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INVESTIGATION OF THE VARIOUS TAPER ANGLE OF THE TIP AND ANGLE OF THE CONICAL SHAPE OF AN AEROSPIKE NOZZLE

[1] Şerif Bilalhan BAYIR, [2,*] Hürrem AKBIYIK

[1] Industrialization Directorate, TUSAŞ – Turkish Aerospace, Ankara, TÜRKİYE
[2] Adana Alparslan Türkeş Science and Technology University, Aerospace Engineering Department, Adana, TÜRKİYE
[1] serifbilalhan.bayir@tai.com.tr, [2] hakbiyik@atu.edu.tr

Highlights

- It has been observed that the taper angle at the tip of the aerospike nozzle and the conical shape angle encountered after the main flow tube are not independent of each other
- The most effective model is a conical shape angle of 45° and a taper angle of 30° at the tip of the aerospike nozzle
- It has been observed that as the amount of cold gas injected into the aerospike nozzle models increases, the differences in thrust value data become more pronounced

***Corresponding Author:** Hürrem AKBIYIK, hakbiyik@atu.edu.tr

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[1] serifbilalhan.bayir@tai.com.tr, [2] hakbiyik@atu.edu.tr

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ABSTRACT: This study considers the design of aerospike nozzles and the thrust measurement experiments conducted with various designs, taking into account existing research in the literature. Unlike other studies, this experimental study examines the effects of the angle of the conical shape and the taper angle at the tip of the aerospike nozzle on thrust. Thrust measurement experiments were conducted using a cold gas system. All measurement results were compared, revealing that the design parameters for aerospike nozzle efficiency in this study were a conical shape angle of 45° following the main flow passage and a tapering angle of 30° at the tip of the aerospike nozzle. Additionally, it appears that the taper angle and conical angle of the aerospike nozzle are interrelated in thrust production.

Keywords: *Aerospike Nozzle, Cold Gas System, Conical Angle, Taper Angle, Thrust Measurement*

1. INTRODUCTION

The aerospace and space industry have been steadily rising, especially in recent years. It is becoming increasingly important for our world and our future. In recent years, especially in the aerospace sector, research has been conducted on technologies that offer efficiency, fuel savings, and no loss of efficiency at varying altitudes, apart from traditional conical nozzles. Therefore, there have been numerous studies on aerospike nozzles in recent years [1, 2]. Aerospike nozzles are seen as an important innovation in future propulsion technology due to their small size, ability to maintain efficiency at different altitudes, and fuel-saving capabilities.

The concept of aerospike nozzles first emerged in the 1960s, and plans were made to use them in various projects such as the "Saturn V rocket". Development efforts for aerospike nozzles also began during that time. In the early 1990s, research on aerospike nozzles was reintroduced, particularly to address the needs arising from NASA's projects. In recent years, numerous studies and research have been conducted on aerospike nozzles to address the production and engineering requirements issues related to their design, and consequently, to solve the cost problem associated with aerospike nozzles. The main reasons for this are the cost issues encountered during production due to the complex design of aerospike nozzles and inadequate engineering requirements, particularly related to the heating problem of the spike section located in front of the aerospike nozzle.

In recent years, with the increase of space exploration attempts, researchers and companies have started to actively work on aerospike nozzle technology again. Similar to plug nozzles, aerospike nozzles fulfill an important need for a wide range of spacecrafts, especially SSTO (Single stage to orbit) vehicles, as they do not encounter efficiency losses despite varying altitudes. In these studies, the main aim is to determine the optimal design for the aerospike nozzle to provide the most efficiency. These studies were based on various parameters and were performed in different experimental or testing environments. The comparison was made between annular-type aerospike nozzles with truncated ratios of 60% and 40% and the non-truncated aerospike nozzle as well as a C-D (convergent-divergent) nozzle [3]. The effects of secondary flow injection applied to the aerospike nozzle were investigated [4, 5]. Tests were conducted on models obtained by modifying the contour of the aerospike nozzle, and their results were compared

***Corresponding Author:** Hürrem AKBIYIK, hakbiyik@atu.edu.tr

[6]. Graphite coating was used to overcome the heating problem inside the aerospike nozzle, and successful results were obtained [7]. A total of six different plug nozzles were tested, including three different module numbers and two different spike types with 20% and full lengths, and the study has demonstrated various differences between them [8]. The effects of base bleed on the flow in truncated aerospike nozzles were examined [9, 10]. The results showed the differences between the open wake and close wake conditions on the truncated linear aerospike nozzle [11]. Eilers et al. (2012) studied about thrust change of the cold-flow aerospike and truncated models. It is reported in the study that the side force I_{sp} is improved for 90% port location [12]. Propst et al. (2014) also reported that the maximum force is reached when injection site located at 90% of the spike length of a nozzle [13]. Fotia et al. (2019) studied about internal nozzle expansion geometry and truncation of aerospike nozzle. It is reported that for thrust efficiency, there is a relation between internal expansion area ratio and nozzle length truncation [14]. Sieder-Katzmann et al. (2021) set up a six DOF force measurement system for cold gas experiments of linear and annular aerospike nozzles. The side-force generations are investigated by using this proposed system. The thrust value of linear nozzle is measured about 39.1 N and the side-force value is about 1.66N [15]. One of the important results reported in the study is that the effectiveness of fluidic thrust vectoring is related with injection position and plug truncation [16].

Until now, the studies in the literature have focused on the length of the spike part of aerospike nozzle, type of flow, angle of spike for thrust vector control, position of the spike in design and aerospike nozzle type. The main aim of the present study is to investigate both the effect of the angle of conical shape and the taper angle at the tip of the aerospike nozzle on thrust. Additionally, in this study, the connection between these two parameters on produced thrust by aerospike nozzle is investigated. In this study, the existing research on aerospike nozzles in the literature are examined, and two parameters are investigated. These parameters are the angle of the conical shape and the taper angle at the tip of the aerospike nozzle. Therefore, a total of 20 different models were generated with various values for these two parameters. Cold-flow experiments were conducted on these models, and their thrust performances were compared.

2. MATERIALS AND METHODS

The design methodology of the aerospike nozzle is defined based on the relevant studies in literature in this field [3, 5, 7, 10, 17-19]. Generally, the decision on whether the aerospike nozzle will be linear or annular, the choice of spike shape as isentropic or conical, and the overall dimensions of the nozzle model are determined by analyzing the findings from relevant literature studies [20-23]. In a specific research study, two different models of aerospike nozzle, namely linear and annular, were tested using simulation environments, and the resulting outlet velocity and maximum pressure values were compared. The study observed that the annular aerospike nozzle was more effective than the linear aerospike nozzle [20]. Another research conducted by Herman and Crimp (1961) focused on exploring and comparing various parameters of spike shapes. It was found that the conical shape caused significantly less performance loss than anticipated and, in some cases, outperformed the isentropic spike model [21]. Additionally, it is known that the production of the conical-shaped spike component is easier. The methods proposed by Rao [22] and Angelino [23] have been preferred and continue to be used in the past. When the results obtained from these two methods with the results from other current methods (AI techniques, numerical and computer-based simulations, experimental studies) are compared, it has been revealed that there is a very little difference between them.

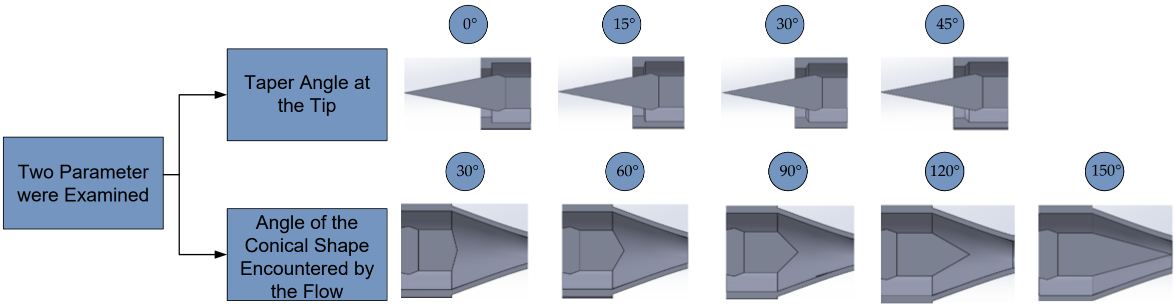

Figure 1. The diagram illustrates the two parameters under examination and their corresponding angle values.

This study has considered the information stated above as well as relevant literature studies and research. Based on these, the general shape, dimensions, spike shape, and other parameters of the 5 aerospike nozzles have been identified.

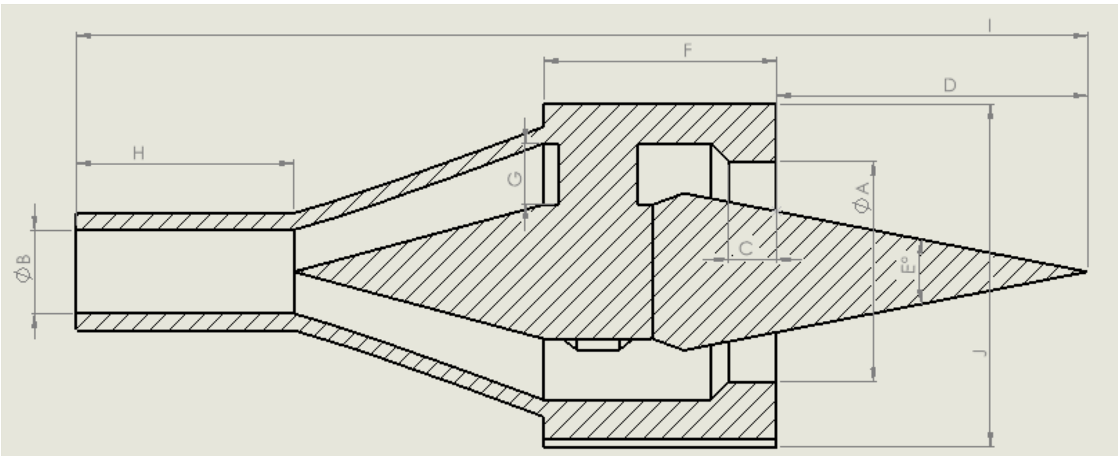

Figure 2. Technical drawing of the aerospike nozzle model.

The parameters determined in Figure 2 can be seen in Table 1.

Table 1. Dimensions of parameters of the aerospike nozzle model

Parameters	Dimensions
A=Throat diameter	26.20 mm
B=Main flow hole diameter	10 mm
C=Length of the cowl	5.68 mm
D=Full spike nozzle from the throat	37.19 mm
E=Spike conical angle	22°
F=Length of the main part	27.80 mm
G=Height of holding rods	7.30 mm
H=Main flow hole length	26 mm
I=Total length	120.86 mm
J=Total thickness	42 mm

To mitigate any potential issues during assembly and other physical processes, the spike is not directly conical. It has a tapered portion towards the base. If the spike were directly conical, even the slightest assembly problem could disrupt the airflow and hinder achieving the desired results.

After the design of the spike and holding rods components of the aerospike nozzle model, the main flow orifice, the conical shape encountered by the main flow, and the outer part were also designed. Based on the research in the literature, it has been observed that the majority of aerospike nozzle models in the literature have a ring-shaped outer part. In this study, the outer part of the aerospike nozzle model is hexagonal instead of circular. The main reason for having the outer part of the aerospike nozzle model in a hexagonal shape instead of a circular shape: to reduce the risk of slippage inside the aerospike nozzle holder during flow testing.

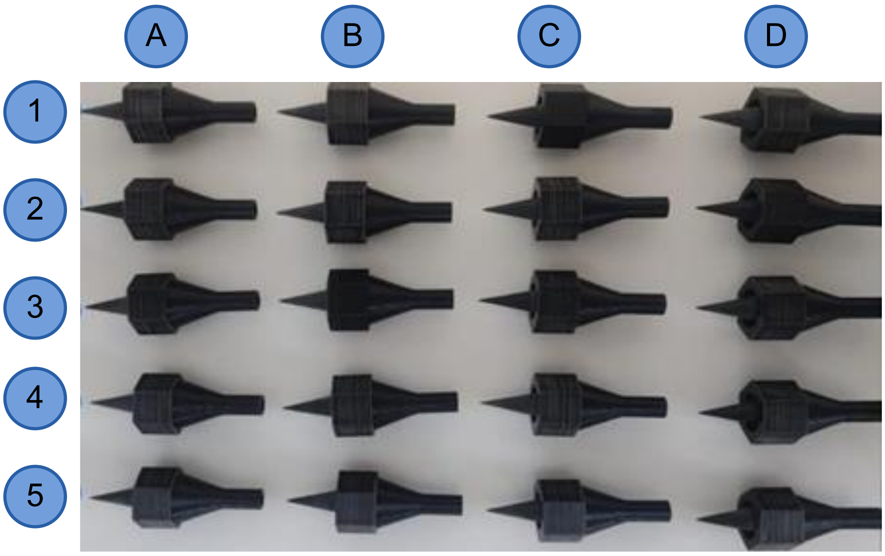

Figure 3. The complete set of produced aerospike nozzle models.

In Figure 3, there are 20 different aerospike nozzle models which are different parameters. These 20 aerospike nozzle models are numbered. The values for two different parameters for the numbered aerospike nozzle 20 models can be seen in Table 2, Table 3, Table 4, and Table 5.

Table 2. The aerospike nozzle models numbered in the series A and their parameter values.

Aerospike Nozzle Model Number	Angle of the Conical Shape	Taper Angle at the Tip
A1	30°	0°
A2	60°	0°
A3	90°	0°
A4	120°	0°
A5	150°	0°

Table 3. The aerospike nozzle models numbered in the series B and their parameter values.

Aerospike Nozzle Model Number	Angle of the Conical Shape	Taper Angle at the Tip
B1	30°	15°
B2	60°	15°
B3	90°	15°
B4	120°	15°
B5	150°	15°

Table 4. The aerospike nozzle models numbered in the series C and their parameter values.

Aerospike Nozzle Model Number	Angle of the Conical Shape	Taper Angle at the Tip
C1	30°	30°
C2	60°	30°
C3	90°	30°
C4	120°	30°
C5	150°	30°

Table 5. The aerospike nozzle models numbered in the series D and their parameter values.

Aerospike Nozzle Model Number	Angle of the Conical Shape	Taper Angle at the Tip
D1	30°	45°
D2	60°	45°
D3	90°	45°
D4	120°	45°
D5	150°	45°

3. EXPERIMENTAL SETUP

In the cold gas experiments, an ATI Gamma Model 6-axis load cell and an Aalborg GFC67 model mass flow meter and controller were used. Subsequently, 20 different aerospike nozzle models were placed onto the aerospike nozzle holder. A 10-millimeter diameter metal rod was placed in the ATI Gamma Model 6-axis load cell. Next, the aerospike nozzle holder was attached to that metal rod. Finally, the thrust values were measured. The role of the Aalborg GFC67 model mass flow meter was to regulate the flow of cold gas injected into the aerospike nozzle models. The amount of cold gas injected was changed using this device, and a total of 5 different cold gas flow rates were used. These 5 different values were determined as 100 Standard Liters Per Minute (SLPM), 200 SLPM, 300 SLPM, 400 SLPM, and 450 SLPM, respectively. After each aerospike nozzle model was placed in the system, the ATI Model 6-axis load cell was used to measure thrust force in the x-direction. For each measurement, 100 different values were obtained for 10 seconds. All measurement data was recorded using the "ATI DAQ F/T" software. Figure 4 shows the schematic diagram of the cold gas experiment and data processing setup. SLPM is the standard

L/m, and the standard density under the calibration conditions of the mass flow meter is 1.29 kg/m³.

Figure 5 represents the overall diagram of the design, production, assembly and experimentation processes. The areas where aerospike nozzles are used, methods to find appropriate design and thrust values for aerospike nozzles used in these areas, experimental test and the process of experimental test are shown.

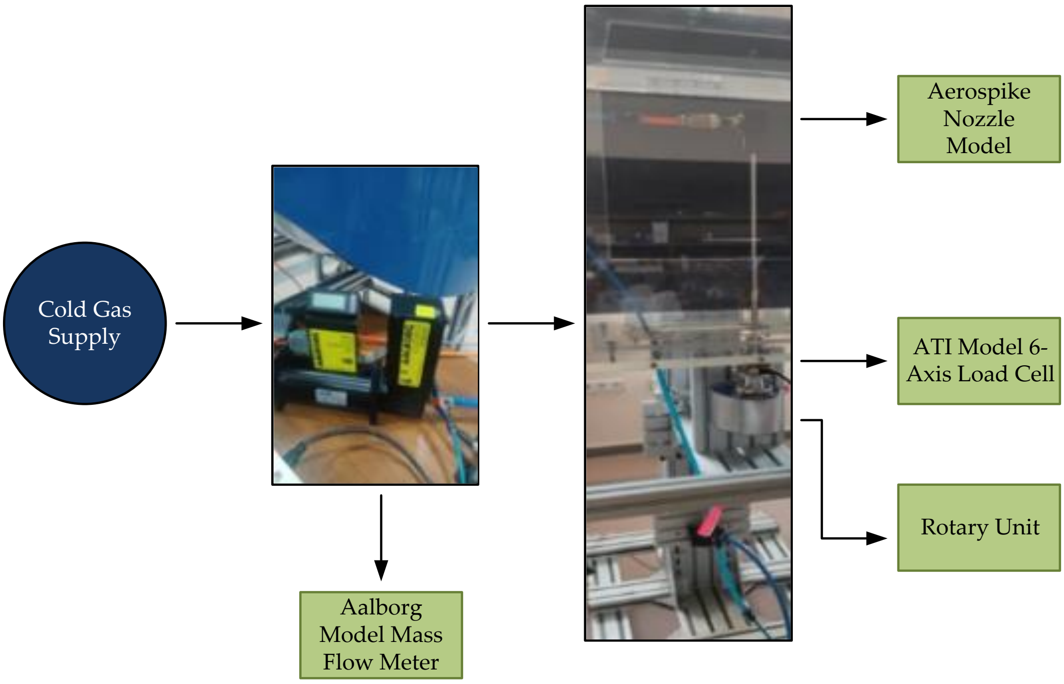

Figure 4. The diagram of the cold gas experiment setup.

4. RESULTS AND DISCUSSION

This section presents the results of the cold gas experiment and discusses the findings. Firstly, a comparison was made among aerospike nozzle models where the conical shape angle encountered at the tip of the aerospike nozzle was kept the same. After that, the five aerospike nozzle models that provided the highest thrust values were compared. It is observed that the aerospike nozzle model with a conical shape angle of 30° encountered after the main flow tube of the aerospike nozzle and a taper angle of 45° at the tip of the aerospike nozzle achieved the highest thrust among all the models.

In Figure 6, a line graph was used to compare the thrust values provided by five aerospike nozzle models; each of these models has a taper angle of 0°. Among these five aerospike nozzle models, it was determined that the model with a conical shape angle of 120° has the maximum thrust for 200, 300, 400, and 450 SLPM values. For 100 SLPM values, it was found that the model with a conical shape angle of 30° has the maximum thrust. Among these five aerospike nozzle models, it was observed that the model with a conical shape angle of 90° has the minimum thrust for all SLPM values. For the 450 SLPM value, it was determined that the model with a conical shape angle of 30° has a value close to the maximum thrust measured in the tests.

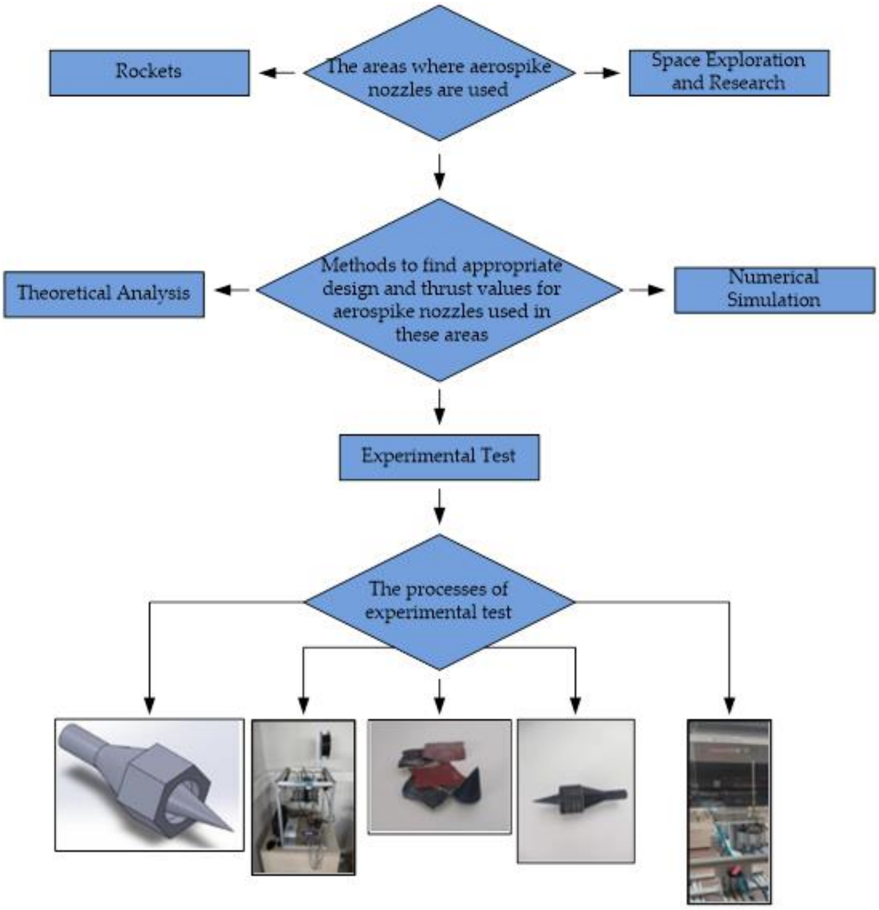

Figure 5. Overall diagram of the design, production, experimentation, and data processing processes.

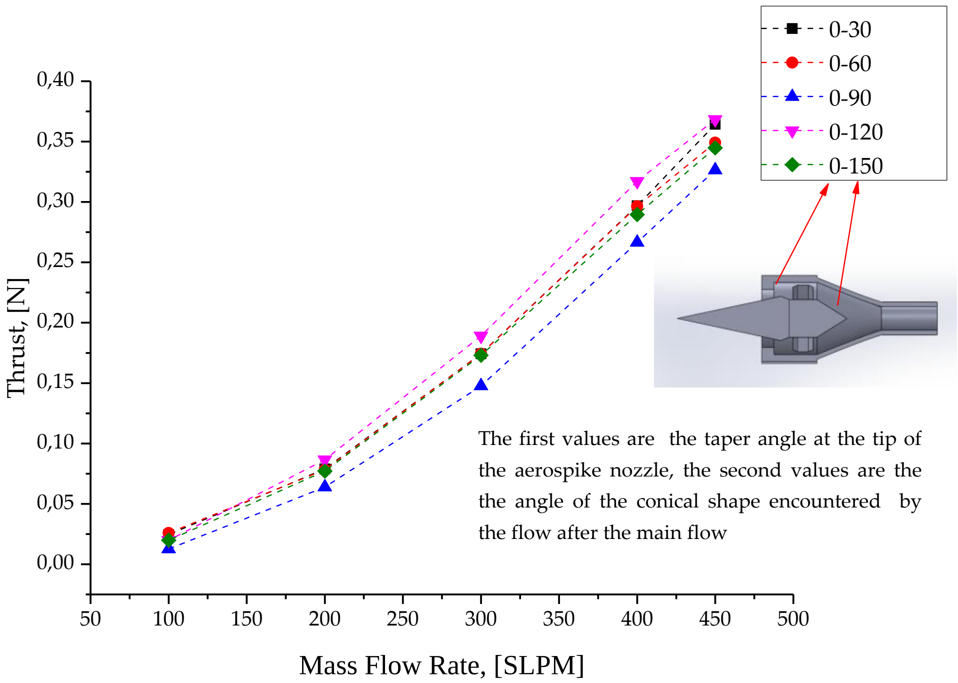

Figure 6. The thrust values vs SLPM for the taper angle of 0° of the tip.

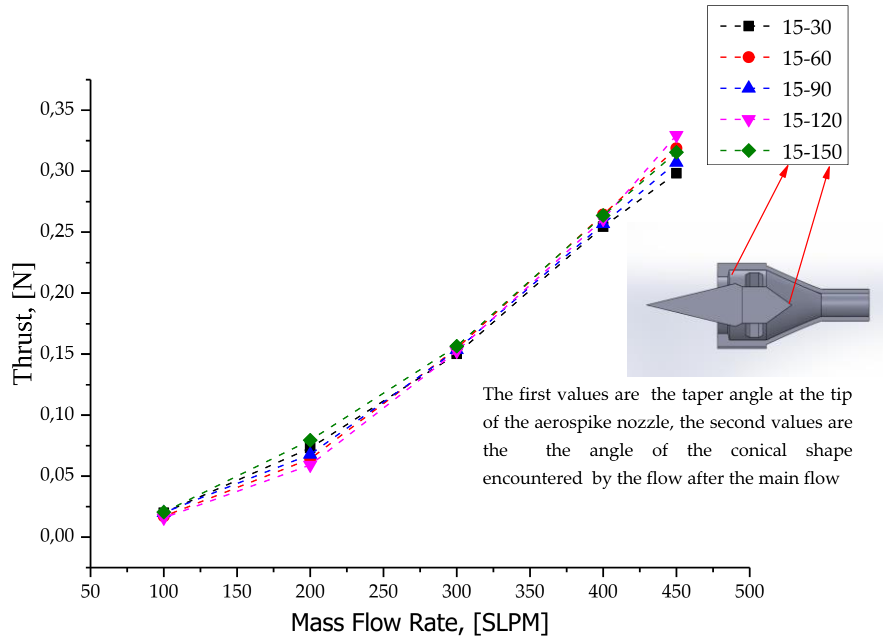

Figure 7. The thrust values vs SLPM for the taper angle of 15° of the tip.

In Figure 7, a line graph was used to compare the thrust values provided by five aerospike nozzle models; each of these models has a taper angle of 15°. It has been observed that the model with a conical shape angle of 120° has the minimum thrust for 100 SLPM and 200 SLPM values. However, it has been observed that the model with a conical shape angle of 120° has the maximum thrust for 450 SLPM values. The model with a conical shape angle of 150° has been observed to have the maximum thrust for 100 SLPM, 200 SLPM, and 300 SLPM values. The model with a conical shape angle of 30° has been observed to have the minimum thrust for 300 SLPM, 400 SLPM, and 450 SLPM values.

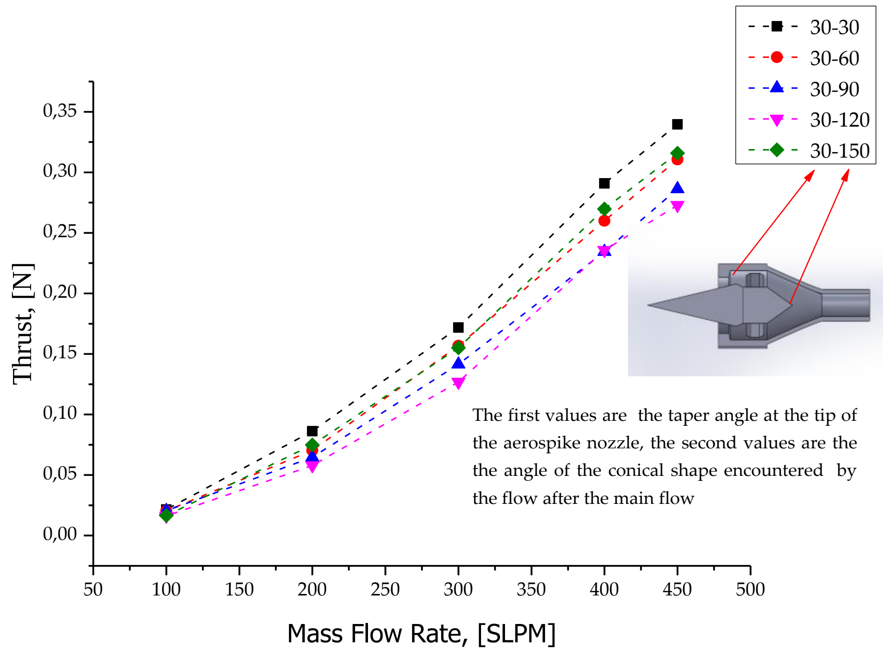

Figure 8. The thrust values vs SLPM for the taper angle of 30° of the tip.

In Figure 8, a line graph was used to compare the thrust values provided by five aerospike nozzle models; each of these models has a conical shape angle of 30° encountered at the tip of the aerospike nozzle. Among these five aerospike nozzle models, it was observed that the model with a conical shape angle of 30° has the minimum thrust for all SLPM values. It was also observed that the model with a conical shape angle of 120° has the minimum thrust for all SLPM values.

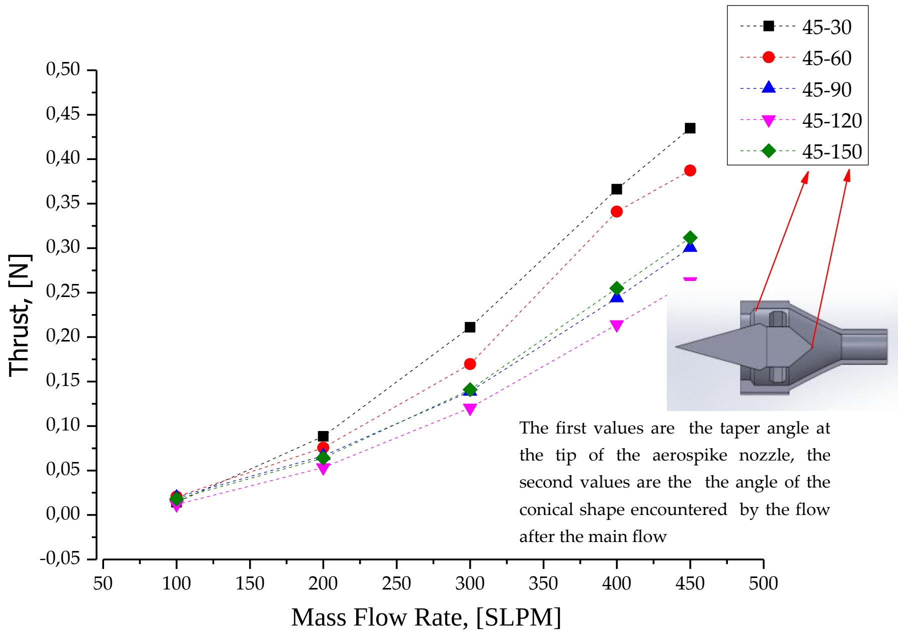

Figure 9. The thrust values vs SLPM for the taper angle of 45° of the tip.

In Figure 9, a line graph was used to compare the thrust values provided by five aerospike nozzle models. Each of these models has a conical taper angle of 45° encountered after the main flow tube of the aerospike nozzle. It was determined that the model with a conical shape angle of 30° has the maximum thrust for 200 SLPM, 300 SLPM, 400 SLPM, and 450 SLPM values. Additionally, the model with a conical shape angle of 30° was one of the two models with the minimum thrust for the 100 SLPM value. It was observed that the model with a conical shape angle of 120° has the minimum thrust for all SLPM values.

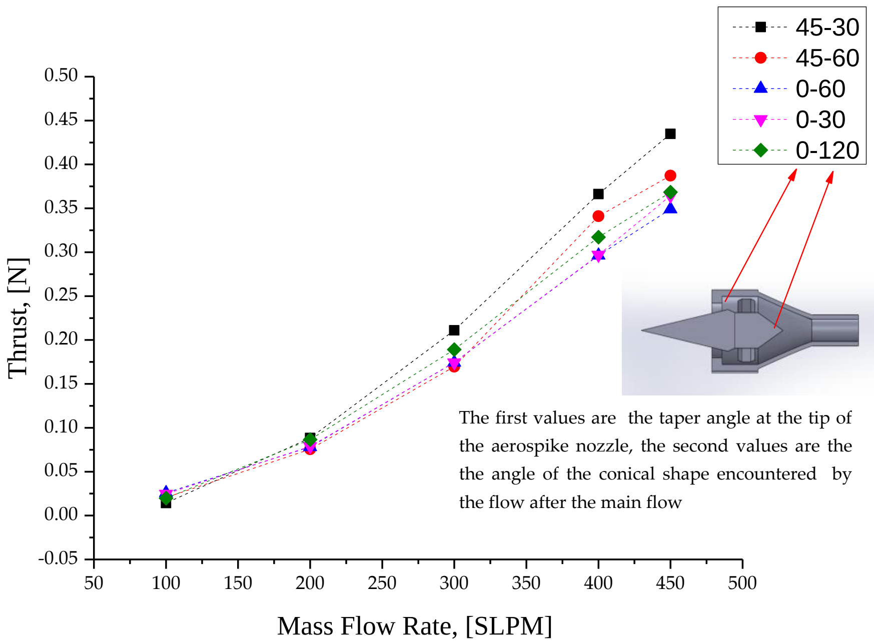

Figure 10. The comparison of the highest thrust values vs SLPM

In Figure 10, a line graph is presented comparing the thrust performance of the top 5 aerospike nozzle models that achieved the best thrust performance in the experiments. As seen in this graph, the aerospike nozzle model with a conical shape angle of 45° and a taper angle of 30° at the tip of the aerospike nozzle has the maximum thrust value for 200 SLPM, 300 SLPM, 400 SLPM, and 450 SLPM. However, it is observed that this model has the minimum thrust value for 100 SLPM. The model with a conical shape angle of 45° and a taper angle of 60° has the minimum thrust value for 200 SLPM and 300 SLPM values. Additionally, the model with a conical shape angle of 0° and a taper angle of 60° has the minimum thrust value for 400 SLPM and 450 SLPM values. It is noted that the models with the minimum value at low SLPM values become models with the maximum thrust value as the SLPM value increases.

In this study, apart from the high thrust values of the aerospike nozzle models, there was a correlation between two parameters investigated in this study. It has been observed that the taper angle at the tip of the aerospike nozzle and the conical shape angle encountered after the main flow tube are not independent of each other. In the above-mentioned graphs, as the taper angle at the tip of the aerospike nozzle changes, it has been determined that the most effective model may have a different conical shape angle encountered after the main flow tube. Finally, it was observed that as the amount of cold gas injected into the aerospike nozzle models were increased, the differences in thrust value data became more pronounced.

5. CONCLUSIONS

In this study, the existing literature on aerospike nozzles was reviewed and parameters that have not been extensively studied, such as the taper angle at the tip of the nozzle and the conical shape angle that occurs after the main flow tube, were investigated. Taper angle values of 0°, 15°, 30°, and 45° were selected for the taper angle at the tip of the aerospike nozzle. For the conical shape angle encountered after the main flow tube, values of 30°, 60°, 90°, 120°, and 150° were chosen. A total of 20 different models were designed and produced by using a 3D printer. The thrust values produced by 20 different aerospike nozzle models were measured and compared in cold gas testing. Based on these processes, the aerospike nozzle model that provided the highest thrust value was determined. Additionally, it was observed that the taper angle at the tip of the nozzle and the conical shape angle encountered after the main flow tube are not independent of each other according to the experimental results. Thus, the impact of these two parameters on the thrust value generated by the aerospike nozzle was observed.

DECLARATION OF ETHICAL STANDARDS

The author declares that the study complies with all applicable laws and regulations and meets ethical standards.

DECLARATION OF COMPETING INTEREST

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DATA AVAILABILITY

Research data has not been made available in a repository.

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