How Do Various Atmospheric Temperatures Affect the Structural Component of Rocket Nozzles?

Suhani Dondapati[1] and Kiara D. Saldanha[2]
Georgia Institute of Technology, Atlanta, Georgia, 30332, United States of America

[1] Dondapati, Suhani, Student, Daniel Guggenheim School of Aerospace Engineering, Georgia Tech, AIAA Student Member
[2] Saldanha, Kiara, Student, Daniel Guggenheim School of Aerospace Engineering, Georgia Tech, AIAA Student Member

I. Abstract

Current rocket designs utilize a rocket nozzle in the engine to perform critical design functions that support the steady increase of thrust of the rocket. When the structural integrity of the rocket nozzle is compromised due to external disturbances such as thermal stressors from the propulsion systems and mechanical stressors, the rocket experiences extreme failure. Rocket nozzles operate under extreme conditions throughout the phases of launch, which can create unpredictable system failures. In order to account for all possible risks in rocket nozzle designs, there are several methods to test and understand what can happen during launches. One way that this is tested is through the analysis of how different component materials of rocket nozzles have done when going through a launch. In this analysis it is seen that temperature gradients happen quite quickly during a launch (300K to 2000K). This sudden temperature change causes the friction component to exponentially rise which allows for stress and fatigue to occur within the rocket nozzle. This stress produces cracks within the nozzle which cause mechanical failure. To go about this, it is best for rocket nozzles to be built with partitioning in place so the sliding and contact surfaces of the launch will be dissipated throughout to reduce the expectancy of cracks. The structural component and the overall need for rocket nozzles is integral to rocket launches and knowing when rocket nozzles do best especially in different atmospheric conditions (launch phases) is extremely beneficial to the knowledge of aerospace.

II. Introduction

Rocket nozzles are integral parts to create thrust for a rocket to go into the air. However, they are also prone to thermal and structural stressors. It is important to understand how multi-nozzle rockets react to external factors, such as extremely high temperatures, exhaust plumes, and pressure compared to single-nozzle rockets. There are many considerations that are generally addressed to extensive Computational Fluid Dynamics models and numerical calculations. Researchers currently have methods to determine all the factors that need to be addressed regarding the integrity of rocket nozzles for successful launches.

III. External Stressors of Rocket Nozzles

A. Structural Components

According to Zhao and Bao, ulti-nozzle rockets are widely used in the rocket industry to provide enough thrust, however, the addition of nozzles onto a design can create faults in structural integrity. The structural component of a rocket nozzle and how they perform in multi-nozzle systems comparatively to single-nozzle systems is crucial to understanding what can be done to enhance the integrity of these systems. The structural components of the rocket nozzles release underexpanded exhaust plumes when launching. This pressure difference during launch attributes to some stressors to the nozzles that can lead to structure failure. Moreover, understanding the structural components, mechanical stressors, and pressure of the rocket nozzles will aid in understanding the stress on rocket nozzles due to high temperatures and thrust during launch [10].

Researchers use numerical and computational models to determine the pressure and stress put on rocket nozzles. With the rise of multi-nozzle rockets, it is important to understand how the exhaust plumes of each of the nozzles interact with each other. This is because interacting plumes may affect the nozzles in different ways that may need more design considerations in order to preserve the thrust and lift needed for a rocket to perform with precision and success. Another consideration for the structural integrity of rocket nozzles is where the stress is concentrated on the nozzle itself when the nozzles are used in launch.

Standard rocket nozzles have an ablation layer, heat insulating layer, and support layer that are made of different components. Therefore, it is also necessary to consider the stressors on each of the different materials of the nozzles and how they erode due to the pressures, exhaust, and sheer forces on the nozzles. In addition, graphite is usually found inside rocket nozzles as a structural component, due to its high temperature resistance, high thermal conductivity, and robustness. However it is still prone to cracking. All in all, these are important considerations for designing a functioning and successful multi-nozzle system for rockets [7].

1. Numerical Modeling and Analysis of Structural Component

According to Zhou and Bao, their calculations for the exhaust plumes in the computational analysis derived from three-dimensional compressible Navier-Stokes equations. These equations are primarily used for calculations at different altitudes and the aerodynamics of the exhaust plumes of a rocket nozzle. This is important to illustrate the numerical modeling in the computational analysis to extract physical points of stress and to illustrate with data which nozzle configurations have extra stressors [10].

2. Computational Analysis of Structural Component

According to Zhou and Bao, geometric models of the rocket nozzles were created using computational modelling with two, three, and four rocket nozzles in three separate configurations. In the computational modelling, the flow fields of the Mach contours of each of the three configurations of rocket nozzles were shown. It was found that the maximum Mach number was in the flow field of the two nozzle configuration, and the lowest Mach number was in the flow field with the four nozzle configuration. This indicates that the underexpanded exhaust plumes between nozzles interact with each other a lot as the number of nozzles increases, which leads to structural compromise [10].

Additionally, Sun et al. found that using a non-linear computational model illustrates points on the nozzle that have high stress from external factors better than traditional models. This was found by comparing the two computational models, the researchers found the non-linear models have higher and more prominent stress points compared to that of traditional models [8]. Raghavendra et al. also used Computational Fluid Dynamics to show the exhaust plumes that are released from the rocket nozzles. They can accurately show how the plumes react to each other and how to successfully configure the nozzles to reduce negative side effects. They created a De Laval nozzle for a hybrid rocket engine, which shows the plumes through ANSYS Testing [5].

B. Thermal Component

In multi-nozzle rockets the thermal component is extremely important to the launch and success of the rocket due to the impact it has on pressure and thrust on the rocket. During the rocket launch the nozzle is the first point of contact to the extreme temperature changes during the lift-off Sun et al. [8]. These changes between thousands of degrees of Celsius result in sizable temperature gradients. These temperature gradients arise not only from the temperature change from the immediate launch but also the fact of the matter that the temperature difference between the inner and outer surface of the nozzle is so great. With this difference coupled with exposure to exhaust gases and changing surrounding atmospheric conditions add to the temperature gradient. Causing such, impacts the nozzle to expand and gives the potential to crack. This is where the structural and thermal component become synchronous as inability to withstand such heat hampers the structural component of the nozzle Junhui et al. [3].

These components combine as the nozzle's composition truly determines how the nozzle reacts when put in such temperature dependent situations. The nozzle is typically made of graphite because of its ability to specifically withstand such high gradients of temperature while keeping the structure intact Sun et al. [8]. Still there is the error that the graphite can fail due to the thermal expansion leading to cracking Acharya et al [1]. Understanding this connection can give insight on how to reduce stress on the nozzle material and ensure longevity of rocket nozzle performance as seen with graphite Acharya et al [1] Typically rocket nozzles are used repeatedly so the action of being proactive can allow for further productivity of said nozzle instead of further complications.

3. Computational Analysis of Thermal Component

As being a common material used for rocket nozzles, graphite has been a common material used in studies about analyzing the structural component of rockets Acharya et al [1]. During analysis it is found that due to the extreme heat the nozzle tends to expand. This is through the launch and breaking the atmosphere as that is when temperatures reach and pass 3000 K which gives the exposure to extreme rapid temperature gradients Junhui et al. [3]. At these temperatures the thermal component of the rocket tends to fail by the material failing, specifically graphite with its protection of thermal conductivity and resistance to high temperature Acharya et al [1]. Thermal shock and erosion can take place leading to the cracking and fracturing of the nozzle despite what material is used, which is the most critical with the prosperity of the rocket. This is where the stress of these issues take place and cause the complications of said rockets.

These stresses are exacerbated by the supersonic flow of exhaust of gases Tian et al [9]. This is with the process of the combustion gases traveling through the nozzle, and increasing the temperature of the material throughout, which results in the extreme heat load or better known as the temperature gradient Nigar et al. [4]. This influx of heat is not constant through the nozzle so this is where it affects the multi stage rocket designs because if the temperature influx is in the one respective nozzle it will lead to transfer this heat to all the nozzles which is where uneven heating and thermal stress intensifies. This allows for the overall thermal load of temperatures to be amplified Sun et al. [7].

To avoid this it is researched and the best solution with the most suitable, productive outcomes is portioning the throat configurations so that the stresses from the heat can be mitigated from transferring through each of the nozzles. It permits thermal expansion to be reduced but does not give the full satisfaction of overcoming cracking Sun et al. [7]. In the case of severe conditions the best use of time would be to optimize the sectioning between segments to avoid nozzle failure during and post launch. Numerical Simulations and advanced finite element modeling (XFEM) are employed to scrutinize the stresses and predict the event of these cracks to partake. With this development it gives valuable insight on how we can take the issues that come from the thermal influx that happens during rocket launches and alleviate the likelihood of them happening and give influence to better thermal performance and durability for said nozzle Harikrishnan et al [2].

4. Solution Analysis of Thermal Component

Hybrid rocket motors give instances of rocket nozzles that are subject to extreme mechanical and thermal stresses. These stresses in part when acted upon affect the performance and durability for the rocket nozzles. Rocket nozzles try to mitigate these stresses by choosing a material that is able to overcome these stresses with temperature and corrosion but not lead to further issues Sun et al. [8]. The main stresses include erosion and cracking which comes from the temperature gradients (1000K - 3000K). The erosion specifically from the thermochemical process of carbon and tungsten reactions with oxidizing species is like H2O and CO2 which degrades the material causing difficulty in future flights found from a study by Solomon & AlemayehuAdde [6]. Moreover, Zhou and Bao have studied that multiple interface nozzle designs hope to prevent stress by alleviating the strength of the material upon the nozzle to reduce the impact of erosion by improving ablation resistance and thermal protection Zhou et al. [10]. This was found through a carbon ceramic throat cap and a copper infiltrated tungsten insert.

IV. Conclusion

With the research conducted it is easily found that the main complication at hand with rocket launches is that extreme atmospheric conditions lead to great thermal influxes in the nozzle components of rocket nozzles. This in part impairs the thermal component of the nozzle where it lacks the ability to succumb to erosion, cracking, and expansion Zhou et al. [10]. These drawbacks give the opportunity for the structural integrity of the nozzle to be impaired which can diminish the quality and longevity of the performance of the respective rocket Nigar et al. [4]. The ability to prevent this comes from the process of choosing the right material that has protection and resistance to high temperatures but also can mitigate the vibrations and reactions leading to erosion and cracking Sun et al. [8]. This also combined with giving a partitioning and interface option to the nozzle design allows for the temperature influx to fully overpower the nozzle which will allow for the cooling process to be alleviated Harikrishnan et al. [2]. These findings can help to give insight to future launches and designs for rocket nozzles as it is one of the most critical and integral parts of the rocket to grant the further and expansion of aerospace knowledge.

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