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Design and Performance Evaluation of a Novel Aerospike Nozzle Compared to a Conventional De Laval Nozzle: Numerical and Experimental Study

Altan Berdan MİNAZ Ahmet MERAM*

[1] KTO Karatay University, Engineering and Natural Science Faculty, Mechatronics. Engineering, Konya, Turkiye

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ABSTRACT

In this study, a uniquely designed aerospike rocket nozzle was developed, and its performance was compared both numerically and experimentally with that of a conventional De Laval rocket nozzle. Nozzles are critical components of rocket engines, responsible for accelerating and directing the high-energy exhaust gases generated in the combustion chamber to produce thrust. The geometry and aerodynamic characteristics of a nozzle significantly influence the overall efficiency, fuel consumption, and mission success of a rocket system. The type of nozzle used in a rocket engine varies depending on the mission profile, atmospheric conditions, and altitude range. Among the most widely used nozzle types are the De Laval and aerospike nozzles. While De Laval nozzles are optimized for specific altitude conditions with fixed geometries, aerospike nozzles can adapt to changing ambient pressures, maintaining high aerodynamic efficiency over a wide range of altitudes.This makes them particularly suitable for Single Stage to Orbit (SSTO) missions. Due to their altitude-compensating nature, aerospike nozzles provide more efficient thrust and reduced fuel consumption, especially at lower altitudes where environmental pressure varies significantly. In this research, both nozzle types were evaluated under identical conditions, including the same combustion chamber and propellant. Numerical analyses were conducted using ANSYS Fluent software to simulate pressure, temperature, and velocity distributions within each nozzle. Mesh structures, boundary conditions, and turbulence models were carefully selected to improve the accuracy of the simulations. Based on the numerical results, performance trends of each nozzle design were assessed, followed by experimental testing in a laboratory environment. Experimental measurements included thrust force, exhaust gas velocity, and temperature, which were then compared with the numerical data. The findings revealed that the aerospike nozzle provided a 18.5% higher thrust (327 N vs. 276 N) than the De Laval nozzle under identical conditions.

Yenilikçi Aerospike Nozulun Geleneksel De Laval Nozul ile Karşılaştırmalı Tasarımı ve Performans Değerlendirmesi: Sayısal ve Deneysel Bir Çalışma

Makale Bilgisi

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Aerospike,
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ÖZET

Bu çalışmada, özgün bir aerospike roket nozulu tasarlanmış ve performansı, geleneksel De Laval roket nozulu ile hem sayısal hem de deneysel olarak karşılaştırılmıştır. Roket motorlarında kullanılan nozüller, yanma odasında üretilen yüksek enerjili gazların kontrollü bir şekilde dışarı atılmasını sağlayarak itki üretiminde kritik rol oynamaktadır. Bu nedenle, bir nozulun geometrisi ve aerodinamik özellikleri, roketin genel verimliliği, yakıt tüketimi ve görev başarısı üzerinde doğrudan etkilidir. Roket motorlarında kullanılan nozul tipleri, görev türüne, atmosferik koşullara ve hedeflenen irtifa aralığına bağlı olarak değişiklik gösterebilir. En yaygın kullanılan nozul türleri arasında De Laval ve aerospike nozülleri yer almaktadır.De Laval nozülleri sabit geometrili ve belirli irtifa koşullarına göre optimize edilmiş tasarımlar sunarken, aerospike nozülleri değişken çevre basıncına uyum sağlayabilen yapıları sayesinde geniş bir irtifa aralığında yüksek aerodinamik verimliliği koruyabilmektedir. Bu özelliği nedeniyle aerospike nozülleri, özellikle Tek Aşamada Yörüngeye Ulaşım (SSTO) görevleri için avantajlı bir seçenek olarak değerlendirilmektedir. Aerospike nozulları, düşük irtifalarda çevresel basınca adapte olabilme yetenekleri sayesinde yakıt tasarrufu sağlayarak daha verimli bir itki üretimi gerçekleştirebilir.Çalışmada, hem aerospike hem de De Laval nozülleri, aynı yanma odası ve aynı yakıt koşulları altında karşılaştırmalı olarak incelenmiştir. Sayısal analizlerde ANSYS Fluent yazılımı kullanılarak nozüllerin basınç, sıcaklık ve hız dağılımları elde edilmiştir. Analizlerde kullanılan ağ yapıları, sınır koşulları ve türbülans modelleri dikkatlice seçilerek simülasyon doğruluğu artırılmıştır. Sayısal analiz sonuçları doğrultusunda, her iki nozulun performans eğilimleri değerlendirilmiş, ardından laboratuvar ortamında yapılan deneysel çalışmalarla bu sonuçlar doğrulanmıştır. Deneysel testlerde, itki kuvveti, gaz çıkış hızları ve sıcaklık ölçümleri gerçekleştirilmiş, elde edilen veriler sayısal sonuçlarla karşılaştırılmıştır.Çalışmanın özgün yönü, klasik nozul tasarımlarına alternatif olarak geliştirilen aerospike yapısının hem simülasyon hem de deney düzeyinde incelenmesi ve performansının somut verilerle ortaya konmasıdır.

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***Corresponding Author:** Ahmet Meram, *mekmeram@gmail.com*

INTRODUCTION

In the design of rocket engines, nozzles are considered a critical component that determines the overall thrust performance of the engine by directing and accelerating the gas flow (AÇIKGÖZ, DEMİR & ÇETİN, 2023, Uyaner, K., T., & Acar, 2024). Nozzles effectively convert the energy of the gas into thrust force and provide the motion of the rocket (Sutton & Biblarz, 2021). These designs are constantly being developed in order to increase both efficiency and aerodynamic compatibility (Bazargan, Karimi, & Mohseni, 2006). Among the nozzle types that directly affect the mission success of rocket engines, the conventional De Laval nozzle and the more innovative design, the aerospike nozzle, stand out. The De Laval nozzle is known for its ability to create thrust at high speeds by increasing the flow rate of gases. This design has been preferred since the first use of rocket engines due to its simplicity and reliability (Anderson, 2004). However, one of the biggest limitations of the De Laval nozzle is its inability to adapt to changing external environmental pressure. This situation can lead to performance losses, especially in high-altitude missions (Sequeira & Sanjay, 2021). In order to overcome these limitations, new designs such as the aerospike nozzle have been developed. Aerospike nozzles offer high efficiency over a wide range of altitudes thanks to their ability to adapt to changing atmospheric pressure (Hagemann & Immich & Van & Dumnov,1998). This feature, known as "altitude compensation", makes aerospike nozzles superior both in the atmosphere and in space vacuum conditions (Wang & Liu & Qin & Matsuo, 1998). Aerospike nozzles, especially in Single Stage to Orbit (SSTO) transportation projects, attract attention with their fuel efficiency and weight advantages(Lash, 2015). Numerical analyses are used as an important tool in understanding the performance differences of nozzle designs (ŞİŞKOLAR, GENÇ, , ÇİFTÇİ, & UYANER, 2022). In this study, the velocity, pressure and temperature contours of both nozzle types were examined with Computational Fluid Dynamics (CFD) analyses performed using ANSYS Fluent software (Dick, 2009). These analyses aim to reveal how the potential theoretical advantages of the aerospike nozzle translate into practical results (Lijo & Kim & Setoguchi, 2010). At the same time, experimental studies play an important role in the validation of theoretical models. In this study, static tests were performed for both nozzle types using potassium nitrate-based rocket fuel and the obtained data were compared. Aerospike nozzles stand out with both higher thrust performance and fuel saving potential at low altitudes (Nakka, 2024, 1 March). In this context, the study compares De Laval and aerospike nozzle types with both numerical and experimental methods, providing a comprehensive analysis that will guide future rocket engine designs. These results aim to shed light on the development of more efficient, economical and environmentally reduced rocket engine designs.

MATERIAL and METHODS

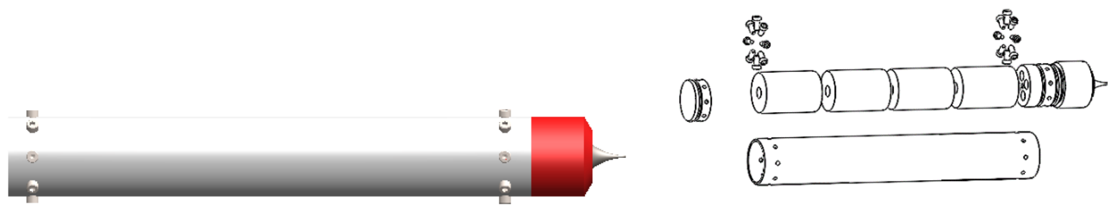
In this study, both numerical and experimental methods were used to evaluate the performance of De Laval and aerospike nozzles. The nozzles were designed in accordance with nozzle theories by considering factors such as pressure chamber, throat radius, and flow angle. The aerospike nozzle consists of two parts, the spike section and the combustion chamber section. The spike section was mounted on the combustion chamber section with the help of an M5 bolt. De Laval and aerospike nozzle designs were performed in Solidworks program. In addition, identical combustion chamber and engine plug were also designed. Aerospike rocket engine is shown in Figure 1 (a). An exploded view of the aerospike rocket engine is given in Fig. 1 (b). The rocket engine consists of nozzle, combustion chamber, fuel grains, bolts and o-rings. A cross-sectional view of the aerospike nozzle is given in Fig.2. The same elements were used in the De Laval rocket engine. The De Laval rocket engine is seen in Fig. 3 (a). Its exploded form is shown in Fig. 3 (b). The De Laval nozzle is shown in Fig. 4.

Numerical Method

Numerical analyses were performed using Ansys Fluent software to examine the flow properties and performance differences. De Laval and aerospike nozzle models were transferred to Ansys as 2D. Unlike the aerospike nozzle, it was modeled as 2D axisymmetric in the external area in order to simulate the flow. In the meshing process, the element size was assigned as 0.2 mm in both models and a total of 42150 nodes were obtained. In order to increase the mesh quality, the nozzles were divided into multiple surfaces and detailed. This method contributes to obtaining more precise results during flow analysis. The method used in this study is ideal for analyzing the flow characteristics inside the nozzle accurately and efficiently. The mesh images of the De Laval and aerospike nozzles are given in Fig.5.

Figure 1

a) Aerospike Rocket Engine and b) Exploded Aerospike Rocket Engine



(a) (b)

Figure 2

Aerospike Nozzle

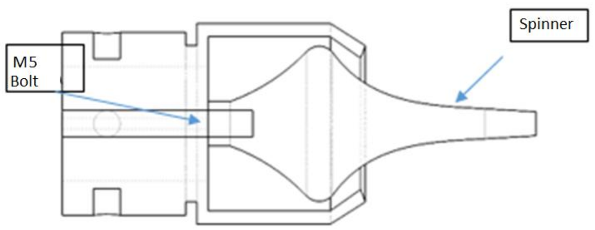
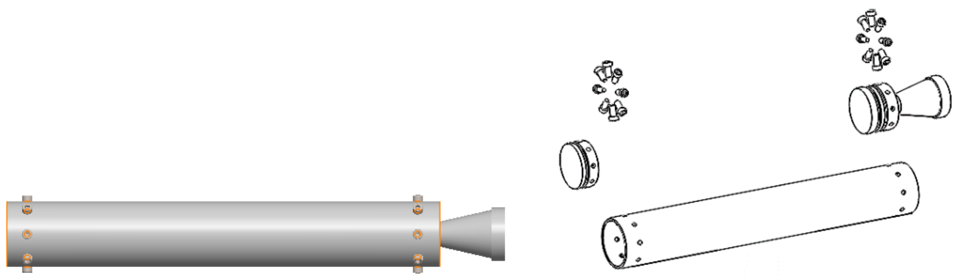


Figure 3

a) De Laval Rocket Engine and b) Exploded De Laval rocket Engine



(a) (b)

Figure 4
De Laval Nozzle

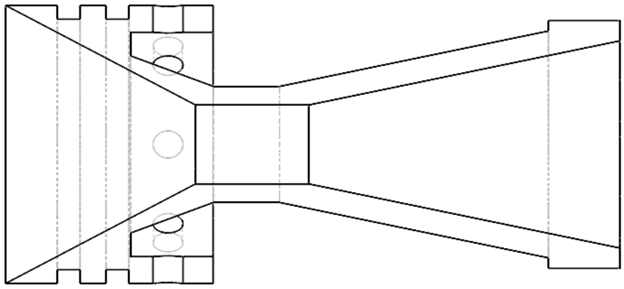
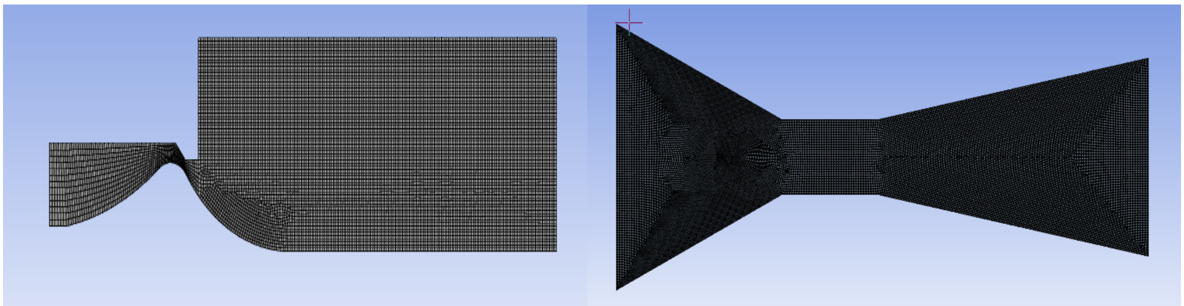


Figure 5
a) Aerospike Nozzle Meshing and b) De Laval Nozzle Meshing



(a) *(b)*

To examine the performance of the nozzles, pressure and temperature inputs were used as boundary conditions. The boundaries were assigned as inlet, outlet and wall. At the inlet, the fluid's speed and temperature values were assigned with certain pressure and temperature inputs. At the outlet, a pressure value close to atmospheric pressure and temperature boundary condition were applied. At the nozzle walls, the interaction of the fluid with the walls was modeled using a no-slip condition (zero slip rate) and the wall temperatures were assigned with a certain value. These conditions were determined to obtain the velocity, pressure and temperature profiles correctly.

The analysis was performed using 2D solutions and the density-based solution method. The energy equation was activated and the viscosity model and standard k-ε models were used. The analysis procedure is shown in Table 1.

Table 1
Analysis Specifications (Kishore & Akash, 2014)

Parameter	Value
Solution Method	2D, Density based
Models	Energy equation: Open, Viscosity model: Standard k-ε, Realizable k-ε, Enhanced wall treatment
Material	Ideal gas
Heat Capacity (Cp)	1880 J/kg·K

Gas Mixing Ratio (Y)	1.19
Viscosity	8.98 x 10^{-5} Pa·s
Thermal Conductivity	0.0142 W/m·K
Molar Mass	27.7 g/mol
Inlet Pressure	100 bar
Inlet Temperature	3300 K
Outlet Pressure	0 bar
Outlet Temperature	1700 K

Experimental Method

In the experimental studies, a potassium nitrate based rocket fuel was used as the fuel of the rocket. The rocket engine was manufactured from steel material to provide high durability and experiments were conducted on a specially designed test stand for the tests. These methods were designed to comprehensively compare the performance characteristics of both nozzle types. Both nozzles were tested on a test stand that was placed vertically and had a load measurement capacity. The purpose of these tests was to evaluate the performance of both nozzles and to observe the effect of nozzle designs by making force measurements. The force data obtained during the tests were used to compare and optimize the effectiveness of nozzle designs.

The De Laval nozzle was manufactured as a single piece. When the material properties of the nozzles were examined, 1040 carbon steel was preferred. The nozzles were machined on 6-axis CNC machines. The combustion chamber and nozzle tip materials are also made of 1040 spring steel and are produced on a lathe. Figure 6 (a) shows the rocket engine elements.

Figure 6
a) Rocket Engine Elements and b) Fuel Cell

(a) (b)

Fig. 6 (b) shows the location of the fuel cell in the combustion chamber. Potassium nitrate rocket fuel was preferred for thrust generation. The fuel consists of potassium nitrate and glucose. 65% of the mixture consists of potassium nitrate and 35% of glucose. First, the amounts were carefully measured using precision scales and then the mixture was caramelized in a pan using an electric stove. The cooking process was completed before the fuel turned completely brown, so the fuel was poured into the mold without getting wet and remaining hot. This process was repeated four times in total. In this way, four fuel grains were produced, and fuel production was completed. A total of 480 grams of fuel was used. The combustion reaction formula of the fuel is given in Eq. (Nakka, 2024, 12 July).

$$C_{12}H_{22}O_{11} + 6.288KNO_3 \rightarrow 3.796CO_2 + 5.205CO + 7.794H_2O + 3.065H_2 + 3.143N_2 + 2.998K_2CO_3 + 0.274KOH$$

Fig.7 (a) shows the igniter wire made of nickel chrome wire, and Fig. 7 (b) shows the ignition system consisting of a 12V dry battery, ignition cable and ignition wire.

Figure 7
a) Ignition Wire and b) Ignition System

(a) (b)

Fig.8 shows a test stand that measures static vertical loads. It is a weight-measuring system that includes load cells. A four-legged mechanism was manufactured to statically fix the rocket engine.

Figure 8
Test Setup

RESULT and DISCUSSION

Numerical Results

Pressure, velocity and temperature contours were obtained for both nozzle types using Ansys Fluent. These analyses were performed to examine the flow characteristics of different nozzle designs and to compare their performances. The obtained contour data visually presents the pressure, velocity and temperature distributions under operating conditions of both nozzles, allowing the effectiveness of the design parameters to be evaluated.

In the analysis performed on the De Laval nozzle, it was observed that the pressure and temperature values were high at the inlet and decreased towards the outlet, as seen in Fig. 9 and Fig. 10. On the other hand, it was determined that the speed increased in the opposite direction, that is, while it was low at the inlet, it increased towards the outlet, as seen in Fig. 11. This situation shows that, in accordance with the characteristic structure of the De Laval nozzle, the gases accelerate and increase the thrust force, creating a flow profile that is compatible with it.

Figure 9

De Laval (left)and Aerospike (right) Temperature Distribution

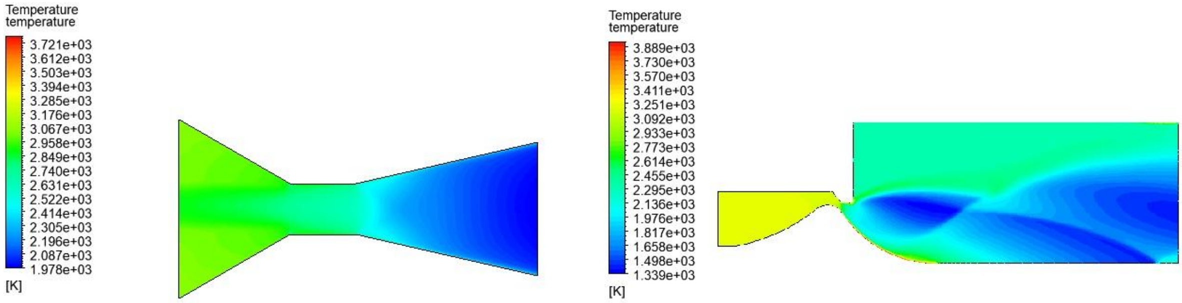


Figure 10

De Laval (left)and Aerospike (right) Pressure Distribution

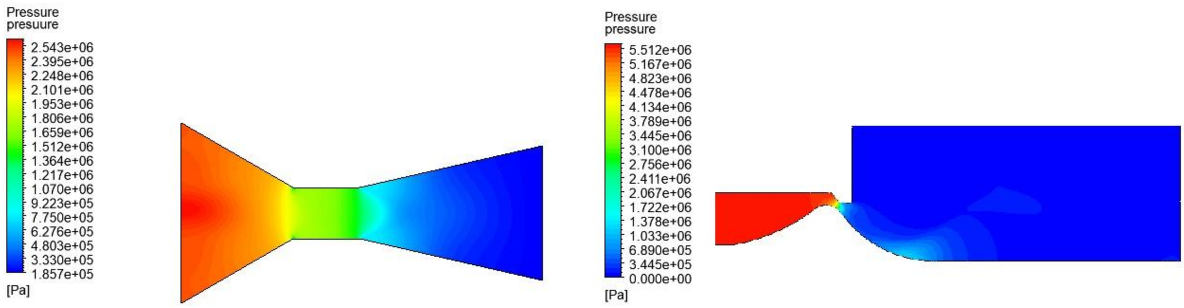
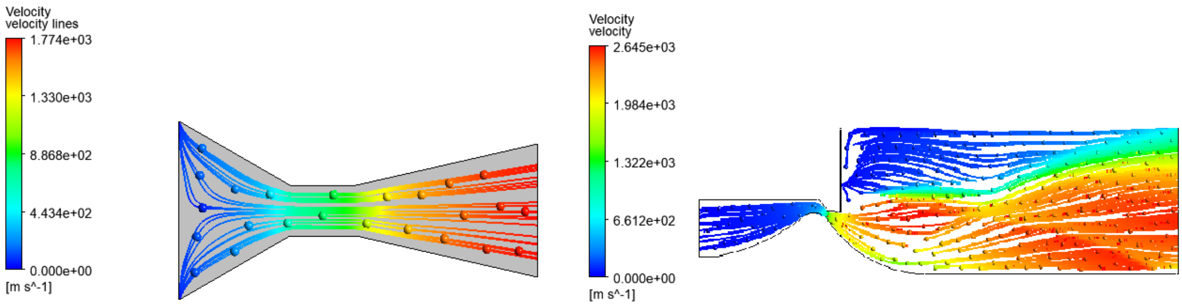


Figure 12

De Laval (left)and Aerospike (right) Velocity Distribution



As a result of the analyses performed using Ansys Fluent, it was observed that the pressure and temperature values decreased towards the nozzle exit, while the speed increased in both nozzle types. When the pressure and temperature values were examined, it was determined that the aerospike nozzle was at lower levels than the De Laval nozzle, as seen in Fig. 12 and Fig. 13. In terms of speed values, it was determined that the aerospike nozzle was at higher levels than the De Laval nozzle, as seen in Fig. 14. These results provide important information to compare the flow performance and effects of both nozzle designs on the thrust force. Numerical results for both type of nozzles are summarized in Table 2. The thrust force calculation is made according to the following equation (Physics Forums, 2024).

$$F = \dot{m}_e \dot{V}_e - \dot{m}_0 \dot{V}_0 + (p_e - p_o) A_e$$

where $(\dot{m}_e)$ is outlet mass flow rate, $\dot{V}_e$ is outlet velocity, p_e is outlet pressure, $(\dot{m}_0)$ is inlet mass flow rate, $\dot{V}_0$ is intlet velocity, p_o is inlet pressure, A_e is outlet area, A_0 is inlet area.

Table 2
Analysis Specifications

Nozzle type	Mass Flow (kg/s)	Outlet velocity (m/s)	Outlet pressure (Pa)	Outlet area (m^2)	Thrust force (N)
De Laval	0.089	1773	185.702	7.07×10^{-4}	289.03
Aerospike	0.085	2162	261.712	6.61×10^{-4}	356.9

Figure 13
De Laval and Aerospike Pressure

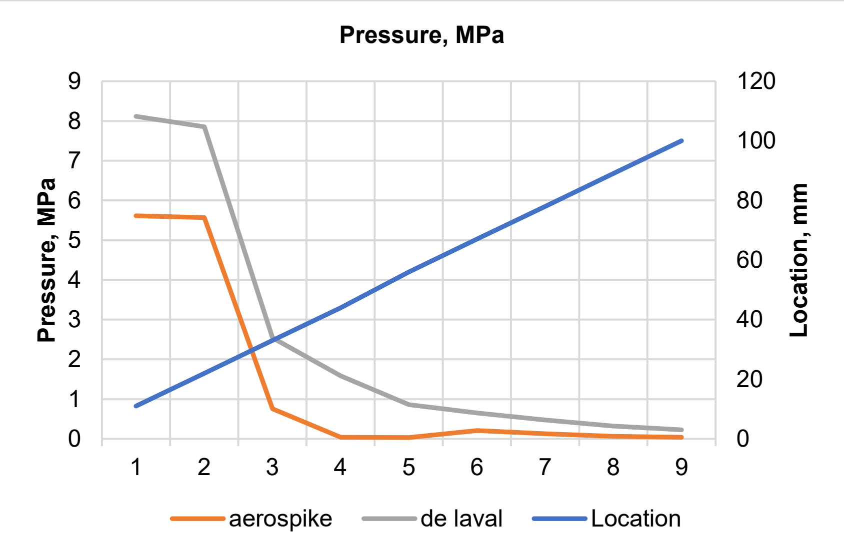


Figure 14
De Laval and Aerospike Temperature

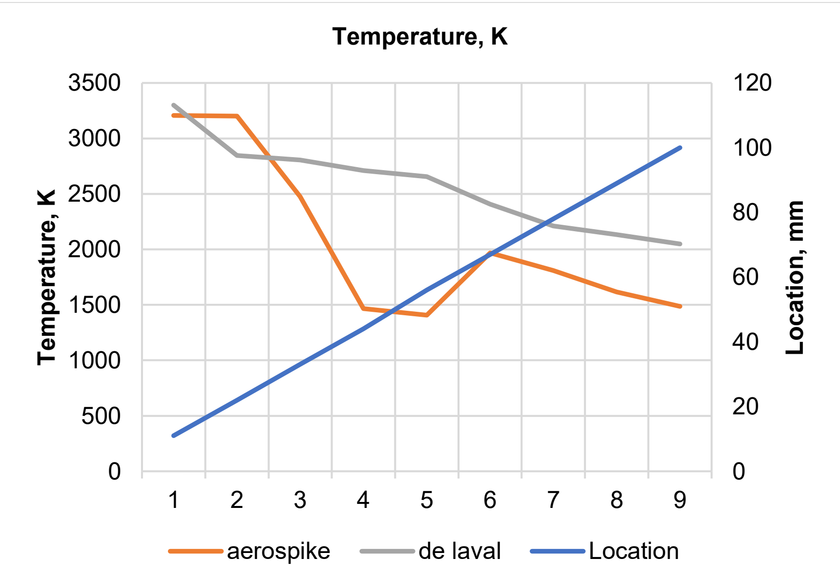
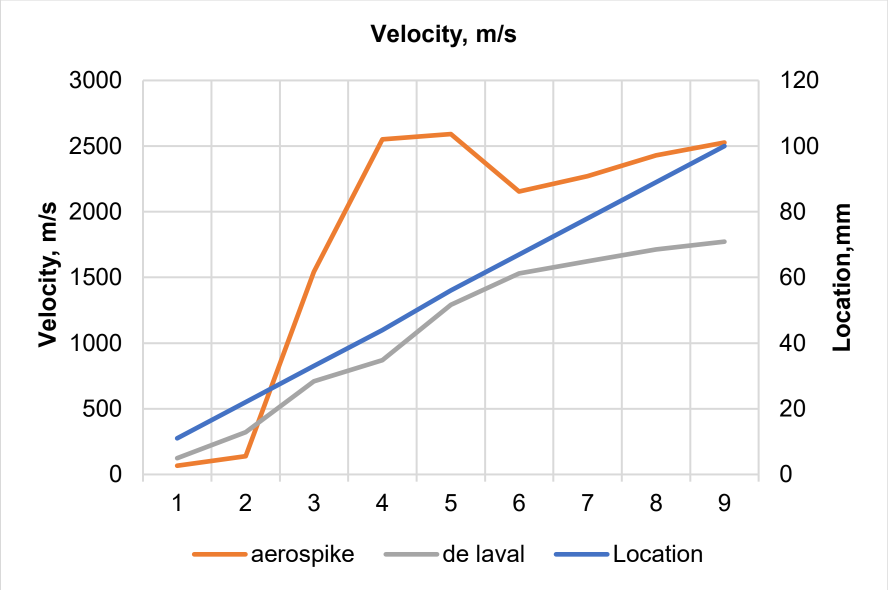


Figure 15

De Laval and Aerospike Velocity



Experimental results

In the static vertical test stand, rocket engines with De Laval and aerospike nozzles were fired separately. Post-combustion images of both rocket motor are shown in Fig. 15.

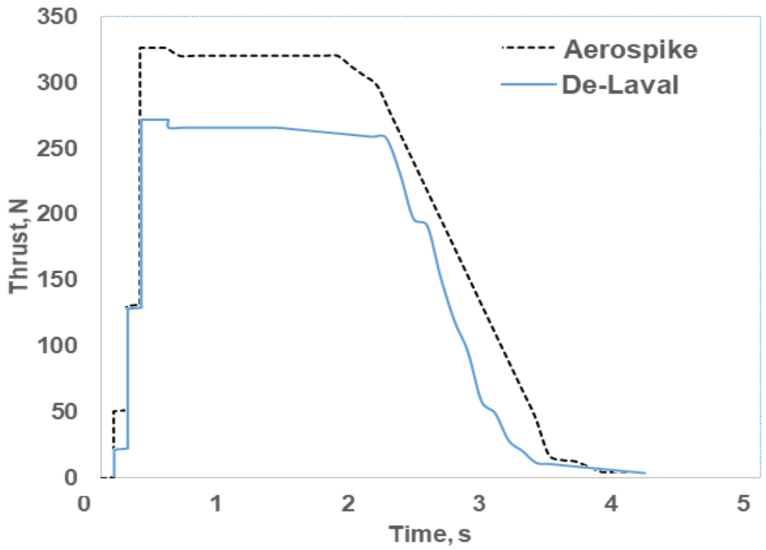
According to the data obtained from the loadcell, a maximum force of 327± 2 N was obtained with the aerospike nozzle, while a maximum force of 276 ± 2 N was measured with the De Laval nozzle. Both rocket motors had similar combustion durations, and these results show that the aerospike nozzle provides a higher thrust force compared to the De Laval nozzle, as seen in Fig. 16. This confirms that the aerospike design demonstrated superior thrust performance under varying pressure conditions. The original experimental setup and controlled fuel mixture used during the test increased the accuracy and reliability of the obtained data.

Figure 16

Post-combustion Images of both Rocket Motor

Figure 17

De Laval and Aerospike Thrust (N)



CFD analysis results revealed that the flow characteristics of aerospike nozzles were more optimized especially in terms of velocity, pressure and temperature distributions. The aerospike configuration produced approximately 18.5% higher thrust force compared to the De Laval nozzle and provided more efficient gas flow. De Laval nozzle, on the other hand, provided a leaner flow profile but showed performance loss due to its inability to adapt to changes in external atmospheric pressure.

The comparison between numerical and experimental results regarding thrust force revealed that the relative error is 4.72%, which is relatively small and indicates good agreement between simulation and experiment for the De Laval nozzle. The relative error is 9.14% for the Aerospike nozzle, which is larger than for the De Laval nozzle, suggesting that the simulation may not fully capture all physical effects (e.g., boundary layer separation, heat losses, or imperfect expansion) in the Aerospike nozzle. When evaluated in terms of material selection and structural properties; aerospike nozzles made of steel were found to be sufficient in terms of strength and thermal resistance, and also exhibited an effective performance in directing the gas flow thanks to their multi-piece compartmented structure. In contrast, the De Laval nozzle with a single-piece structure remained limited in terms of altitude adaptation despite its structural simplicity.

CONCLUSION

In this study, conventional De Laval nozzle and aerospike nozzle designs were compared numerically and experimentally. Modeling was performed in SolidWorks software; numerical analyses were conducted using ANSYS Fluent software. Experimental studies were completed on potassium nitrate based solid fuel engines manufactured from steel in a specially designed test setup.The ability of aerospike nozzles to adapt to changing altitude conditions shows that they offer significant advantages in terms of both fuel efficiency and thrust optimization. The consistency of the experimental and numerical data obtained reinforced the validity of the study. The test setup and analysis methodology used constitute a reference for similar future studies.

In future studies, it is thought that tests with different fuel compositions and material types will allow the performance of aerospike nozzles to be evaluated in a broader perspective. In addition, high-resolution 3D CFD simulations for different mission scenarios and altitude profiles can further expand the application areas of this technology. Comprehensive studies on the production methods and cost-effectiveness analyses of aerospike nozzle designs will be guiding in terms of the commercial applicability of this configuration.

Ethical Statement

No Need.

Author Contributions

Research Design (CRediT 1) Author 1 (100%)

Data Collection (CRediT 2) Author 1 (100%)

Research - Data Analysis - Validation (CRediT 3-4-6-11) Author 1 (50%) - Author 2 (50%)

Manuscript Writing (CRediT 12-13) Author 1 (50%) - Author 2 (50%)

Revision and Improvement of the Text (CRediT 14) Author 1 (50%) - Author 2 (50%)

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Conflict of Interest

No.

Sustainable Development Goals (SDGs)

Sustainable Development Goals: Does not favour

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