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Impact of nozzle profile on ballistic performance and structural loads

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Impact of nozzle profile on ballistic performance and structural loads

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Abstract. A nozzle is a device that is designed to regulate the direction and characteristics of the combustion gas products of jet engines. So, the nozzle performance has a significant impact on the mission achievement. This paper is concerned with the internal ballistics of the nozzle aiming to estimate pressure and thermal loads on its walls. Computational fluid dynamics is applied to analyse the effect of changing nozzle internal profile on the resulting thrust, flow energy losses, and nozzle wall structure. Area ratios at the inlet, critical, and exit sections are considered as constraints for the examined design. Two different sets with 4 different profiles for each are investigated. The results show thrust, entropy losses across the nozzle and the static pressure and temperature at nozzle wall. Bell shape profiles produce better performance compared to other profiles. Changing the internal profile of the nozzle causes significant change in pressure and temperature loads acting on nozzle wall structure.

1. Introduction

A nozzle is a device that is used to convert pressure and thermal energy, generated in the combustion chamber of the engine, into a high velocity jet flow of temperature and pressure at its exit. The converging diverging nozzle contour includes a convergent part, throat, and a divergent part. Each part affects the flow in a different way and must be considered in the analysis of the nozzle performance [1].

Nozzle contours can be categorized into two major types, conical nozzles, and bell nozzles. The conical nozzle profile has a fixed diverging angle and so can be easily produced for any acceptable expansion ratio. The conical profile are presently used for short nozzles when simple design is desired over performance [2], [3].

To enhance the efficiency by turning the flow momentum axially, contour or bell nozzles were introduced. Compared to the conical nozzle, they are generally shorter and lighter. The design of non-linear contour is however difficult and incorrect design prompts the undesirable occurrence of shocks within the nozzle.

There are other several derivatives of the two main nozzle profiles including dual bell, double bell, multi divergent angles, and arc-based nozzle.

Thrust is a key feature performance merit of the nozzle. A higher thrust reflects a better nozzle design. It is also important that losses in flow energy are reduced. However, in many cases, the ability of nozzle structure to withstand structural and thermal loads is of a special interest. Hence., understanding both ballistic performance and structural loads is sought. A nozzle profile is a key feature that is believed to decide both factors.

The method of characteristics (MOC) has been a leading technique for designing contour nozzles. It is based on the theory for centered expansion waves for supersonic flow [4] and was applied in early attempts for designing thrust optimized nozzles by Guderley and Hantsch [5].

Rao developed a much simpler technique for nozzle contouring that was broadly used in 1960's [2], [6]. Rao and Shmyglevsky developed a way to alter MOC method in order to generate an optimum nozzle which was much shorter; the 'bell nozzle'. This approach used a combination of Lagrangian multipliers and MOC while maintaining the length of the nozzle as constant constrain. A distinctive contour that can be produced to maximize thrust for a specified length was described by Rao [7] often referred to thrust optimized contour (TOC). Rao developed the approximation through a list of contour points using skewed parabola; thrust optimized parabola (TOP).

The geometric parameters of bell profile according to Rao approximation are shown in fig. 1 below.

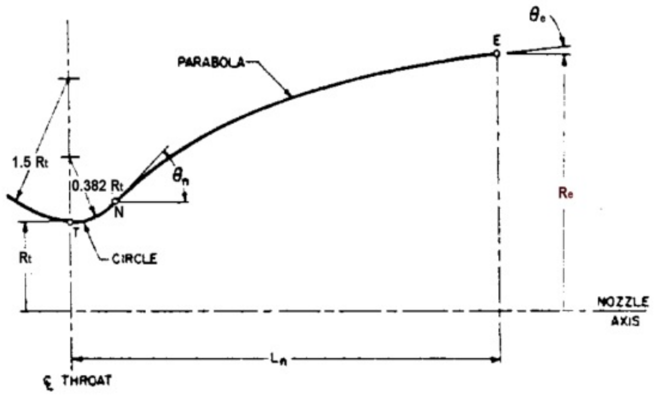

Figure 1. Sketch of a nozzle showing nomenclature and construction of parabola [7].

Ashwood et al. [8] studied the benefit of using a profiled divergent part and the effect of divergence angle on the thrust. The results show that the profiled nozzle gives about 2 percent more thrust than the conical one. Madhu et al. [9] numerically simulated expansion through different profiles for rocket nozzle. They found that the contoured nozzles produce higher exit velocity and higher degree of flow separation compared to conical nozzles. Dumitrescu et al. [10] presented a study and a design of a Laval nozzle, and obtained its influence on the performances. They concluded that the design parameters play an important role in determining the maximum attainable performance. Ömer, and Günaltay [11] investigated the design and flow differences of two different nozzle geometries and their structural effects on two different materials. They stated that bell nozzle obtains a slightly better performance by reaching a higher maximum Mach number and hence pressure inside the nozzle is decreased and thereby decreasing the structural effects on the nozzle walls.

Thies and Jordan [12] studied the effect of changing the nozzle configuration at entrance, throat and exit on thrust and specific impulse efficiencies. They found that a generous throat contour radius and a smooth exit cone increase both nozzle throat and thrust efficiencies. Joe [13] developed a method for designing compressed truncated perfect nozzles and developed a procedure for predicting the performance of such nozzles. The results show that in all cases the Rao nozzle has higher performance than compressed truncated perfect nozzles. Sreenath and Mubarak [14] studied and analyzed four different types of bell nozzles and one dual bell nozzle numerically. They stated that the dual bell nozzle has better overall performance than the single bell-shaped nozzle. At low altitudes, a vehicle could save 25-30% more fuel by using a dual bell nozzle. Mubarak [15] designed a double parabolic nozzle and compared its performance with conical and bell nozzle designs and concluded that the double parabolic nozzle achieved higher values of discharge and thrust coefficients than the conventional conical and bell nozzles. Singh et al. [16] developed a way to identify the optimum nozzle geometry that maximizes critical pressure ratio while minimizing pressure drop across the nozzle, they found that a lower diverging angle and no elongated throat resulted in a higher critical pressure ratio. Schomberg et al. [17]

compared a total of ten arc-based nozzle contours numerically to an existing thrust-optimized design. The results show that an increase in thrust of 0.25% could be achieved in an equivalent arc-based nozzle compared to the existing design. The analysis of the arc-based nozzles indicated that the contour angles had the greatest effect on thrust.

The nozzle is exposed to several thermal and mechanical loads acting on the internal wall as compressive stresses while the throat is the most exposed region to high temperature and pressure. Cozart [18] analyzed the stress distribution of a 3-D braided conical nozzle under mechanical and thermal loading conditions and it was concluded that radial stress is mildly compressive through most of the nozzle structure and the nozzle responds to internal pressure and thermal loading by tensile hoop stress distribution. Gomaa et al. [19] studied the thermo-structural response of a conical nozzle made of both steel and composite material. They addressed the loads acting on the nozzle due to combustion gases temperature and pressure. Wall temperature and pressure were obtained from experimental results. Gong et al. [20] investigated the thermo-structural response of submerged nozzles. They found that the stresses increased clearly in case of combining both thermal and mechanical loadings much more than in the case of each one separately. The hoop stress at throat insert was found to increase at first and then decrease with the time.

It's clear that the previous studies were almost totally devoted to understanding and optimizing nozzle ballistic performance in terms of thrust. On the other hand, the studies on thermal and structural stresses on nozzles did not take into full consideration enhancing the ballistic performance.

The aim of the present paper is to compare a variety of nozzle profiles. Namely, conical, bell, and modified bell. The objective is to estimate the structural and thermal loads acting on nozzle walls. These loads are derived from simulating the internal flow for given chamber pressure and expansion ratio. In addition, the impact of nozzle profile on its performance (in terms of thrust and losses) is addressed.

2. Case study and Methodology

2.1. Case study

A total of eight nozzle profiles are examined, they are grouped into two sets. Set 1 is characterized by a profiled convergent section with inlet-to-throat area and length-to-throat radius ratios of 45.4 and 8.87, respectively. Nozzles of set 1 are attached to a chamber of 73.2 bar, 3475.8 K, and 0.8 bar for combustion pressure and temperature and exit pressure, respectively. Set 2 is characterized by a conical convergent section with inlet-to-throat area and length-to-throat radius ratios of 5.23 and 2.59 , respectively. Nozzles of set 2 are attached to a chamber of 24.13 bar, 2964.7 K, and 1 bar for combustion pressure and temperature and exit pressure, respectively. For each set, four divergent profiles are used namely: conical, 3-angle conical, conventional bell, and modified bell, fig.2. The conical profile has the angle of 12^o for set 1 and 15.3^o for set 2 while the 3-angle profiles has the angles of 23^o , 12^o , and 4.1^o for set 1 and 28^o , 15^o , and 7^o for set 2 respectively at 30%, 30%, and 30% of divergent lengths.

The bell profiles are constructed based on Rao approximation for the method of characteristics [7]. A MATLAB code is developed to generate the bell nozzle contours using quadratic Bézier curve equations for the given data namely:

α, Equivalent conical nozzle half angle,
Rt, Throat diameter,
Re, Exit diameter,
θ_n, Angle of bell contour start point, and
θ_e, Angle of bell contour end point.

Fig. 3 shows the values of θ_n and θ_e for different expansion ratios ε.

The conventional bell profile is based on fig. 3 for the present cases, $\varepsilon = 4.59$, and hence $\theta_e = 9.5^o$, and $\theta_n = 19.5^o$ for set 1 $\varepsilon = 4$, and hence $\theta_e = 9.2^o$, and $\theta_n = 19^o$ for set 2.

At low area ratios, values of both angles θ_n, θ_e are relatively close to each other as shown in fig. 3. which generates a bell contour that is relatively similar to the conical contour.

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A modified bell is proposed in the present study by putting θ_e equal zero to produce axial flow at the exi

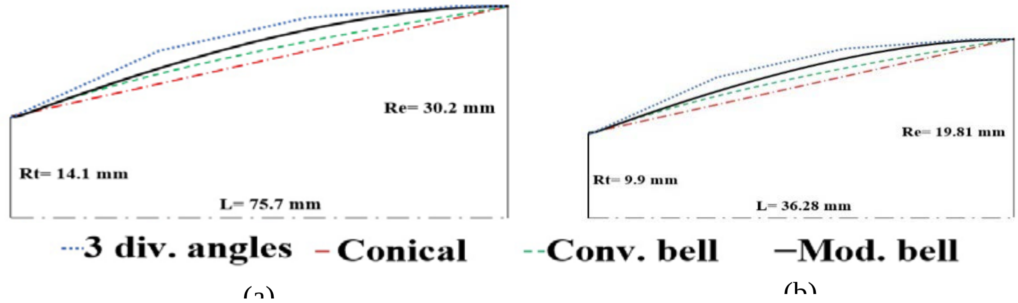

Figure 2. Sketches of the four divergent profiles for set1 and set 2, respectively.

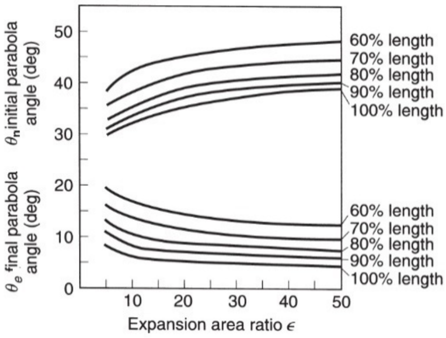

Figure 3. The initial angle θ_n and the exit angle θ_e for bell nozzles as functions of the nozzle area ratio [21].

The goal of study is to address the thermal and structural loads on the nozzle walls as well as its ballistic performance. Thrust of nozzle is adopted as a measure of nozzle ballistic performance. As for losses, entropy change across the whole nozzle is taken as the measure. The ratio of thrust to losses is introduced here as a measure of ballistic performance indicator (PI) of the nozzle profile. Flow static pressure and adiabatic wall temperature are adopted as measure for structural and thermal stresses on the nozzle, respectively.

2.2. *Flow simulation setup*

A 2D axisymmetric domain is constructed for each case. The boundary definition is illustrated in fig. 4. At the inlet, a pressure inlet is defined where absolute and total pressures are set to chamber pressure. At the exit, pressure outlet boundary is defined where total temperature is set equal to chamber temperature. The nozzle walls are set as adiabatic to nullify heat transferred no-slip condition is applied.

A commercial CFD solver is used. The second-order discretization scheme is applied for a density-based solver. Since focus is on nozzle profile, air as an ideal gas is used to represent combustion gas products.

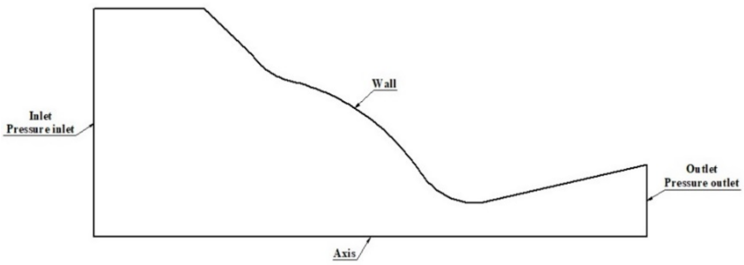

Figure 4. The boundary definition.

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2.3. Meshing

Table. 1 Number of divisions and the bias factor for each edge.

Mesh No.	Sizing Type	V1.. V9	H1, H2	H3, H4	H5, H6	H7, H8	H9, H10	H11, H12	H13, H14	H15, H16	Nodes Number	Elements Number
1	No. of divisions	100	50	30	20	120	50	10	7	150	44238	43700
	Bias Factor	10	__	__	__	3	__	__	__	5		
2	No. of divisions	150	50	30	20	120	75	15	10	225	82446	81750
	Bias Factor	15	__	__	__	3	__	__	__	5		
3	No. of divisions	225	50	30	20	120	115	25	15	335	160686	159750
	Bias Factor	15	__	__	__	7	__	__	__	7		
4	No. of divisions	340	50	30	20	120	175	40	25	500	327701	326400
	Bias Factor	15	__	__	__	15	__	__	__	7		
5	No. of divisions	550	50	30	20	120	270	70	50	750	749911	748000
	Bias Factor	15	__	__	__	24	__	__	__	12		

The fluid domain is made up of linear hexahedral elements that have been meshed. Since the edges are simple, the mesh can be transformed to structured meshing with Mapped Face Meshing. The number of divisions and the bias factor are varied on the inlet, exit, nozzle walls, nozzle axis and other edges, as seen in fig. 5.

A structured grid is generated for each case. The grid is made clustered at the walls, and nozzle throat to capture key flow details with high resolution. A grid sensitivity check is made for five different forms of meshes obtained by adjusting the number of divisions (see fig. 6, and table 1).

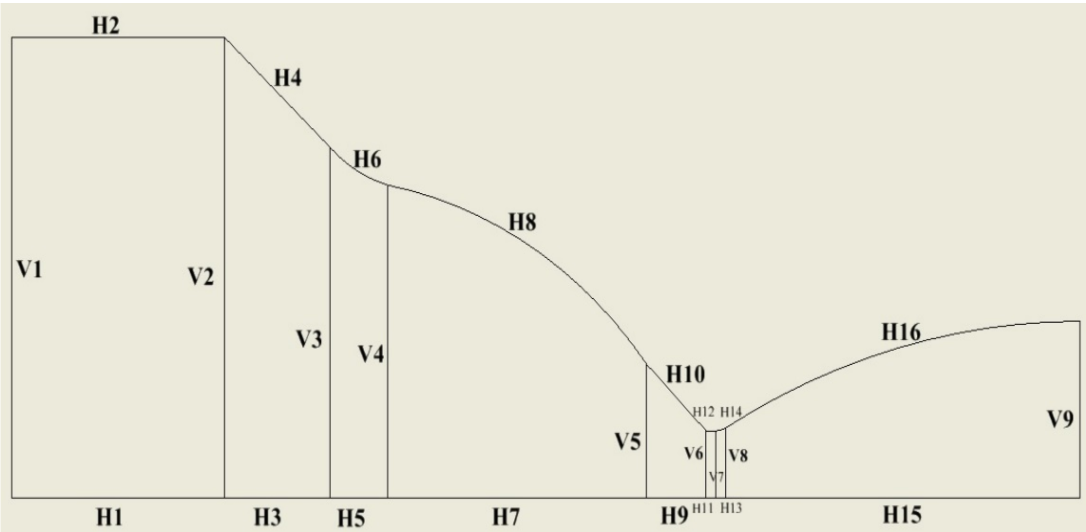


Figure 5. Nozzle edges and their nomenclature.

Mesh 5 has been selected as the most appropriate mesh due to the results convergence.

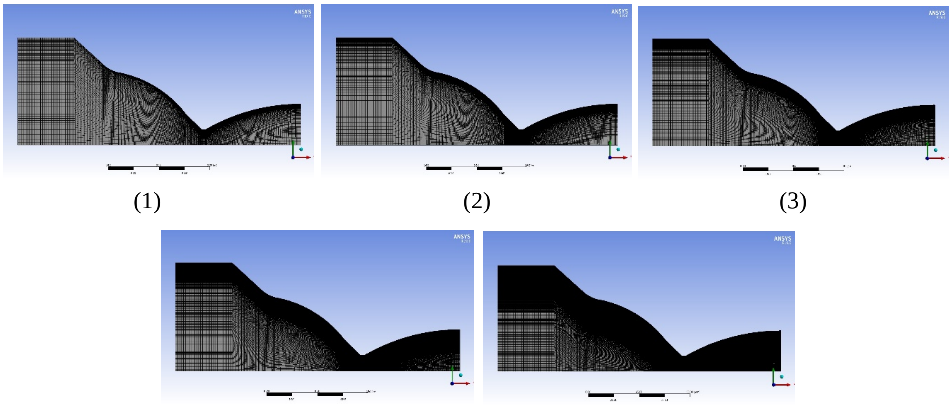


Figure 6. Mesh variation for mesh sensitivity analysis.

3. Results and Discussion.

3.1. Validation of the flow solver
A validation is done for commercial CFD package by comparing experimental results in NASA technical report [22] to these of numerical simulation. For validation, a conical nozzle with 15º half angle and area ratio 8 is chosen while the inlet-to-exit pressure ratio is varied. Shown in fig.7 the error is less than 8%.

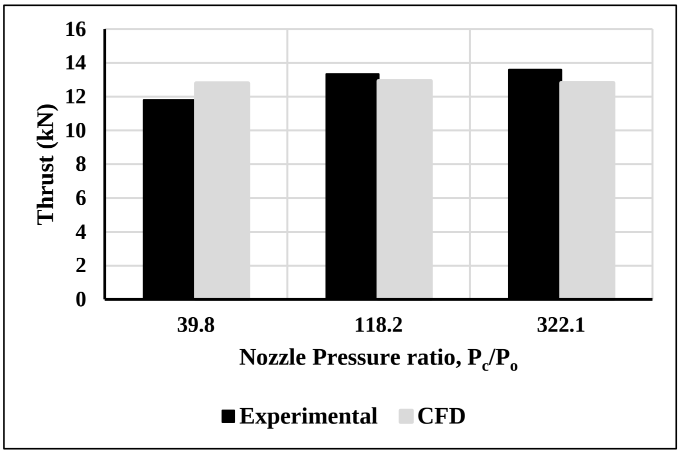


Figure 7. Results of validation for CFD solver.

3.2. Nozzle ballistic performance.
Fig. 8 shows the ballistic performance for both sets 1, and 2 for the different profiles. Thrust (F) at outlet section and the difference between flow's entropy (ΔS) at outlet and inlet sections and the ratio F/ΔS are all displayed in the figure.

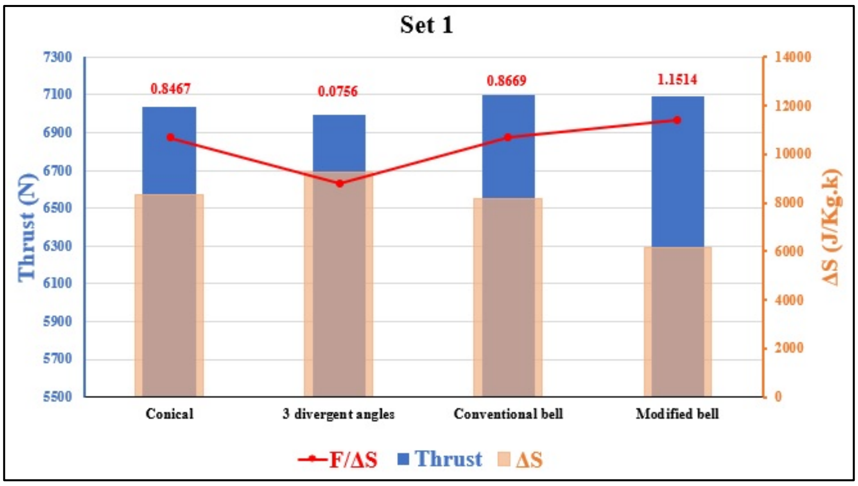
It is shown that the 3-angles profile has the lowest performance and the highest losses while the conventional bell profile has the highest performance but not the lowest losses. The bell profile yields a slight improvement in nozzle PI compared to the conical one.

Through the modification in the conventional bell profile (assuming angle of bell contour end point θ_e equal to zero) lower losses values attained which leads to a higher PI as shown in modified bell profile.

The variation in Mach number contours with internal profile change is illustrated in fig. 9. It can be shown that due to simple modification for conventional bell profile, the position of the shock wave is shifted from inside the nozzle to outside which is desirable as far as ballistic performance is concerned fig. 9. c, and d.

3.3. Nozzle structural loads.

Fig. 10. Shows the contours for wall pressure and adiabatic temperature for the nozzle profiles examined. It is shown that the 3-angles and conventional bell profiles have the lowest static pressure and adiabatic wall temperature compared to those in the conical profile. The 3-angles profile is not considered as a potential candidate profile due to its poor ballistic performance. So, and as expected, the modified bell profile that has the highest PI also has the lowest thermal and mechanical loads hence the lowest thermo-mechanical stresses acting on the nozzle wall structure.



(a

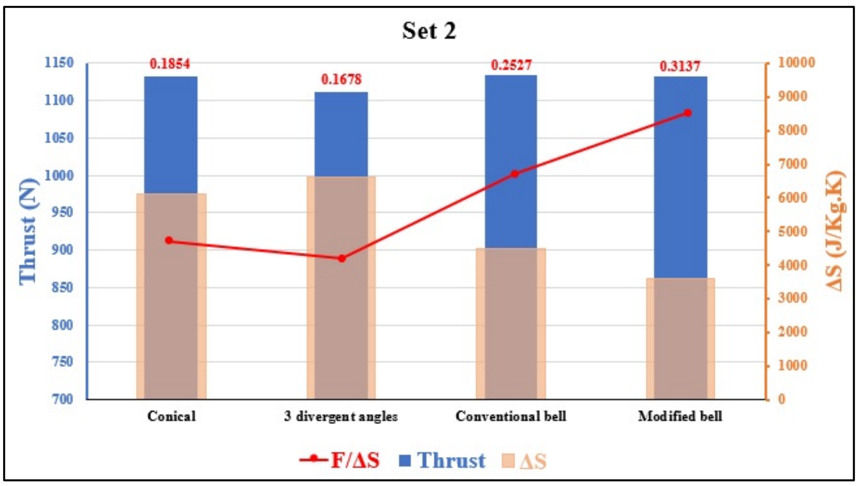


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Figure 8. Ballistic performance parameters of nozzle profiles of (a) set 1, and (b) set 2.

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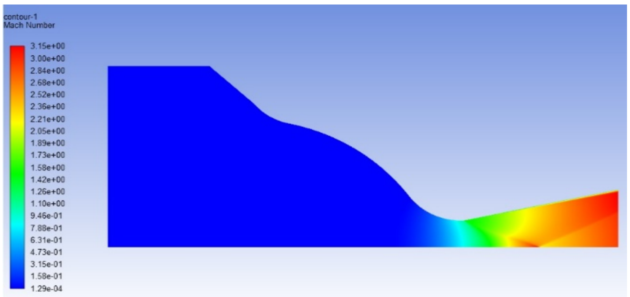
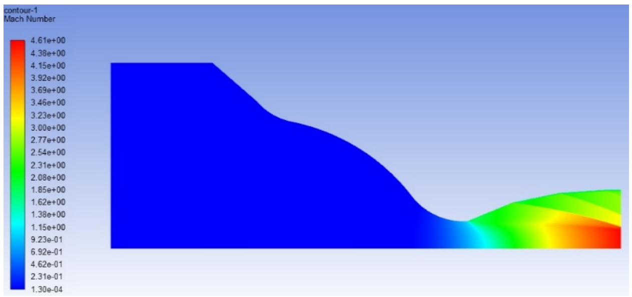


(a)



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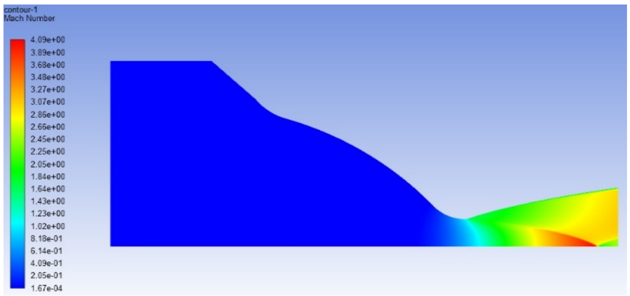
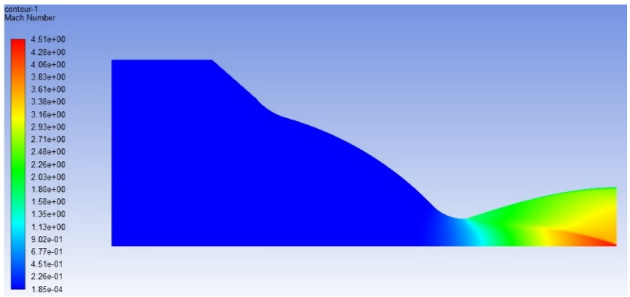


(c)



(d)

Figure 9. Mach number Contours of set 1 for (a) Conical, (b) 3-angles, (c) conventional bell, and (d) modified bell profiles.

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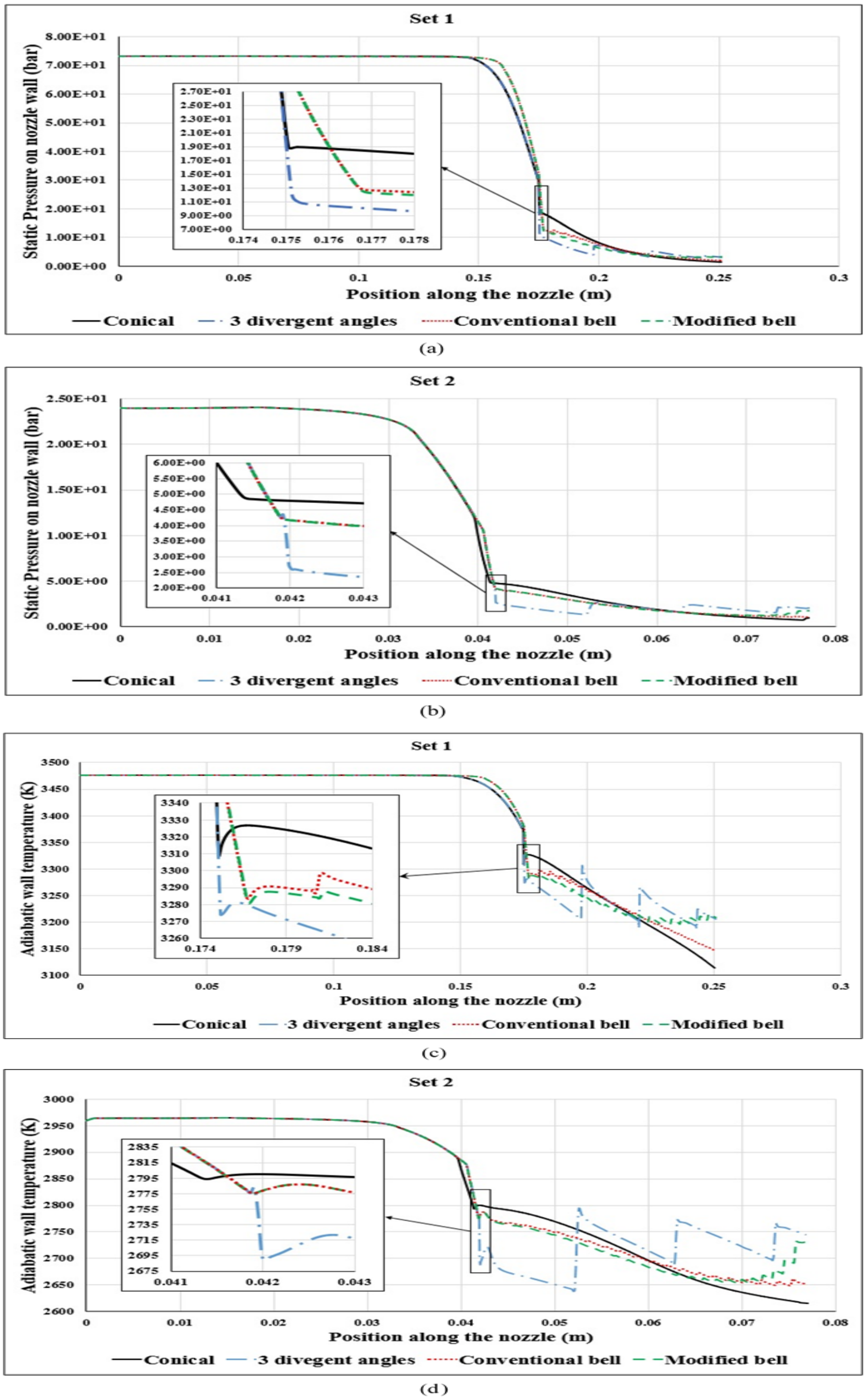

Figure 10. (a, and b) static pressure on nozzle walls for set 1, and 2, respectively, and (c, and d) adiabatic wall temperature for set 1, and 2, respectively.

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4. Conclusion

The objective of the present paper was to investigate the impact of nozzle profile on both ballistic performance and structural loads. Eight different profiles were examined including conical, 3-angles, conventional bell, and a proposed modified version of it. The following can be stated as conclusions of the present research.

- Bell contoured nozzles has better PI than the conical contoured nozzles.
- Three-angle profile has the lowest PI because of its sharp edges that exist along the divergent part.
- Regarding the performance indicator results, bell contoured nozzles have also the lowest acting pressures and temperatures which produce the lowest thermo-mechanical stresses on the nozzle wall structure.
- Rao method is more effective with long nozzles that have large area ratios. In short nozzles (as in the present cases), the bell contours act as truncated below its full profile which is needed to generate an axial flow at exit. By modifying the profile to produce an axial thrust at exit, both ballistic and structural loads are improved.

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