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A Comprehensive Review of Dual-Bell Nozzles

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Abstract

A dual-bell nozzle is an altitude-compensating nozzle that is an essential part of an engine, especially one designed to convert the high-temperature, high-pressure combustion gases efficiently into high-velocity exhaust to produce thrust in a rocket. Various studies have been conducted on nozzles, but a comprehensive review of the dual bell nozzle has not been conducted. It is proposed to conduct a review of the dual-bell nozzle. The research reviews highlighted the design, performance, experimental, analytical, and application studies conducted on the dual-bell nozzle. The study evaluates geometric sensitivity, transition behavior complexity, side-load challenge, and advanced thermo-structural materials, as these themes are of significant importance for the study, development, design, and manufacturing of dual-bell nozzle vehicles. It represents a well-validated concept with higher performance for next-generation aerospace vehicles.

Keywords: Altitude adaptive nozzle; Dual bell nozzle; Performance; Rocket

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Introduction

The dual-bell nozzle represents a significant advancement in propulsion systems and delivers adaptive performance across a wide range of altitudes. It operates in two distinct modes—sea-level and altitude—making it efficient for both low- and high-altitude conditions. The concept of the dual-bell nozzle was introduced by Cowles and Foster in 1949, and Rocketdyne filed a patent for it in 1960 (Nurnberger et al., 2010). The dual-bell nozzle consists of two contours between the exit and throat, with a baseline contour partitioned by an inflection wall from the extension contour (Stark et al., 2016). The dual-bell nozzle consists of a convergent section, a throat, and a divergent section. Two circles with different radii define the throat and convergent parts, and the divergent part comprises the base or primary nozzle and the extension, which is the secondary nozzle, starting with a higher radius than the base nozzle (Nasuti et al., 2002).

After that, the concept was verified through experiments and analysis of the dual-bell nozzle (Hagemann et al., 2002). They emphasized its potential to improve efficiency and performance during rocket ascent. This foundational research laid the groundwork for subsequent studies by

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outlining and optimizing the nozzle. Horn and Fisher were among the forerunners in investigating dual-bell nozzles. For their advancement, they presented an initial framework that was further developed into a basis for compensatory improvements in theoretical and experimental approaches. They evaluated the design's feasibility and the operational advantages. The studies focused on the simple design of dual-bell incorporation into other altitude-compensating alternatives and highlighted the dual-bell nozzle as a practical solution for aerospace applications.

The contour design procedure for the dual-bell nozzle has evolved and been used to analyze the feasibility of nano-satellite or sounding rocket launchers. The contour design supports the effective development of the dual-bell nozzle and demonstrates its applicability to nano-satellite development (Davis et al., 2015).

Some of the analytical investigations that were conducted on the design, optimization, and performance evaluation of the dual-bell nozzle's geometry and contour are summarized in the following table:

Table 1. *Numerical investigations were conducted on the dual bell nozzle (Authors).*

Investigators	Studies	Focus of investigations
(Davis et al., 2015)	Numerical	Outlining the procedure of dual bell nozzle contour
(Toufik et al., 2016)	Numerical	Designing of dual bell nozzle
(Kbab et al., 2017)	Numerical	Designing the profile of dual bell nozzle
(Kumar et al., 2019)	Numerical	Optimizing the nozzle by dual bell technique
(Navenprabu et al., 2022)	Numerical	Unsteady thermal modeling and regenerative cooling of thrust chamber in semi-cryogenic engine
(Chada & Akella, 2023)	Numerical	Prediction performance of solid rocket motor by utilizing CFD
(Modak et al., 2023)	Numerical	Designing and optimizing performance

As computational fluid dynamics (CFD) capabilities improved over time, investigators' activities focused on flow analysis of the dual-bell nozzle in 1990. Practical studies and confirmatory tests were conducted at Rocketdyne and in Europe by the Future European Space Transportation Investigation Program (FESTIP) at the European Space Agency (ESA) (Horn & Fisher, 1994). They investigated four contour combinations to find an extension contour that would provide higher altitude than two baseline contours and the best flow transition.

Horn and Fisher found that the performance of the dual-bell nozzle is lower than the theoretical value due to losses in aspiration in the low-elevation mode and a non-optimized contour in the high-altitude mode (Horn & Fisher, 1994). They found that the dual-bell nozzle could produce enough thrust to carry an extra 12.1% payload compared to a conventional convergent-divergent (CD) nozzle with the same expansion ratio. Verma et al. (2015) indicated that the first numerical study was performed by Goel and Jensen in 1995. After that, numerous numerical and experimental investigations of the dual-bell nozzle were conducted in Europe and the USA.

The dual-bell nozzle consists of three geometric features: the contour of the inner base nozzle, the contour of the outer extension, and an inflection wall between the two contours. The contour inflection connects the first part of the nozzle to the extension inflection part and prepares two stable operation modes. These modes of operation are as follows: At low elevation, the flow separates from the inflection due to the high ambient pressure and is controlled symmetrically, limiting the production of high-amplitude side loads. This inflection, or point of separation, moves to the end of the extension as the environmental pressure decreases when the rocket enters high-altitude mode. This extension becomes fully developed and improves performance at high elevation by providing a large area ratio (Hagemann et al., 1997).

The base nozzle, or first contour, operates at low altitude, while the extended nozzle assists operation at high altitude. This is used to avoid over- and under-expansion in the bell nozzle (Navenprabu et al., 2022).

At higher altitudes, the flow is attached to the nozzle wall due to the higher expansion ratio, so performance in vacuum improves (Martelli et al., 2007). Simplicity in design and control of flow separation are the main advantages; lower weight, better performance, and easier cooling are additional benefits of the dual-bell nozzle (Hagemann, 1998). An investigation was conducted numerically and experimentally to analyze and evaluate the distribution of heat flux on the dual-bell nozzle (Génin, 2013).

The profile of the dual-bell nozzle was designed, and the flow behavior was analyzed using the method of characteristics. The heat flux value in high-elevation mode increases by about 40%, but during the transition at sea level, the inflection of flow separation increases in a controlled, symmetrical way, indicating that flow separates at the contour inflection under sea level conditions (Kbab et al., 2017). Thrust increased thanks to a smaller area ratio, and side load generation continued to decrease. Nozzle pressure ratio (NPR) increases due to a decrease in ambient pressure during flight. When the transition NPR is reached at a particular altitude, the separation point leaves the contour inflection and moves rapidly forward to the nozzle exit (Génin et al., 2013).

A computational fluid dynamics study was performed to forecast the performance of a solid rocket motor in a pintle–dual-bell nozzle. After the simulation, they found that the specific impulse of the solid rocket motor varies with altitude due to changes in ambient pressure. They highlighted that the efficiency and thrust of the rocket increase with increasing specific impulse (Chada & Akella, 2023).

Flow simulation in the dual-bell nozzle was performed using the method of characteristics to create and account for the base nozzle profile. On the other hand, the profile of the second curve was determined to generate constant pressure. As an alternative to the nozzle profile, Foster and Cowles (1949) suggested a nozzle with an inflection profile. This study supports high side loads (Kbab et al., 2016).

Analysis of the effect and testing of various turbulence models on pressure gradient behavior during flow transition were performed (Schneider & Génin, 2016), and they provided improved results for stress turbulence from the Reynolds to the Spalart–Allmaras models.

The idea of the position and shape of the separation front was developed by analyzing the shock in the region of the contour inflection, which indicates good agreement between numerical and experimental results in the sea-level mode. At higher values of NPR, the calculated position of separation is located more upstream than the experimental measurement (Génin & Stark, 2011).

Experimental research was conducted to study the effect of Reynolds number on the transition behavior of a dual-bell nozzle, with analysis and testing performed in a high-elevation simulation chamber. Experimental results indicate that the Reynolds number significantly affects the characteristics of dual-bell nozzles, validating performance behavior under simulated high-altitude operating conditions (Verma et al., 2013). In another paper, they conducted an experimental investigation of the dual-bell nozzle to examine the dependence of transition behavior on the environmental pressure inflection. The study results demonstrate that transition behavior in the dual-bell nozzle is strongly related to inflection of environmental pressure, which affects the stability and overall performance of the nozzle (Verma et al., 2014). Another experimental investigation has been conducted on the feasibility of dual-bell nozzles, showing that cold tests exhibit greater steadiness between the two modes of operation at the transition pressure (Kimura et al., 2009).

Some of the analytical investigations that were conducted on flow behavior, thermal analysis, and evaluation of the dual-bell nozzle are summarized in the following table:

***Table 2**. Numerical investigations conducted on dual bell nozzle (Authors).*

Investigators	**Studies nature**	**Focus of investigations**
(Génin et al., 2012)	Numerical	Behavior of flow in a dual bell nozzle
(Stark et al., 2012)	Numerical	CFD analysis
(Genin et al., 2013)	Numerical	Optimizing behavior of transitional through variation
(Schneider & Génin, 2016)	Numerical	Different turbulence models and gradients in feeding pressure affect the transition behavior of dual bell nozzle flow.
(Akib et al., 2019)	Numerical	Critical Assessment of elevation shows it can be adjusted using computational fluid dynamics.
(Ferrero et al., 2022)	Numerical	Parametric investigation analysis of transition fluidic control
(Kbab et al., 2023)	Numerical	Supersonic Flows
(Shankar. et al., 2015)	Numerical	Thermal analysis by APDL Code and structural evaluation by ANSYS

Sneak transition refers to the partial and gradual shift of the flow separation point from sea level mode (or first bell) forward to high altitude mode (or second bell), instead of a sharp or sudden flow transition (Verma et al., 2015).

Unstable flow conditions that occurred during sneak transition or in real conditions were examined by conducting cold-gas tests on a subscale dual-bell nozzle at sea-level conditions (Verma et al., 2015). The results of the investigation indicate that the flow is highly unsteady and is the source of significant side loading.

As far as bell-contour design is concerned, the main drawback of a conventional nozzle is decreased performance at higher elevations. Some loss occurs in the nozzle thrust, known as "separation of combustion gases." Maximum geometrical efficiency requires a long nozzle, but this also increases drag (Kumar et al., 2019). The Rao method is an analytical technique used for designing the contour of a bell rocket nozzle to achieve high efficiency with reduced weight and length (Rao, 1958).

A dual-bell nozzle can be outlined conventionally by using the method of characteristics, the inverse method of characteristics, and Rao's truncated nozzle contour method (Navenprabu et al., 2022). The converging section with a given diameter is an arc related to the throat radius, and the throat radius is determined by applying chemical equilibrium to NASA's method, which is used to produce rocket engines with the desired output thrust. Throat radius, convergent section, first contour, second bell contour, length of nozzle, and exit diameter all have distinct relationships with each other. Dual-bell nozzle parameter values are determined by Rao's contour design and equations that provide the following parameters for designing a dual-bell nozzle (Navenprabu et al., 2022).

Table 3. *Rao's equation (Navenprabu et al., 2022)*

Throat Radius, Rt	**Lb/Rt**	**Ltot/Rt**	**Area Ratio**	**Inflection angle deg**	**Rb calculated**	**Re calculated**
10mm	6.2	14.5	16	21^0	33.61mm	52.05mm

Geometrical optimization was conducted on a dual-bell nozzle, and the result indicates that the Rao method and geometrical optimization are closely related (Modak et al., 2023).

At sea level and at altitude, specific impulse and thrust were calculated for each contour, along with the NPR corresponding to the transition altitude, and these were used to evaluate the payload mass results from the two methods. The results demonstrate contours that depend on specific impulse and thrust variation across altitude and sea level, with a transition NPR that predicts payload capacity precisely (Shankar et al., 2015).

From a material selection perspective, the alloy of copper with silicon, zirconium, and silver is used for the combustion chambers and inner wall. It does not produce oxide in fuel-rich, non-corrosive gaseous mixtures, so it is reliable at very high operational temperatures and has good thermal conductivity. These alloys provide structural integrity to the combustion chamber along its wall. Better structural integrity is achieved with an alloy of silver-zirconium-copper (with less silver), but it has lower thermal conductivity than oxygen-free copper in this alloy. Stainless steel is used for the outer casing or jacket (Navenprabu et al., 2022).

Inconel alloys, such as Inconel 625 or Inconel 718, are used under thermal load in dual-bell nozzle structural parts and nozzle walls due to their excellent corrosion resistance, high-temperature strength, and weldability (NASA, 2009).

Carbon-carbon composites are used in nozzle throat inserts and thermal protection systems due to their resistance to high temperature and low thermal expansion (Glass, 2008). Because of their extremely high strength and high melting points, refractory metals such as molybdenum, tantalum, and niobium are utilized in nozzle throats and high heat zones (Sutton & Biblarz, 2017).

Their recommendations also indicate that stainless steel is utilized in nozzle support jackets, base flange connections, low-budget tests, mounting brackets, and initial prototypes.

On the other hand, most stainless steels, such as stainless steel 304 or stainless steel 316, have a number of limitations: they cannot withstand extreme thermal shock and oxidation, and they lose their strength at temperatures above ~600°C. Due to their high thermal conductivity, copper alloys such as CuCrZr are used in regenerative cooling systems (Hill & Peterson, 1992). A study conducted on the material structure of the dual-bell nozzle is summarized in the following table:

Table 4. *Used materials in dual bell nozzle (Kumar et al., 2019)*

Materials	**Aluminum alloys, high-strength steels, fiberglass resin composites**	**Iron, nickel, cobalt, iron-nickel, iron-nickel-cobalt-chromium base alloys.**	**Molybdenum, tantalum, columbium, tungsten.**	**Graphite, pyrolytic graphite.**
Sustained Temperature	300°F	500 °F	1,900 °F	4,500 °F

A layer of carbon-carbon composites has the ability to act as both a structural material and an ablative layer. In solid rocket nozzles, they have replaced existing standard materials such as silica cloth, phenolic or carbon, which were used for ablative liners and structural shells. They claim that new nozzle design concepts permitted by carbon-carbon composites can be achieved with only one material, serving as both the structural joint and ablative liner. Also, they highlighted that this single material design and new nozzle concept reduce the nozzle's volume, weight, and envelope, resulting in increased missile thrust performance (Shankar et al., 2015).

The higher temperatures in the nozzle cause the structure to be unable to sustain high stress and erosion. To address these challenges, composite materials were introduced, as illustrated in Figure 1 below (Numberger et al., 2010).

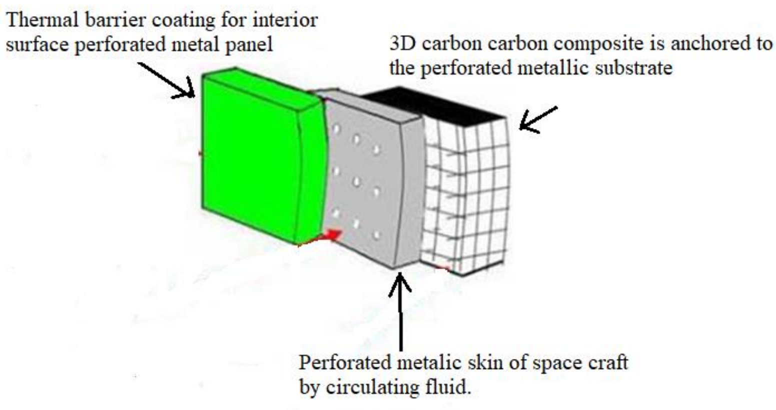

Figure 1. *Layers of temperature protective system (Nu¨rnberger et al., 2010)*

Unstable thermal modeling of altitude-adjustable dual-bell nozzles with regenerative cooling of the thrust chamber in semi-cryogenic engines was performed. Their investigation found that a lower coolant chamber number identified the inner wall temperature across the channel with minimum possible pressure loss, and they found that the coolant decreased the temperature of nozzle materials below the melting point (Navenprabu et al., 2022).

From the cooling film perspective, some research has been conducted under hot and cold conditions. Considerable points are the impact of the cooling film and the influence of outer flow on the transitional flow behavior.

Characteristic studies of dual-bell nozzles using Mach computational fluid dynamics (CFD) were conducted to study the behavior of fluid parameters such as Mach number, pressure, temperature, and velocity vectors under-expanded conditions (Akib et al., 2017). In another study, they examined behaviors of fluid parameters like pressure, temperature, Mach number, and velocity vectors (Akib et al., 2019). The results of their study are illustrated in the following figure:

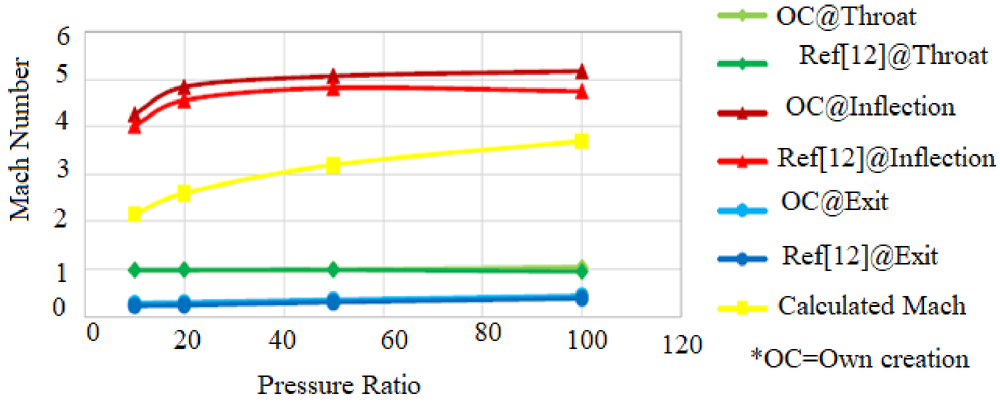

Figure 2: *Relation of Mach numbers and pressure in the dual-bell nozzle (Akib et al., 2019).*

The dual-bell nozzle has overall 90% better performance compared to the conventional bell-shaped nozzle. At low altitudes, the efficiency is much higher thanks to restricting the expansion of exhaust gases by ambient atmospheric pressure. It is claimed that a vehicle using a dual-bell nozzle at low altitudes also saves 25–30% more fuel compared to a conventional nozzle (Kumar et al., 2019).

From the viewpoint of contour optimization of the dual-bell nozzle, several studies have focused on optimizing the dual-bell nozzle contour to improve performance. Experimental exploration was performed to analyze the transitional behavior of dual-bell nozzles and emphasized the significance of contour optimization (Génin & Stark, 2007). Later, they further refined these insights by studying the behavior of transition using advanced computational techniques (Génin & Stark, 2013). Their findings highlighted that optimized contour designs reduce flow separation and transition losses of the nozzle significantly.

By using computational fluid dynamics (CFD) to optimize nozzle designs through the dual-bell technique, improvements in thrust efficiency and reduced structural stress during transitions were highlighted (Kumar et al., 2019). Similarly, another study integrated performance optimization methods for increasing design efficiency and provided a comprehensive framework for future studies (Modak et al., 2023).

A parametric study was performed on fluidic control in dual-bell nozzles to examine how fluidic mechanisms influence transition behavior (Ferrero et al., 2022). Their investigation pointed out precisely the significance of fluidic control for achieving seamless mode transitions. An exploration was conducted on the influence of boundary layer states on nozzle transition. Their results emphasize the role of surface conditions in determining nozzle performance (Barklage & Radespiel, 2018). The performance optimization of dual-bell nozzles was investigated as a case study in the Ariane 5 rocket (Stark et al., 2016). Their investigation highlighted that dual-bell nozzle extensions could improve performance considerably by adjusting for variable altitudes. The researchers focused on achieving a smooth transition between sea-level and vacuum operations.

From a design and performance evaluation perspective, the performance features of dual-bell nozzles have been analyzed extensively to ensure operational reliability. The elevation adjustability of dual-bell nozzles was examined (Stark et al., 2012). Their study focused on performance across different atmospheric conditions. A study on the synthesis of thermo-structural behavior revealed that during transitions, the thermal stresses experienced influenced material selection and nozzle longevity (Shankar et al., 2015).

An investigation focused on the evaluation of the design and performance of dual-bell nozzles recommended innovative configurations for improving adaptability and reinforced the significance of experimental validation alongside numerical studies (Kbab et al., 2017). Another study explored design and performance metrics of dual-bell nozzles, providing important insights into their application in aerospace engineering (Toufik et al., 2016). A CFD simulation was carried out for forecasting solid rocket motor performance in pintle–dual-bell nozzles, and its results illustrated the dual-bell design's versatility in different propulsion systems (Chada & Akella, 2023). Génin and Stark (2011) examined hot flow in dual-bell nozzles, providing experimental data for validating computational models and informing design enhancement. The conducted investigation highlighted the operational reliability of dual-bell nozzles under thermal and mechanical stresses. More recently, an investigation was conducted on supersonic flows in innovative nozzle designs, including dual-bell nozzles (Kbab et al., 2023). This study emphasized the potential for further improvement in nozzle efficiency and adjustability, reinforcing the dual-bell nozzle's viability as a next-generation propulsion solution.

Navenprabu et al. introduced a thermal modeling approach for dual-bell nozzles with regenerative cooling in semi-cryogenic engines. Their work bridged the gap between thermal management and structural integrity, emphasizing the importance of temperature distributions on nozzle performance (Navenprabu et al., 2022). From the viewpoint of unsteady flow conditions during transition, a study was performed on unstable flow dynamics during the "sneak" transition phase of dual-bell nozzles. The research demonstrated that this phase involves intricate fluid interactions that impact nozzle performance and structural integrity (Verma et al., 2015).

Martelli et al. (2007) utilized improved numerical simulations and experimental validation to provide details of the underlying mechanisms that manage the transition. Experimental studies analyzed flow transition phenomena in dual-bell nozzles. Their work involved wind tunnel experiments and high-speed flow visualizations for characterizing transition behavior under variable operating conditions. The study underscored the significance of nozzle geometry and transition zone design in influencing performance. Their investigation emphasized the need for precision in controlling transition phases to avoid performance losses or structural instabilities. A parametric analysis was performed to study flow behavior in dual-bell nozzles. By varying geometric parameters, they provided a deeper understanding of the interaction between design choices and operational efficiency, enabling more targeted optimization strategies (Martelli et al., 2007).

An investigation was performed on flow transition behavior under cold flow conditions. These numerical studies offered insights into shock-wave dynamics and separation behavior, which are critical for predicting operational stability (Schneider & Génin, 2016). Detailed CFD analysis of dual-bell nozzle features demonstrated the capability of computational methods for forecasting performance metrics accurately. A subsequent study by the same authors critically assessed the elevation adjustment of dual-bell nozzles and provided valuable data to optimize nozzle geometries for different flight phases (Akib et al., 2019). The results emphasized the need for advanced fluidic control mechanisms. Future research could also explore the use of novel materials and manufacturing techniques for enhancing durability and performance (Ferrero et al., 2022).

Experimental studies have played a significant role in validating the theoretical predictions of the dual-bell nozzle. Coupled experimental and computational investigations were conducted to synthesize dual-bell nozzle performance under variable conditions (Davis et al., 2015). Their work provided insights into flow dynamics and transition mechanisms, which are significant for operational reliability.

Génin and Stark (2012) conducted experimental studies to validate numerical models. Their investigation results confirmed the robustness of dual-bell nozzles in transitioning between modes while maintaining structural integrity. These works underscore the necessity of integrating experimental data with numerical simulations for comprehensive nozzle evaluation.

Nasuti et al. (2002) conducted numerical simulations to explore the transition mechanism between operational modes in dual-bell nozzles. They identified that critical parameters affect flow separation and reattachment, contributing to the optimization of nozzle geometry for smoother transitions.

A comprehensive experimental and numerical study was performed on heat flux in dual-bell nozzles, providing insights into the thermal characteristics and flow dynamics within these nozzles (Génin et al., 2013). Similarly, Génin et al. (2013) explored dual-bell nozzle flow through experimental setups and numerical simulations, emphasizing the transition between operating modes and the associated fluid dynamic phenomena. Further experimental studies were conducted on the effects of ambient pressure fluctuations on dual-bell transition behavior (Verma et al., 2014). Their research highlighted the sensitivity of nozzle performance to external pressure variations, which is crucial for real-world applications in varying atmospheric conditions.

Side-load phenomena in dual-bell nozzles were investigated, identifying critical factors influencing nozzle performance during mode transitions (Génin & Stark, 2010). Their findings underscore the importance of phenomenological understanding in optimizing dual-bell nozzle designs.

Verma et al. (2013) examined the influence of Reynolds number on transition behavior, revealing how variations in flow properties affect nozzle performance under different conditions.

Experimental and numerical investigations were performed for optimizing transition behavior (Génin, 2013). Numerical and experimental examinations have explored the different aerodynamic characteristics of dual-bell nozzles (Hagemann et al., 2002). Different features of nozzle extension and wall inflection were investigated with a focus on transition behavior as related to types of nozzle extension (Frey & Hagemann, 1999). The flow behavior of the dual-bell nozzle was computationally analyzed for two operations—changing NPR in transition from one mode to another (Génin et al., 2012).

There are various investigations that have been conducted experimentally and numerically in a coupled manner on performance, transition behavior, heat flux, aerodynamics, and ambient pressure in dual-bell rocket nozzles. Some of them are summarized in the following table:

Table 5. *Experimental and numerical investigations that were conducted on dual bell nozzles (Authors)*

Investigators	Studies	Focus of investigations
(Horn & Fisher, 1994)	Experimental	Performance features of dual bell nozzles
(Frey & Hagemann, 1999)	Experimental &Analytical	Transition behavior relationship of the type of nozzle on extension
(Hagemann et al., 2002)	Analytical &Experimental	Aerodynamic features
(Génin & Stark, 2007)	Experimental	Cold test and transition pressure
(Génin & Stark, 2010)	Experimental	Features of side load
(Génin & Stark, 2011)	Numerical and Experimental	Hot flow testing
(Genin et al., 2013)	Numerical and Experimental	Determination of the distribution of heat flux
(Genin et al., 2013)	Experimental and Numerical	Planar dual bell nozzle under several test conditions
(Verma et al., 2013)	Experimental	Reynolds number influence on dual bell transition behavior
(Verma et al., 2014)	Experimental	Impact of fluctuating environmental pressure on the dual bell transition
(Verma et al., 2015)	Experimental	Unstable flow conditions encountered during sneak transition
(Barklage & Radespiel, 2018)	Numerical and Experimental	The boundary layer state impact on transition

The conducted studies indicate that although numerous studies have been performed on the dual-bell nozzle, there is a lack of review studies on it, which makes it particularly important to conduct this research. The primary objective of this study is to advance understanding and development of the dual-bell nozzle as a significant propulsion technology for rockets, airplanes, and space shuttles. Specifically, to address the objectives of this study, the following research questions have been formulated:

1. What studies have been performed on dual-bell nozzles from various perspectives?
2. Is the dual-bell nozzle a promising nozzle for next-generation vehicles, especially for rockets?

3. What would be the action of the dual-bell nozzle at both sea level and high-altitude modes?

Methods and Materials

From a methodological perspective, the utilized method is a narrative review.

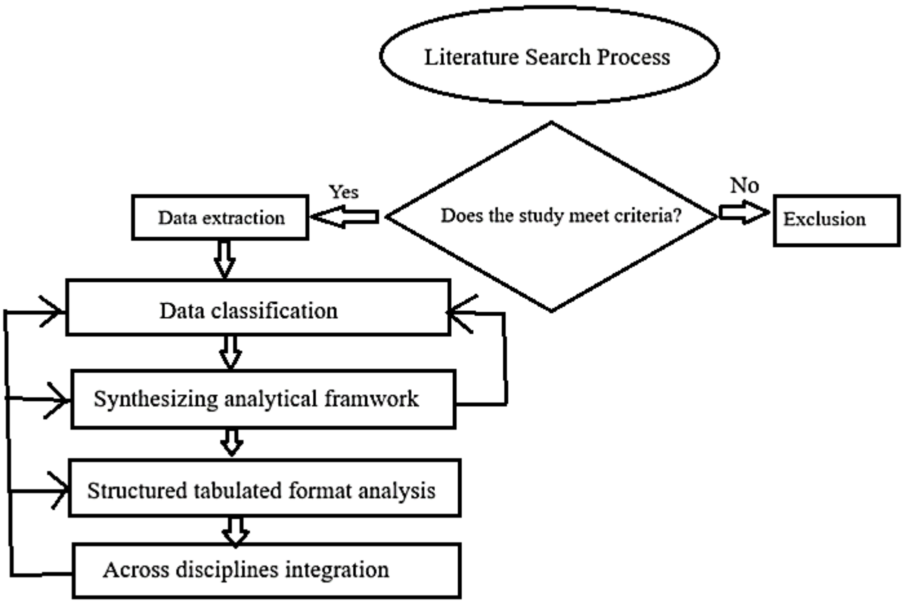

Figure 3. *Applied method for conducting this review (Authors)*

The method was developed to synthesize available studies on the dual-bell nozzle. This study emphasizes transition behavior, side load generation, performance development, thermal criteria, utilized materials, flow physics, and geometric optimization. The methodology used is shown in the figure above. It consists of several stages described in the following steps:

Search Strategy

A structured, keyword-based literature review was conducted to identify related investigations. To find relevant sources, the following terms were used individually and in combination: dual-bell nozzle, transition, altitude-compensating nozzle, flow separation, side load, thermal stress, hot-firing test, inflection point, CFD analysis, inflection design, utilized material, optimization, performance, and erosion of dual-bell nozzle. During the search and study, some data were outside the scope and were excluded.

Exclusion Criteria

The excluded data include general studies on nozzles that do not explicitly address dual-bell nozzle content. Other excluded data include studies lacking technical depth, duplicate works, and nonspecific sources.

Data Extraction

The data with the following criteria were included:

1. Direct focus on design, performance, inflection, CFD analysis, and optimization of the dual-bell nozzle.

2. Computational or experimental work addressing the flow separation part of the dual-bell nozzle.
3. Theoretical studies that contribute to understanding the physics of the dual-bell nozzle.
4. Publications with quantifiable findings or reproducible methodologies.

Data Classification, Synthesis, Tabulation and Integration

Data extracted from the included sources on the dual-bell nozzle were reviewed, categorized, and analyzed into one or more tables. These categories were defined under standardized headings including performance optimizations, geometric optimizations, CFD analysis, thermal loads, and utilized materials. These classifications enabled systematic comparison and organization of the collected data.

An analytical framework was developed for synthesizing diverse study findings to ensure a coherent interpretation of the results. Theoretical, numerical, and experimental results were organized and tabulated systematically to facilitate clear evaluation and comparison across different studies.

Findings from propulsion, fluid dynamics, and high-temperature materials were integrated to build a complete understanding of the dual-bell nozzle concept. The conducted methodology provides a systematic and transparent review of the dual-bell nozzle's history.

Findings

The literature review findings highlight considerable improvements in the transition mechanism, design, optimization, thermal behavior, and CFD analysis of the dual-bell nozzle. The study found that the dual-bell nozzle, as an altitude-compensating nozzle, is significantly important among nozzles in rocket engines. Leeper (2011) indicates the dual-bell has 3-5% better performance than conventional nozzles, and the dual-bell has higher specific impulse at both low and high altitudes than traditional nozzles, gaining 3-6% more specific impulse. Like expansion-deflection nozzles, it has the same erosion, but its more complex shape mitigates some effects of erosion at high NPR. It has an efficiency between 70-80% (Abadie & Manuel, 2022).

Martelli et al. (2007), Génin et al. (2013), and Kbab et al. (2023) performed parametric optimization consistently. Their findings are summarized as follows:

- Precise location of the inflection point stabilizes the separation line in sea-level mode.
- Smoothed wall contour transition delays early reattachment.

Génin and Stark (2010) and Verma et al. (2013, 2014) conducted investigations on the transition between modes that caused considerable side loads, especially during partial attachment. The studies demonstrated the following results:

- Asymmetric separation bubbles caused side loads.
- Variation of Reynolds number significantly impacts load magnitude.
- Variation in environmental pressure increases instability.

Schneider & Génin (2016), Akib et al. (2017, 2019), Kumar et al. (2019), and Chada & Akella (2023) conducted CFD-based studies on the dual-bell nozzle. Their findings indicated:

- Numerical simulations precisely predict separation lines, shock structure, and wall pressure distribution.
- CFD simulation enables geometry contour optimization without extensive physical testing.

Heat load synthesis indicates that the dual-bell nozzle produces localized peak thermal loads due to the impact of separation-induced shock (Génin et al., 2013).

- Heat flux is highest near the inflection point and separation line.
- In altitude mode, reattachment redistributes thermal load downstream.
- Thermal management is essential for material integrity.

The dual-bell nozzle is more complex due to the dual expansion zones, but in manufacturing, it is easier than expansion-deflection and aerospike designs.

Discussion

Several investigations have been performed on the dual-bell nozzle across numerical, experimental, and analytical studies. The studies on the dual-bell nozzle highlight geometry sensitivity, transition behavior complexity, side load challenges, and advanced thermo-structural materials. This discussion integrates these themes for tabulated and structured analysis and evaluation of the limitations and future potential of the dual-bell nozzle in modern launch vehicles. Assessments on the concept of dual-bell, strengths, limitations, and loads caused by pressure and temperature are tabulated in the following table:

Table 6*: *Executed research performed on the concept, load, and thermal load of dual-bell nozzle

Types of studies	Sources	Focus of study	Main finding
Analytical and conceptual report of NASA	(Horn & Fisher, 1994)	Dual bell nozzle as Altitude compensation	Early assessment of concept and altitude potential compensation
Critical assessment	(Frey & Hagemann, 1999)	A critical assessment of dual bell nozzle	Strengths, limitations, and practical challenges discussed
Critical assessment	(Hagemann et al., 1998)	A critical assessment of dual bell nozzle	Detailed performance and transition issues evaluation.
Experimental and numerical	(Génin, 2013)	Dual-bell nozzle heat flux numerically and experimentally studied.	Thermal loads documented and experiments compared with predictions.
Experimental study of side loads	(Génin & Stark, 2010)	Side loads in dual bell nozzles, part I: Phenomenology	Side load phenomena identified during transition and structural implications.
Experimental testing of hot flow	(Génin & Stark, 2011)	Hot flow testing of dual bell nozzles	Confirmed transition behavior and performance trends in heated conditions by hot flow test.
Numerical study of thermo-structure	(Shankar et al., 2015)	Dual-bell nozzle thermo-structural study.	Analysis of thermo-structure indicates structural implications and thermal stresses.

NASA technical report	(Glass, 2008)	Hot structure and ceramic matrix composite (CMC) TPS for hypersonic vehicles	CMCs review for high-temperature TPS and applications of hot-structure.
Textbook	(Sutton & Biblarz, 2017)	Rocket Propulsion Elements (9th ed.)	Covering propulsion systems and fundamentals of nozzles
Book	(Hill & Peterson, 1992)	Mechanics and Thermodynamics of Propulsion (2nd ed.)	Propulsion mechanics that contain dual bell nozzle.

Heat load synthesis and summarization of the above table indicate that the dual-bell nozzle produces localized peak thermal loads due to the impact of separation-induced shock (Génin et al., 2013). Heat flux is highest near the inflection point and separation line.

The performance of the dual-bell nozzle is higher compared to the conventional nozzle due to the altitude compensation phenomenon that enables the nozzle to change the separation line of exhaust gases. This inflection and separation capability result in complicated geometry that needs precise design. Leeper (2011) portrayed that the dual-bell nozzle has higher performance at lower NPR, but lower performance at higher NPR, and it has 3-5% better performance than conventional nozzles.

Extensive research has been conducted on pressures, flows, and transition behaviors of the dual-bell nozzle, including experimental, numerical, and simulation studies as illustrated in the following table:

Table 7. *Studies conducted on the flow and transition phenomena of dual-bell nozzle*

Types of studies	Sources	Focus of study	Main finding
Unsteady flow experimental	(Nasuti et al., 2002)	Conditions of unsteady flow during sneak transition of dual-bell	Transient phenomena characterized during transition and their impact on steady
Numerical simulation	(Horn & Fisher, 1994)	Study the operation of transition between two modes.	Parameters and flow features control the transition mode via CFD.
Experimental	(Numberger et al., 2010)	Flow transition on dual bell nozzle	Shock movement, transition behavior, and experimental transition criteria measured
Experimental computational	(Davis et al., 2015)	Computational and experimental research of a dual-bell nozzle	Combined test and CFD for characterizing flow and validating models.
Historical overview	(Shivag & Ujjwal, 2021)	Rocket nozzles: 75 years of research and development	Nozzle development survey that includes dual bell nozzle.
Numerical / Parametric study of CFD	(Martelli et al., 2007)	Dual bell nozzle follows numerical parametric synthesis.	Parametric CFD recognized flow sensitivity and transition for operating conditions and geometry.
Numerical	(Genin et al., 2012)	Numerical study of dual-bell nozzle flow field	Flow field features and mechanism of transition detailed by CFD analysis.

Numerical CFD	(Kbab et al., 2023)	Numerical study of supersonic flows in a dual-bell nozzle.	Supersonic flow behavior and performance insights resulted from numerical study.
Numerical of cold-flow transition	(Schneider & Genin, 2016)	Numerical study of the cold-flow transition behavior of a dual-bell rocket nozzle.	Cold-flow tests of CFD simulations showing transition criteria and unstable features.
Experimental (Reynolds number influence)	(Verma et al., 2013)	Effect of Reynolds number on transition phenomena of dual-bell	The study indicated that Reynold numbers influence transition characteristics and scaling.
Experimental study of fluctuations in ambient pressure	(Verma et al., 2014)	Ambient pressure fluctuations influence the transition behavior of a dual bell.	Ambient pressure fluctuations affect transition timing and behavior.
CFD analysis	(Akib et al., 2019)	Critical analysis of dual bell nozzle by utilizing CFD.	CFD-based analysis highlighted the practical limitations and advantages of the dual bell nozzle.
Experimental on parametric of fluid control	(Ferrero et al., 2022)	Parametric study of dual-bell nozzle transition fluidic control.	Investigated fluidic control parameters for managing transition.
NASA technical material review report	(NASA, 2009)	Materials applied for rocket nozzle	Survey of material selection and nozzle materials guidance.
CFD criteria analysis	(Akib et al., 2017)	Criteria analysis of dual bell nozzle by using CFD.	Characterization of CFD flow field and performance metrics.
Experimental	(Génin & Stark, 2007)	Experimental research conducted on dual bell nozzles	Experimentally documented the flow features and transition of dual-bell nozzle.
Experimental and Numerical	(Genin et al., 2013)	Dual bell nozzle flow studied experimentally and numerically.	Combined numerical and experimental CFD tests were conducted to map flow behavior and validate the models.

As summarized above, flow analysis and numerical simulations precisely forecast the separation line, shock structure, and wall pressure distribution. The synthesis of studies indicates that CFD simulation enables geometry contour optimization without extensive physical testing.

Conclusion

The conducted review confirms that the dual-bell nozzle is among the most promising altitude-adaptive nozzles, delivering high performance across varying environmental pressures. Fundamental, theoretical, experimental, and analytical studies have been established to improve the performance of the dual-bell nozzle in both sea and altitude modes during a controlled transition. Subsequent experimental studies, such as hot- and cold-flow tests, clarified the separation behavior, the influence of the boundary layer, and the formation of side loads. Advances in computational fluid dynamics have enabled contour optimization, flow-field analysis, and transition prediction, thereby considerably accelerating design refinement. Thermal modeling, material considerations, and regenerative cooling strategies are being actively studied and indicate requirements for practical application. Overall, the review indicates that the remaining challenges are ensuring structural reliability and managing unsteady transitions, especially, but the dual-bell nozzle represents a well-validated concept with clear advantages for next-generation vehicles.

Author Contributions

- Mohammad Amir Sadiqi conceptualized, conducted the investigation, wrote, analyzed, and reviewed the manuscript.
- Mohammad Aref Naimzad supervised the study.

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