, this study investigates all combinations of the specified parameters. The pressure data extracted from Fluent software is then imported into ANSYS software for subsequent static structural analysis of the nozzle wall.

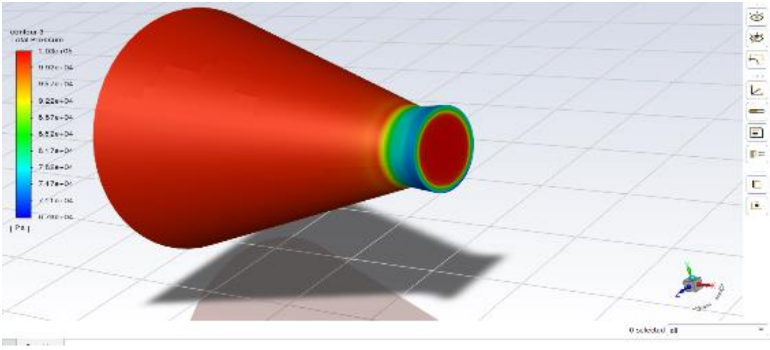


Fig. 4. Total pressure In the nozzle

3. Static Structural Analysis

The pressure data obtained from the CFD analysis, which pertains to the nozzle wall surfaces, serves as critical boundary conditions for the subsequent static structural analysis. In the engineering data specifications, brass is designated as the chosen material for the nozzle.

In the static structural analysis, the fluid geometry is excluded from consideration, with the focus directed solely on the outer dimensions, specifically the thickness of the nozzle walls. To ensure proper structural assessment, fixed supports are applied at both the inlet and outlet regions of the nozzle. For a visual representation of the meshed model utilized in the static structural analysis, please refer to Figure 5.

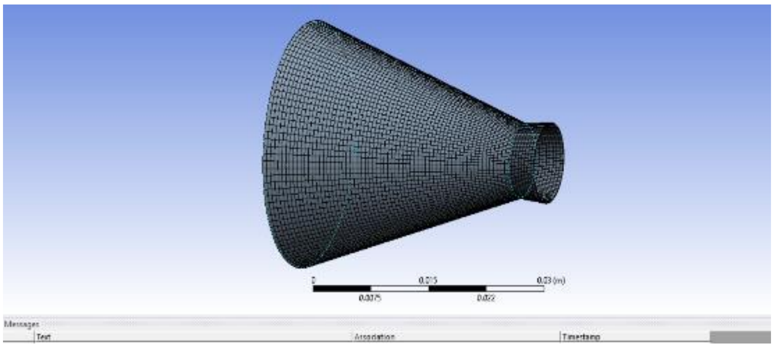


Fig. 5. Meshed model static structural

Following the meshing process, the pressure data obtained from the inner surface of the nozzle is imposed as a boundary condition. Subsequently, the resulting deformation and the corresponding equivalent stress values are meticulously documented and analyzed.

4. Results and Discussion

The primary objective of this research endeavor is to quantify the deformation and equivalent stress levels within the nozzle. Figure 6 visually depicts the comprehensive deformation distribution throughout the nozzle. Notably, the maximum deformation occurs at the nozzle inlet, while the minimum deformation is observed at the nozzle exit.

Figure 7 provides a graphical representation of the equivalent stress distribution within the nozzle. It is noteworthy that the maximum equivalent stress is concentrated at the nozzle inlet, while the minimum equivalent stress is situated at the nozzle exit.

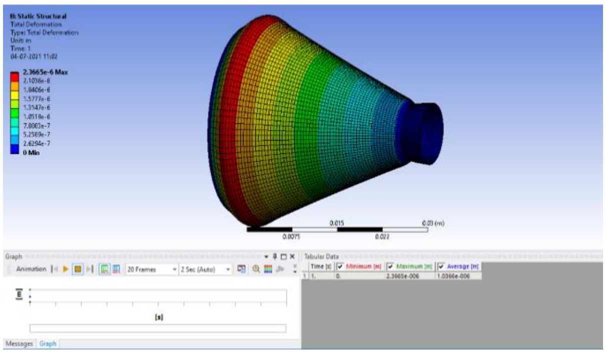


Fig. 6. Deformation in the nozzle

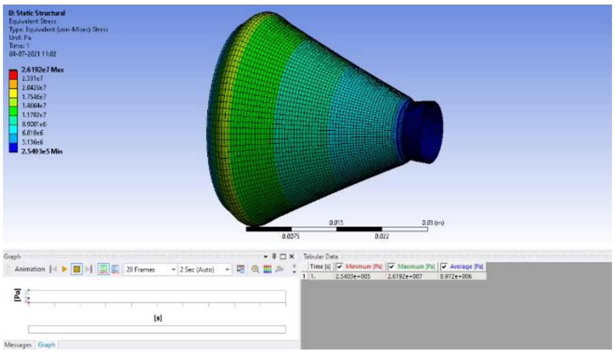


Fig. 7. Equivalent Stress

To facilitate a practical interpretation of the outcomes derived from the CFD analysis, the study employs Minitab software to graphically illustrate the principal effects of critical factors. These factors encompass the Mach Number, Nozzle Pressure Ratio, and the thickness of the nozzle. Through these visual representations, the research aims to elucidate the impact of these factors on both deformation and equivalent stress within the nozzle, thus enhancing the practical applicability of the findings.

Figure 8 has been generated by averaging the maximum deformation values across all cases and Mach number settings. Analysis of Figure 8 reveals a discernible trend: as the Mach number increases, there is a corresponding decrease in deformation magnitude. Consequently, at higher Mach numbers, the deformation incurred is notably diminished. Specifically, at Mach 1.5, the deformation reaches its peak, while at Mach 3.0, it reaches its nadir.

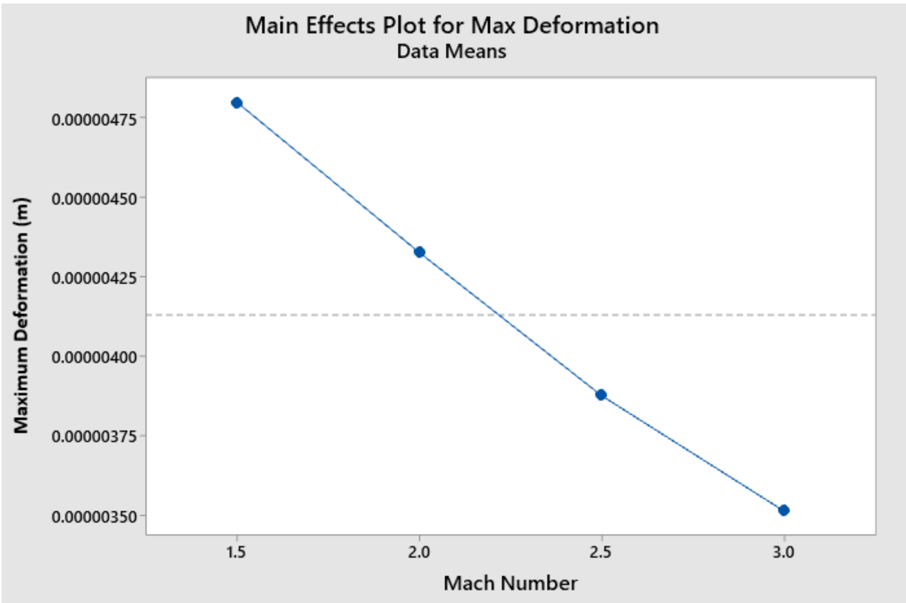


Fig. 8. Effect of Mach number on maximum Deformation

Figure 9, on the other hand, is constructed based on the mean values of the minimum stress across all cases and Mach numbers. Upon examining Figure 9, a pronounced trend emerges: with increasing Mach numbers, the minimum stress experiences a substantial reduction, particularly within the Mach number range of 1.5 to 2.5. Remarkably, the maximum minimum stress is observed in nozzles operating at Mach number 1.5.

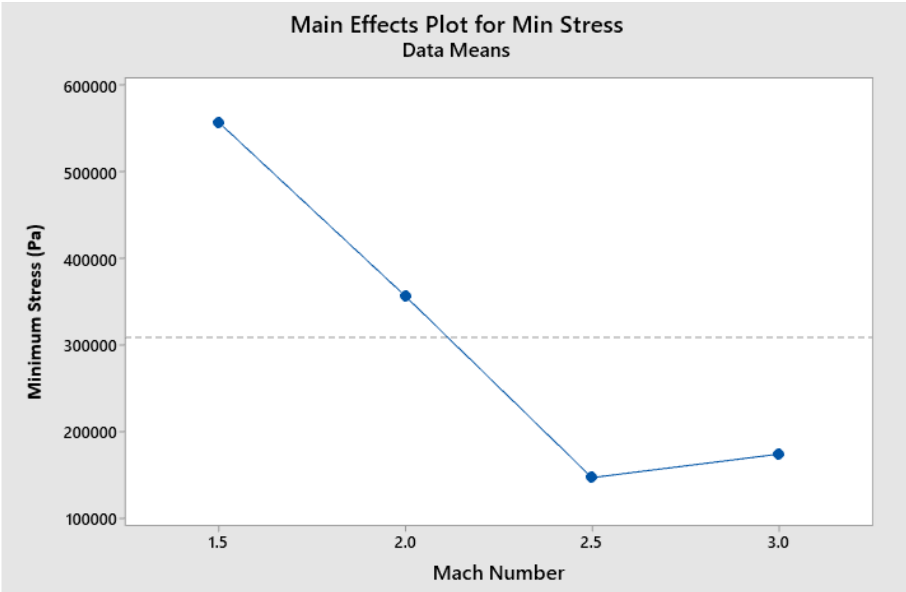


Fig. 9. Effect of Mach number on Minimum Stress

Figure 10 has been generated based on the mean values of the maximum stress across all cases, specifically at Mach numbers of 1.5, 2.0, 2.5, and 3. An examination of Figure 10 reveals a clear trend: as the Mach number escalates, there is a corresponding reduction in the maximum stress magnitude. Notably, the minimum value of maximum stress across all nozzles is observed in the case of a nozzle operating at Mach number 3.0.

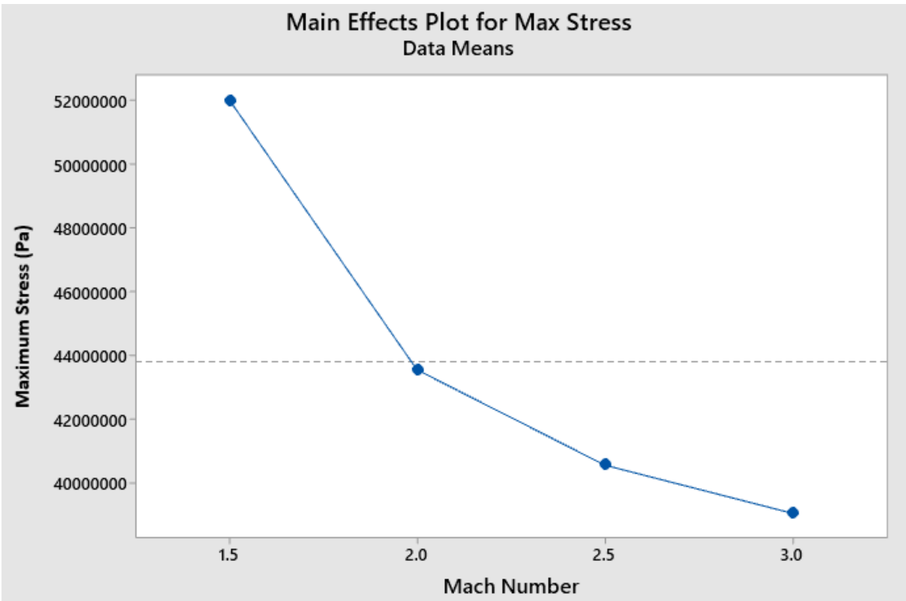


Fig. 10. Effect of Mach number on Maximum Stress

Figure 11 has been generated based on the mean values of maximum stress across all cases, considering various nozzle thicknesses: 1 mm, 2 mm, 3 mm, and 4 mm. A thorough analysis of Figure 11 reveals a distinct pattern: as the thickness of the nozzle increases, there is a concurrent reduction in the maximum stress levels. Remarkably, the maximum stress is observed at a nozzle thickness of 1 mm, and it gradually diminishes with increasing thickness.

This observation underscores the critical role played by nozzle thickness in determining the Factor of Safety (FOS) of the nozzle. If the maximum stress surpasses the material's ultimate tensile strength, it signifies a potential failure risk for the nozzle, emphasizing the significance of nozzle thickness in structural integrity considerations.

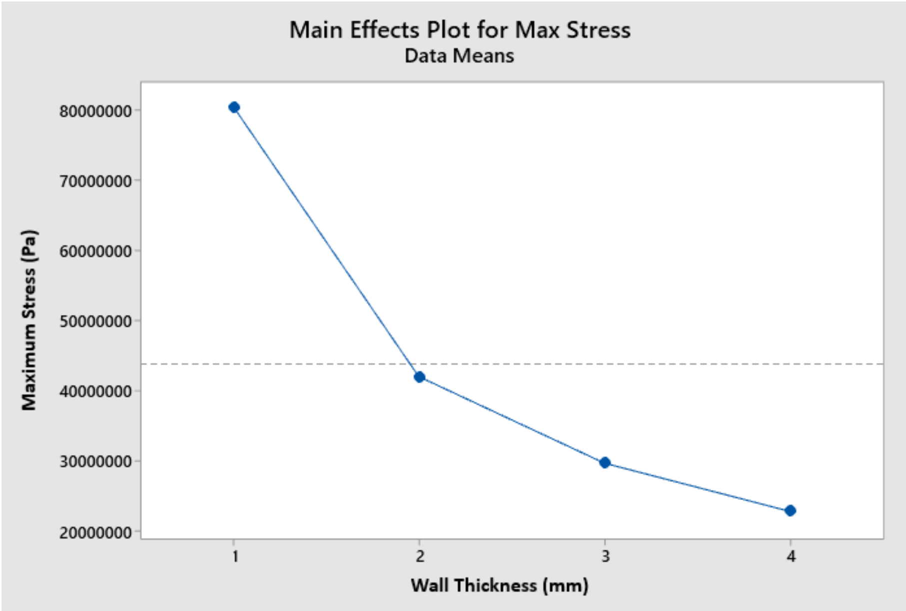


Fig. 11. Effect of Thickness on Maximum Stress

Figure 12 has been constructed based on the mean values of maximum stress across all cases, specifically considering various nozzle thicknesses: 1 mm, 2 mm, 3 mm, and 4 mm. An examination of Figure 12 reveals a consistent trend: as the nozzle thickness increases, there is a corresponding reduction in the minimum stress levels. Notably, the maximum stress occurs at a nozzle thickness of 1 mm, after which it progressively diminishes with increasing thickness.

Figure 13 has been generated by calculating the mean value of maximum deformation across all cases, specifically at various nozzle thicknesses: 1 mm, 2 mm, 3 mm, and 4 mm. An analysis of Figure 13 reveals a consistent pattern: as the nozzle thickness increases, there is a corresponding reduction in the maximum deformation. Notably, the maximum deformation occurs at a nozzle thickness of 1 mm, implying that increasing the nozzle thickness can effectively mitigate deformation.

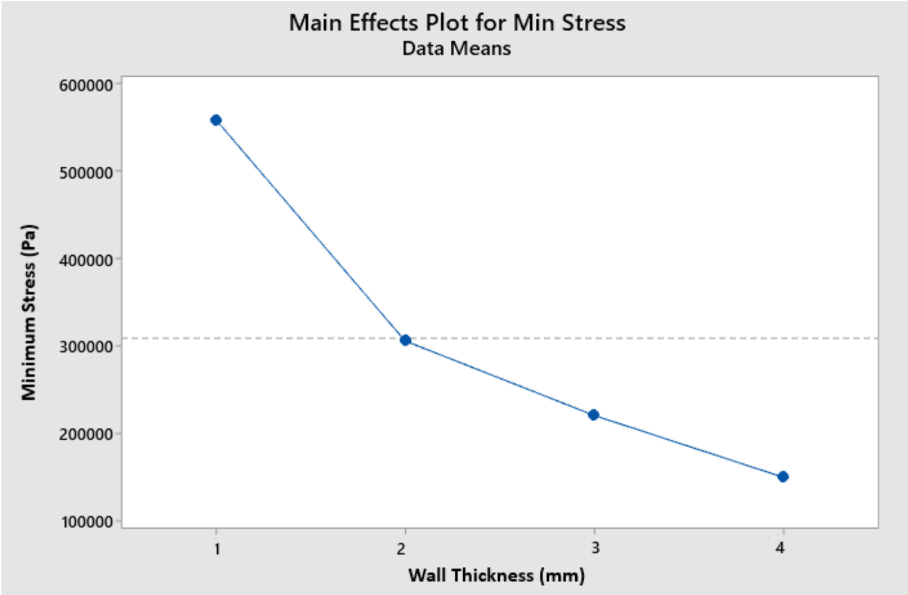


Fig. 12. Effect of Thickness on Minimum Stress

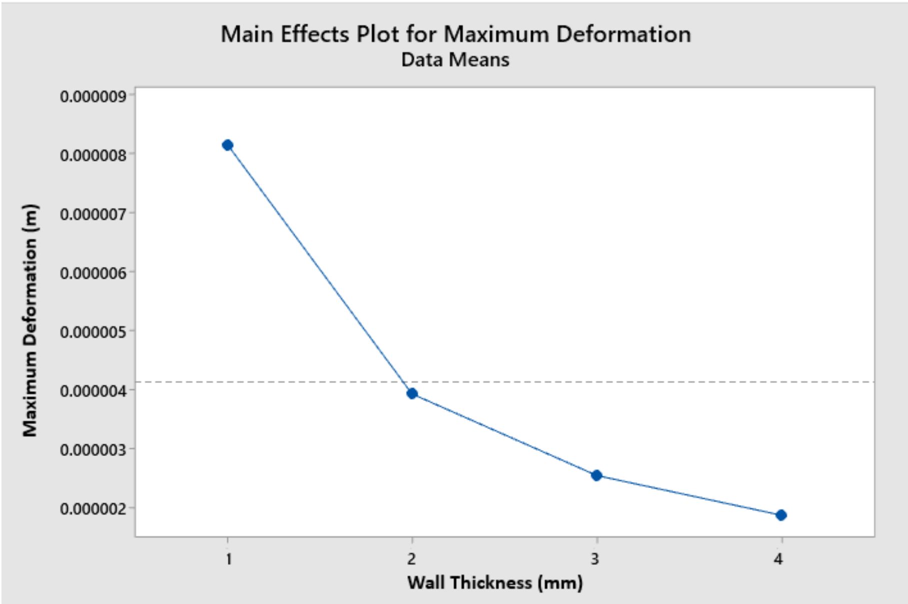


Fig. 13. Effect of Thickness on Maximum Deformation

Figure 14 has been generated by calculating the mean value of maximum deformation across all cases, specifically at various Nozzle Pressure Ratios (NPR) of 2, 4, 6, and 8. Upon examination of Figure 14, it becomes evident that as the NPR increases, there is a concurrent increase in the maximum deformation.

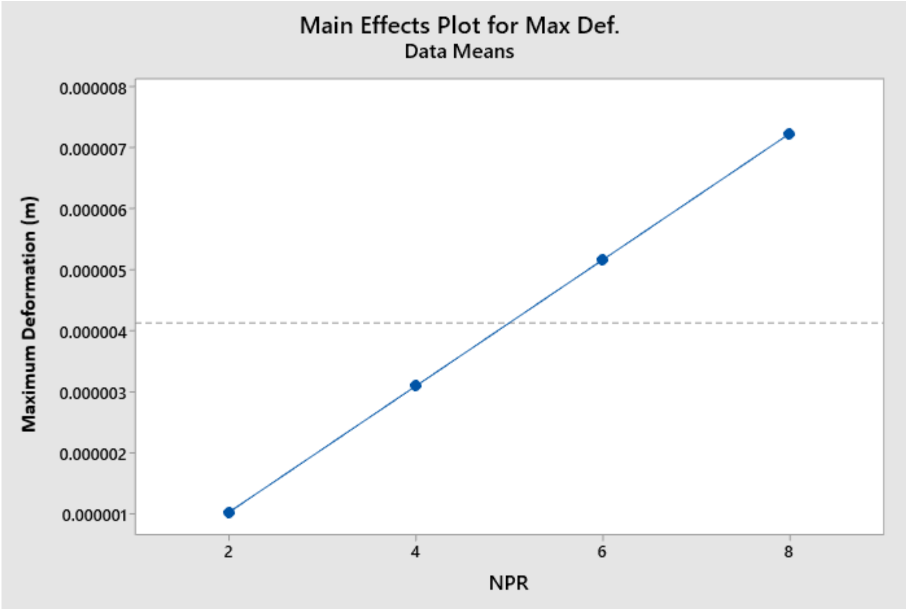


Fig. 14. Effect of NPR on Max Deformation

Figure 15 has been generated by calculating the mean value of minimum stress across all cases, specifically at various Nozzle Pressure Ratios (NPRs) of 2, 4, 6, and 8. An analysis of Figure 15 reveals a clear trend: as the NPR increases, there is a corresponding increase in the minimum stress values.

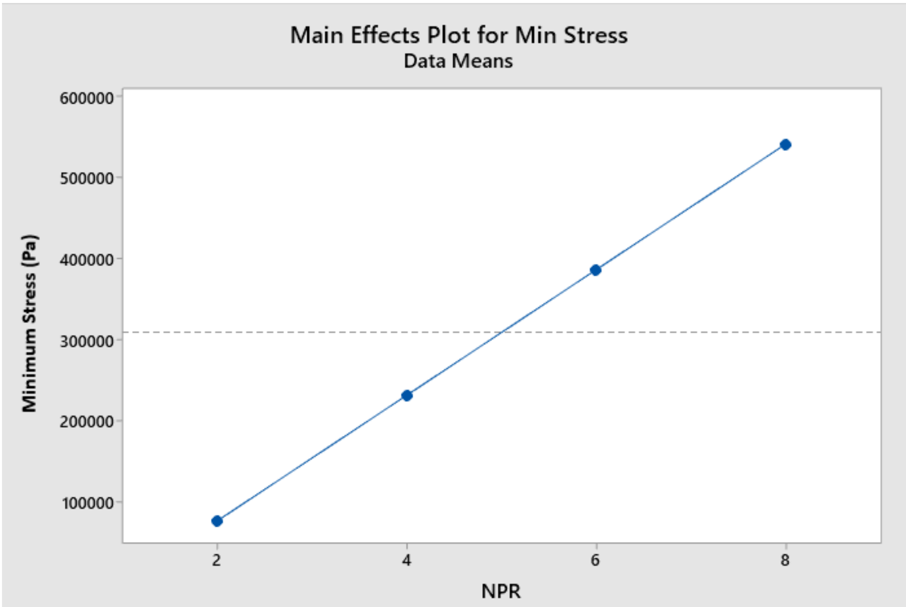


Fig. 15. Effect of NPR on Minimum Stress

Figure 16 has been generated by calculating the mean value of maximum stress across all cases, specifically at various Non-dimensional Pressure Ratios (NPRs) of 2, 4, 6, and 8. An analysis of Figure 16 reveals a discernible pattern: as the NPR increases, there is a corresponding increase in the maximum stress values.

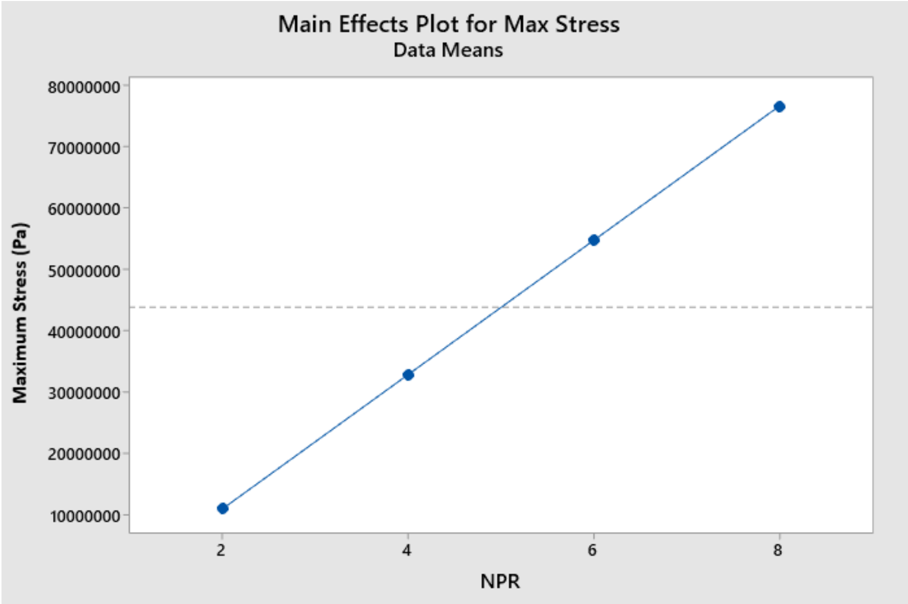
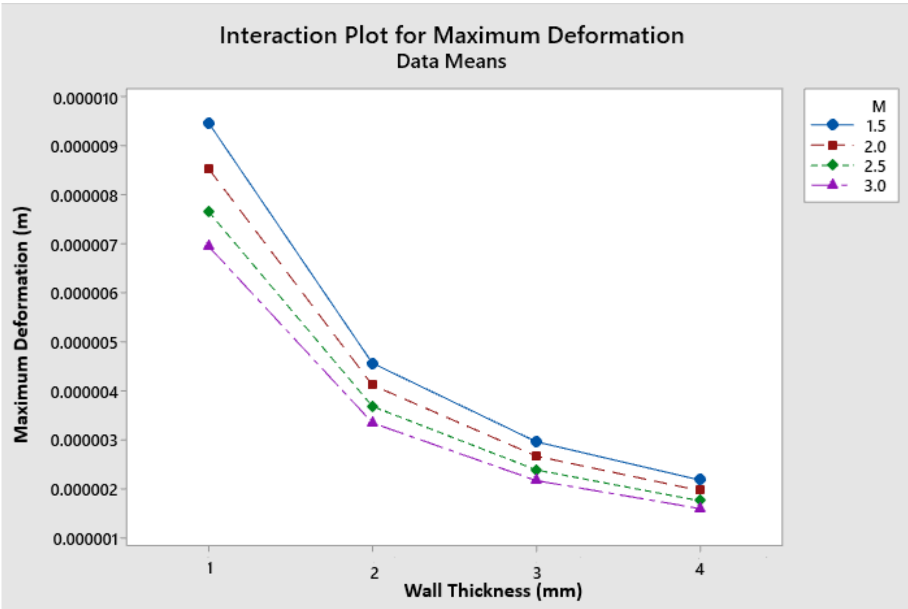
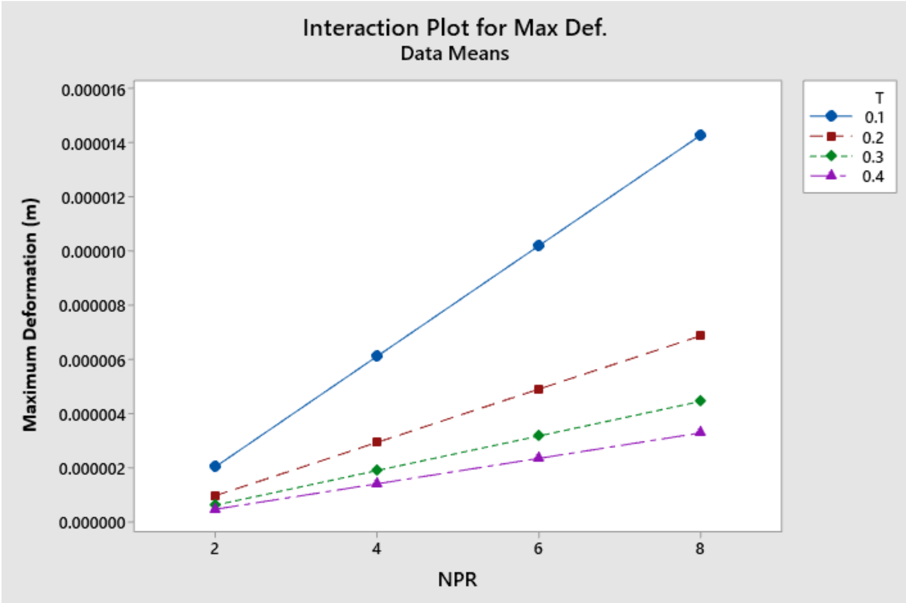


Fig. 16. Effect of NPR on Maximum Stress

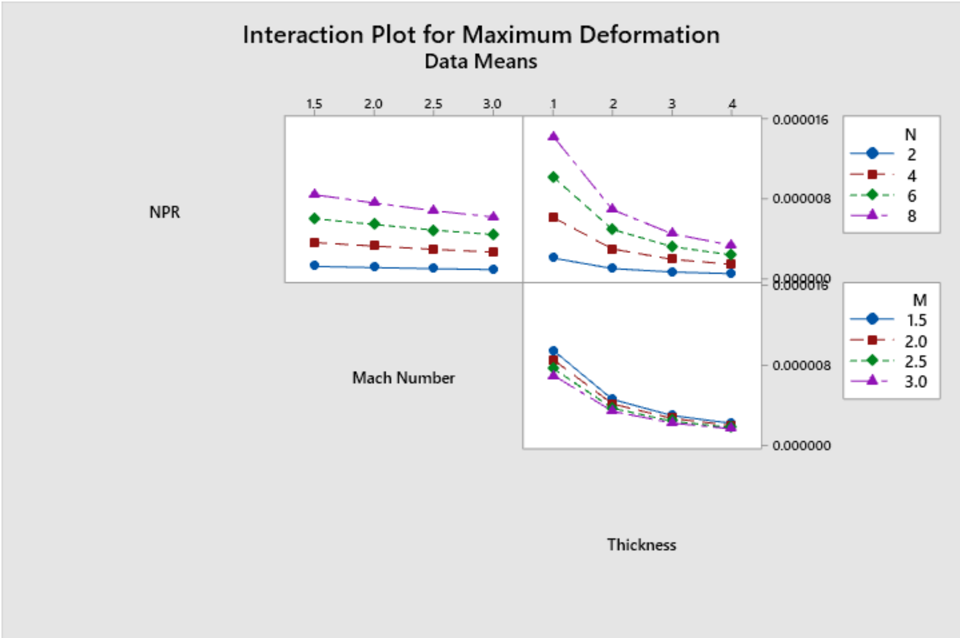
Figure 17(a)-(c) depict interaction plots among the three key factors: Mach number (M), thickness of the nozzle (T), and nozzle pressure ratio (NPR). Analysis of these plots reveals that these factors, M, T, and NPR, exhibit negligible interaction with each other. In essence, all three factors demonstrate independence and a lack of meaningful interactions among themselves.



(a)



(b)



(c)

Fig. 17. Interaction Plot for (a) Thickness and Mach number (M), (b) Thickness (T) and NPR, (c) Mach number (M), NPR, and Thickness in mm (T)

The determination of the nozzle's Factor of Safety encompasses all cases, and it hinges on the utilization of the ultimate tensile strength of the material, specifically brass, with a known and the magnitude of the ultimate tensile strength remains constant, while the maximum stress developed varies under different conditions. Considering all the scenarios with Mach numbers, nozzle thickness of 1 mm, and NPR 4, the stress developed amounts to 78,621,901 Pa. Then the calculated factor of safety is 6.359.

Likewise, the Factor of Safety (FOS) is computed for all cases and the results are graphically represented using Minitab software.

Figure 18 illustrates the mean FOS values across all cases, considering various nozzle thicknesses: 1 mm, 2 mm, 3 mm, and 4 mm. A discernible trend emerges from Figure 18: as the nozzle thickness increases, the FOS also experiences an increase. Notably, the highest value of the Factor of Safety is observed at a nozzle thickness of 4 mm.

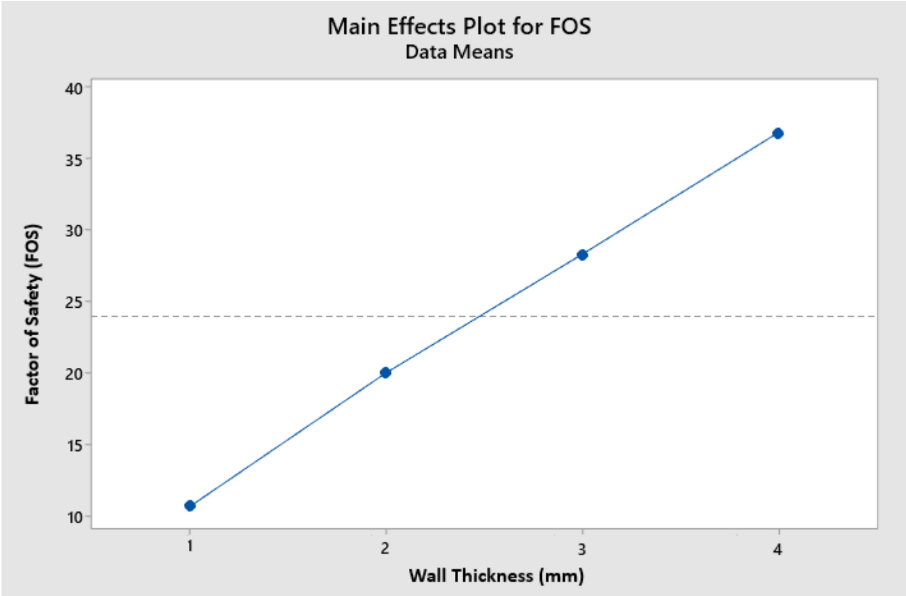


Fig. 18. Effect of Thickness of Nozzle on the factor of safety

Figure 19 has been generated by calculating the mean Factor of Safety (FOS) values across all cases, specifically at Mach numbers of 1.5, 2.0, 2.5, and 3.0. Analysis of Figure 19 reveals a clear trend: as the Mach number increases, there is a corresponding increase in the FOS.

Similarly, Figure 20 is constructed based on the mean FOS values across all cases, considering nozzle pressure ratios (NPRs) of 2, 4, 6, and 8. Examination of Figure 20 indicates a distinct pattern: as the nozzle pressure ratio increases, there is a corresponding decrease in the FOS.

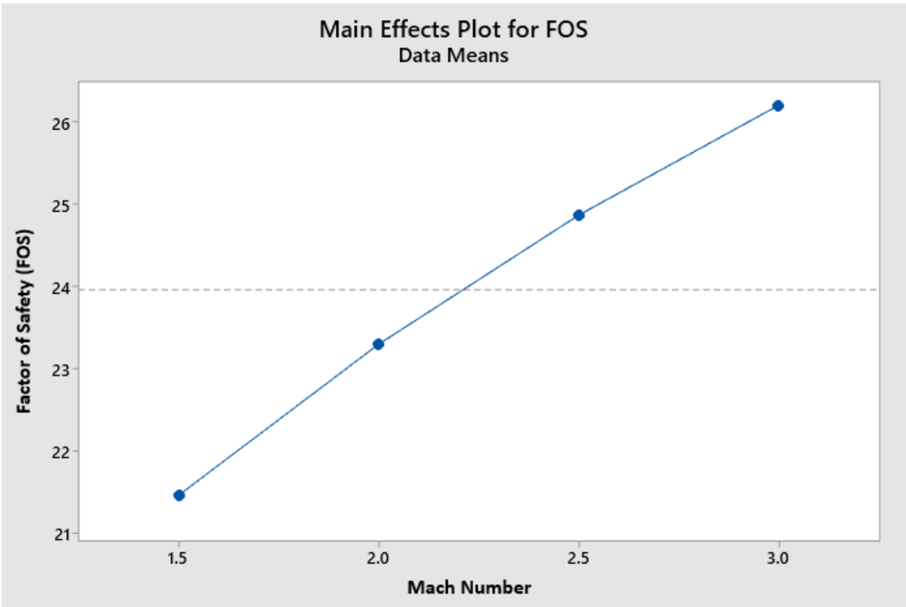


Fig. 19. Effect of Mach Number on the factor of safety

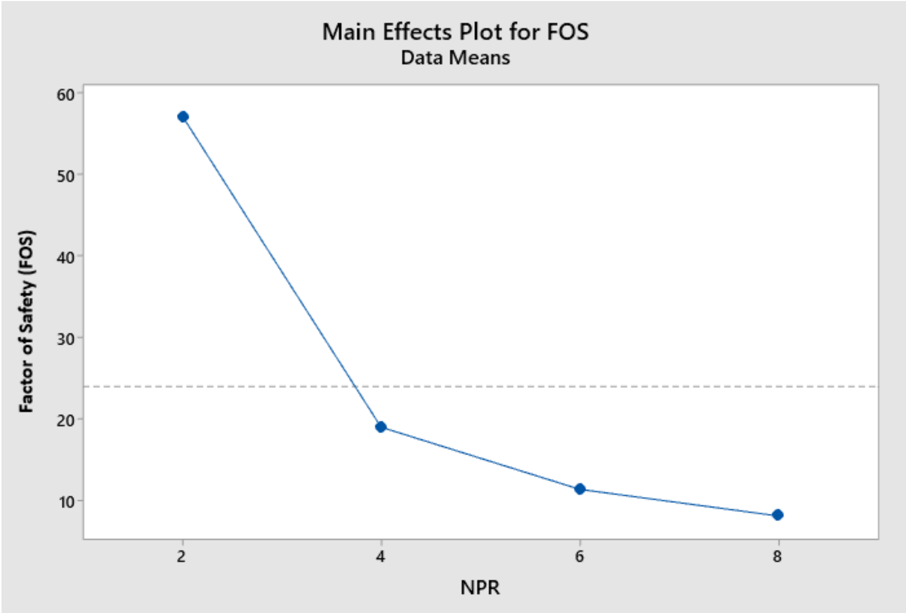


Fig. 20. Effect of NPR on the factor of safety

To determine the volume of material required for the fabrication of the nozzle, we begin by creating 3D models of the nozzle. Specifically, we model the nozzle for Mach number 1.5, with a thickness of 1 mm, using Brass as the chosen material. Our focus in this study is material optimization, primarily for the outer section of the nozzle. To facilitate this optimization, we have designed the outer part of the nozzle in a hollow configuration.

The process involves first drawing the nozzle by the Mach number of 1.5 and a thickness of 1 mm. Subsequently, we employ Ansys Software to compute the mass of the nozzle. the obtained the precise mass of the nozzle based on the selected material, which in this case is 1.82 grams.

In parallel, a traditional-type outer nozzle with a constant outer diameter along the axial length is also created, and its mass is computed. The dimensions for this traditional nozzle are established by referencing previous research papers, and its mass is calculated accordingly. The results reveal that for a 1 mm thickness, a significantly higher mass of 7.08 grams is recorded which is almost 4 times greater. This weight disparity is of particular significance in the context of rocketry, where even small variations in weight can exert a substantial impact on rocket performance. The mass of the nozzle can be determined similarly for all remaining conditions. Collectively, these findings yield valuable insights into material optimization for nozzle design under various conditions.

5. Conclusion

The comprehensive analysis undertaken by considering various parameters and their respective values has yielded several significant findings:

(i) Deformation of the nozzle:

The deformation of the nozzle exhibits a notable minimum value at NPR 2, Mach number 3.0, and a thickness of 4 mm. This implies that as the nozzle's thickness and Mach number increase, the deformation of the nozzle also increases, while it decreases with a reduction in NPR.

(ii) Equivalent stress:

Optimal conditions for equivalent stress are observed at Mach number 3.0, NPR 2, and a thickness of 4 mm, where stress levels reach their lowest point. At these specific conditions, the Factor of Safety (FOS) for the nozzle reaches its maximum value, amounting to 95.56. Consequently, the likelihood of nozzle failure becomes negligible.

(iii) Material optimization:

In the pursuit of material optimization, we have determined that at Mach 1.5 and a thickness of 1 mm, the mass of the nozzle is a mere 1.82 grams, whereas the standard nozzle mass is significantly higher at 7.08 grams. This weight disparity is particularly consequential in the context of rocketry, where even minor variations in mass can exert a profound impact.

In essence, material optimization not only contributes to cost reduction but also reduces the overall weight of the rocket. It is essential to strike a balance between minimizing mass and ensuring that deformation and stress within the nozzle remain within acceptable limits. These findings collectively underscore the significance of material optimization in enhancing rocket performance and cost efficiency.

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