High-Speed Flight

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Abstract

This research paper investigates the performance characteristics and material considerations of a bell-shaped nozzle designed for high-speed aerospace applications. The nozzle operates under specific conditions, including a stagnation temperature of 1000 K, stagnation pressure of 505 kPa, and a pressure ratio of 0.0939. The bell nozzle geometry features a throat diameter of 1 cm, exit diameter of 2 cm, convergent length of 2 cm, and divergent length of 6 cm, with an average divergent angle of 15 degrees. The study evaluates the nozzle's performance at an altitude of 48,000 feet and a flight speed of 3900 meters per second. The temperature distributions, Mach number effects, pressure ratios, and material properties for different sections of the nozzle are analyzed to optimize its structural integrity and efficiency.

1. Introduction

Nozzle design is critical in aerospace propulsion systems, especially for applications requiring high performance and efficiency in extreme conditions. Bell nozzles, also known as contoured nozzles, are designed to provide smooth expansion of exhaust gasses, minimizing flow separation and managing expansion waves to achieve near-perfect expansion (RAO). The objective of this research is to evaluate a bell-shaped nozzle's performance at high altitude and high-speed conditions and assess the effects of temperature, pressure, Mach number, and material selection on the nozzle's durability and efficiency for optimization purposes.

At an altitude of 48,000 feet, where the ambient pressure is significantly lower than at sea level, achieving maximum thrust efficiency requires the exit pressure to match the ambient pressure (Gatech). The altitude of 48,000 feet is the maximum altitude at which the nozzle can operate, which is the mean altitude for most supersonic aircrafts. This study's relevance lies in optimizing nozzle performance for conditions encountered in high-speed aerospace vehicles, ensuring maximum efficiency and structural integrity under extreme thermal and mechanical stresses.

1.1 Problem Statement

For a nozzle operating at 48,000 feet altitude, the nozzle geometry and materials must withstand high temperatures and pressures. The pressure ratio of 0.0939, corresponding to the given stagnation pressure of 505 kPa and ambient conditions at high altitudes, is a critical parameter influencing nozzle performance.

1.2 Objectives

This paper aims to:

- Assess the performance of the bell-shaped nozzle under specific conditions.
- Analyze temperature distributions and material choices for different sections of the nozzle based on centerline temperature and Mach number.

- Evaluate the effect of key parameters such as area ratio, pressure ratio, and Mach number on nozzle efficiency.

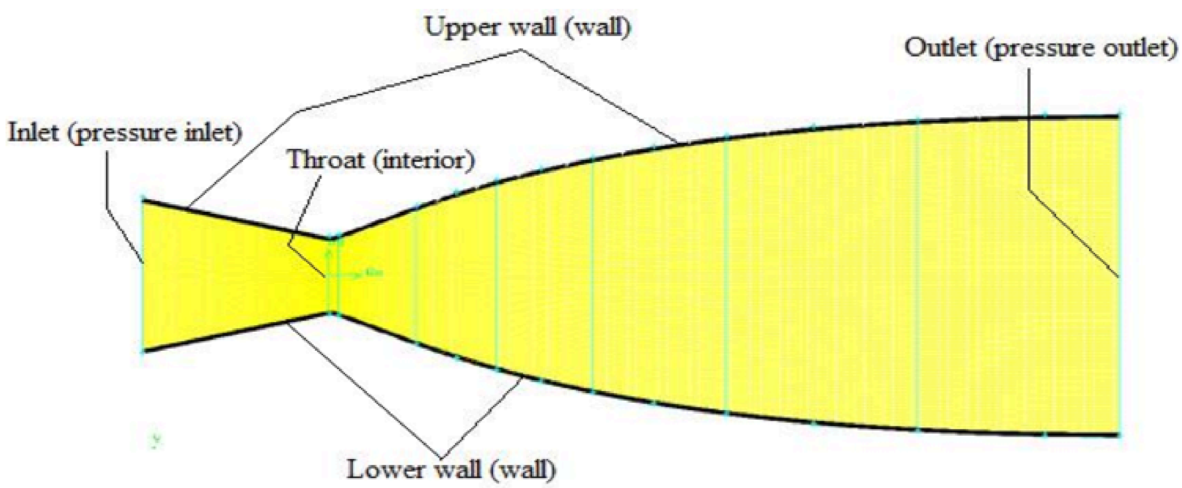
2. Nozzle Design Parameters

2.1 Geometry

The bell-shaped nozzle in this study has the following geometric properties:

- **Nozzle throat diameter**: 1 cm
- **Nozzle exit diameter**: 2 cm
- **Convergent length**: 2 cm
- **Divergent length**: 6 cm
- **Average divergent angle**: 15 degrees

Figure 1: Nozzle Design



The convergent-divergent design ensures smooth flow transition, with the bell contour optimizing the exhaust flow to avoid flow separation while maintaining efficiency at the exit (Thomas).

2.2 Stagnation Conditions

The initial stagnation temperature and pressure are given as:

- **Stagnation temperature**: 1000 K
- **Stagnation pressure**: 505 kPa

These conditions are critical for calculating the nozzle's expansion process and the final exit properties, such as pressure and Mach number. These are also typical exit conditions for a combustor.

2.3 Pressure and Area Ratios

The pressure ratio is defined as the ratio of exit pressure to stagnation pressure. At high altitudes, the pressure ratio plays a vital role in determining nozzle performance through thrust generation and nozzle expansion (NASA). The pressure ratio is defined as

$$Pressure\ Ratio\ =\ \frac{\rho_e}{\rho_0}$$

the temperature ratio is defined as

$$Temperature\ Ratio\ =\ \frac{T}{T_0}$$

where T is the static temperature while T_0 is the stagnation temperature. while the area ratio for the nozzle is determined from the exit and throat areas:

$$Area\ ratio\ =\ \frac{A_e}{A_t} = \frac{\pi d_e^{\ 2}}{\pi d_t^{\ 2}}$$

Here, the area ratio is A_e/A_t = 4.

This ratio affects the Mach number at the exit and the efficiency of the expansion process (Hall).

3. Performance Analysis

3.1 Mach Number and Flow Properties

The Mach number at different sections of the nozzle is crucial for understanding the nozzle's performance. For a bell-shaped nozzle, the flow accelerates from subsonic in the convergent section to supersonic in the divergent section. Based on the given data, we analyze two cases:

Case 1: Mach 2

At Mach 2, the temperature and pressure ratios are:

T/T_0 = 0.5087, p/p_0 = 0.0939, Static Temperature = 508.77 K

Given a stagnation temperature of 1000 K, the static temperature is:

$T = T_0 \times (T/T_0) = 1000 \times 0.5087 = 508.77$ K

This temperature corresponds to the material constraints, and stainless steel can be used due to its high-temperature resistance.

Case 2: Mach 1.5

At Mach 1.5, the temperature and pressure ratios are:

T/T_0 = 0.5926, p/p_0 =0.1602, Static Temperature = 592.57 K

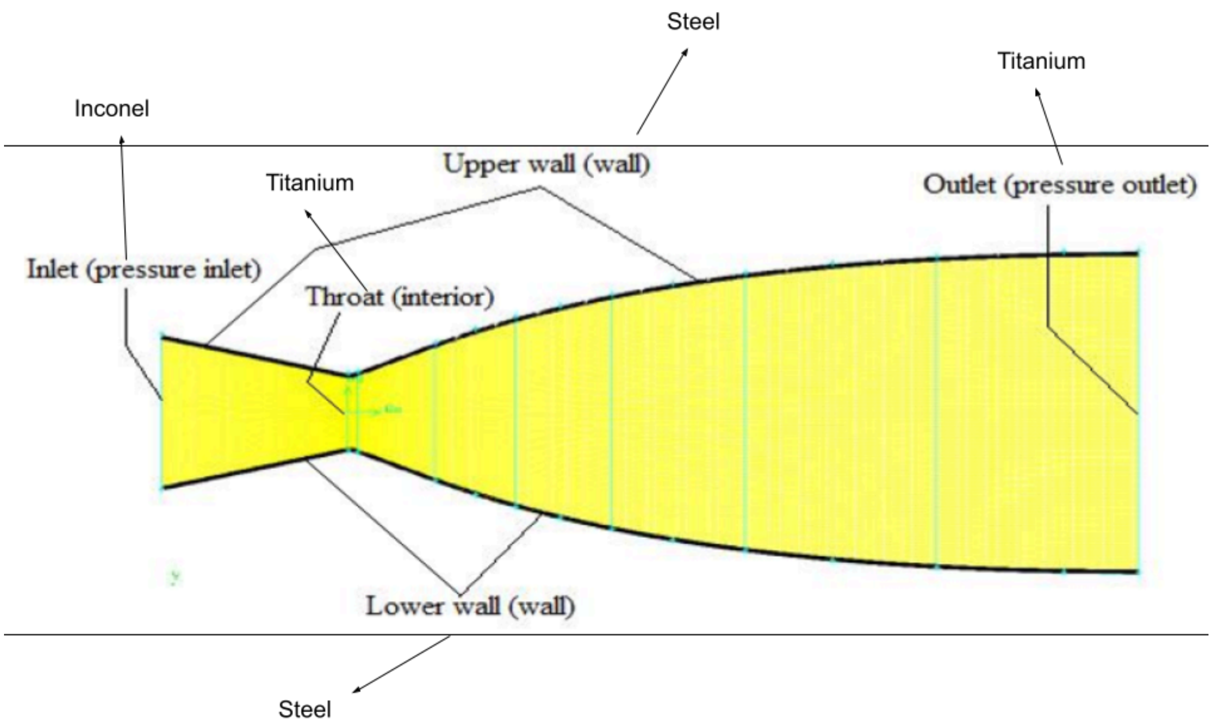
This temperature increase requires the use of materials like stainless steel or titanium for the nozzle structure.

3.2 Material Selection

The nozzle experiences varying temperatures along its length due to the high-speed flow. Proper material selection is critical to ensure structural integrity under thermal and mechanical stress (Wessels). The materials for different sections of the nozzle are selected based on their thermal properties and maximum operating temperatures:

- **Titanium** (TiAl): Used for temperatures up to 556 K for Mach 2.0 (AMT).
- **Stainless Steel** (304): Used for temperatures up to 690 K for Mach 1.5 (AZoM).
- **Inconel** (625): Used for temperatures above 800 K, such as at Mach 1.25 (Specialmetals).

Figure 2: Material Selection in Nozzle



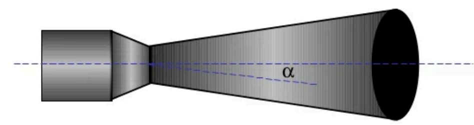
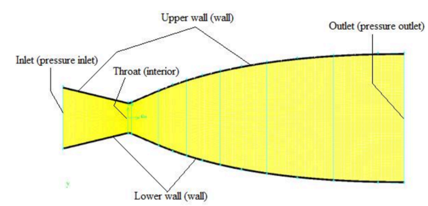
These materials provide the necessary strength and heat resistance required for sustained operation at high speeds and altitudes. Different materials are selected on several factors such as cost. Titanium is used for the outlet and the throat due to having a high strength-weight ratio. Steel is used for upper and lower wall due to its balance of strength and cost effectiveness. Inconel is used in the inlet due to its high heat capacity.

4. Results and Discussion

4.1 Nozzle Efficiency

The bell-shaped nozzle efficiently manages the expansion of gasses, with the exit pressure matching the ambient pressure at high altitudes. This design minimizes shock losses and avoids flow separation, which would otherwise reduce thrust efficiency (USU). The bell shape also reduces weight and size compared to traditional conical nozzles, making it an ideal choice for high-performance aerospace applications (Thomas).

Table 1: Comparison between Nozzle Designs

Conical Nozzle	
Bell Nozzle	

4.2 Thrust Maximization

Since the exit pressure equals the ambient pressure, the thrust produced is maximized, leading to optimal performance at 48,000 feet. The curved design of the bell nozzle ensures that expansion waves are properly managed, preventing over-expansion or under-expansion (Polezhaev and Chircov). The nozzle generates around 205 kN of thrust, which is based off of the mass flow rate and the velocity.

5. Conclusion

The findings of this research are reasonable because they align with established principles of compressible flow, nozzle dynamics, and material science. The nozzle's design, featuring a smooth bell shape, ensures efficient thermal energy conversion into kinetic energy, as expected for high-speed aerospace applications. The calculated temperature and pressure ratios follow isentropic flow relationships, validating the predicted performance along different nozzle sections. The matching of exit pressure to ambient pressure at 48,000 feet optimizes thrust, consistent with the principle that nozzle efficiency is highest when these pressures are equal.

Material choices are also well-founded, with titanium, stainless steel, and Inconel selected based on their thermal resistance and mechanical properties suitable for the corresponding temperature regions. This approach aligns with industry practices for handling high-temperature environments in aerospace propulsion, further supporting the reasonableness of the conclusions drawn from the data.

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