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# Dual Nozzle for Supersonic Flight Regimes: Review

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## ABSTRACT

**Rocket propulsion has been a pivotal technology in humanity's quest to explore and understand the cosmos. The efficiency and performance of rocket engines are essential considerations in this endeavour. One crucial aspect of rocket design is the choice of nozzle configuration, with dual nozzle systems featuring prominently in the field. This review paper aims to comprehensively explore and analyse the dual nozzle setup, focusing on the two most prevalent configurations i.e., the bell and conical nozzle respectively. The objective of this review is to provide a consolidated overview of existing research and insights into the performance and behavior of dual nozzle configurations. This review paper serves as a comprehensive resource for researchers, engineers, and practitioners interested in dual nozzle systems. By synthesizing existing knowledge and insights, we aim to contribute to a deeper understanding of the complexities and performance factors associated with dual nozzle configurations in various engineering applications.**

**Keywords: Bell nozzle, Conical nozzle, Propulsion, Review**

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## INTRODUCTION

The bell nozzle is an important component of the rocket motor system and plays a crucial role in the overall performance of a rocket. The design of the bell nozzle consists of an integrated throat, an entry and an exit cone, and a thermal protection system. The bell nozzle is designed with a cone inflection angle of 16.The paper reviews and summarizes the developments in the design and shape of rocket nozzles, including the bell nozzle. The nozzle shape has the largest radiative flux past the neck, while the throat has the highest heat flux due to the mass-flow rate per unit area. The distribution of nozzle wall pressure is strongly influenced by the Mach number of the injected secondary flow, leading to undesirable side loads[1].Dual bell nozzles are a type of altitude-adaptive nozzle used in rocket engines to optimize thrust generation at different altitudes. They offer a one-step altitude adaptation and have a characteristic contour inflection that divides the nozzle into a base and an extension. At sea level, the contour inflection forces the flow to separate controlled and symmetrically, resulting in increased sea level specific impulse (Isp) compared to conventional nozzles. At the designed altitude, the flow attaches abruptly to the wall of the extension, resulting in a transition to high-altitude mode and higher vacuum performance. The major advantage of dual bell nozzles is the absence of any moving parts, making them easier to implement in already operating rocket engines with only minor design and structural changes required. The concept of applying a contour inflection in dual bell nozzles was first mentioned by Foster and Cowles in a study on flow separation in supersonic nozzles. Rocketdyne later patented the dual bell nozzle in 1968.Experimental studies have been conducted to investigate side load generation during the transition from one operating mode to the other. The side load peak during retransition (nozzle shutdown) was shown to be significantly higher than during transition, although some studies have reported higher side loads during the transition to high-altitude mode[2].

A conical nozzle is used to convert high enthalpy stagnation gas into hypervelocity flow through a contraction-expansion process. The enthalpy flow in the nozzle can be divided into three regions: an equilibrium region, a non-equilibrium region, and a frozen region .The effects of a conical nozzle under different expansion angles, curvature radius of the throat, throat radius, and convergence angle of the convergent section are investigated .The thermo chemical non-equilibrium effects in the conical nozzle are sensitive to the maximum expansion angle and throat radius, but not to the radius of throat curvature and contraction angle. Decreasing the maximum expansion angle and increasing the throat radius led to the flow approaching an equilibrium state. The maximum expansion angle and throat radius not only affect the position of the freezing point but also the flow field parameters such as temperature, Mach number, and species mass fraction [3].

A gas dynamic model of supersonic expansion in a conical nozzle has been developed to describe the expansion of a real (supercritical) gas flow .The model is based on the Redlich-Kwong equation of state and can be used to study the formation of clusters, microcapsules, and condensation in the expanding gas flow .The conical nozzle serves as a carrier for the main gas flow, against which the processes of interest occur .The model has been experimentally verified for clustering in argon (Ar) and krypton (Kr) flows, using the Rayleigh scattering method to measure the sizes and densities of the clusters .The proposed model has also been tested in experiments involving relativistic laser action on a krypton cluster jet, with the aim of creating X-ray sources and accelerated electron beams[4].

A conical nozzle is a nozzle with a conical shape in the downstream region, which is used in various industrial and natural processes. The dynamics of a compound droplet moving in a conical nozzle have been studied using front-tracking-based simulations. The compound droplet experiences three stages of deformation in the conical nozzle: the entrance stage, the transit stage, and the exit stage. The maximum deformation in the axial direction occurs during the transit stage, while the radially maximum deformation occurs during the exit stage. The acceleration induced by the conical region can cause the inner droplet of the compound droplet to break up into smaller droplets during the exit stage. The conical angle (α) is one of the parameters that affect the transition between finite deformation and breakup modes of the inner droplet[5].

The conical variable nozzle is a component of a 3D article manufacturing apparatus. It consists of a nozzle unit, a support plate, an adjusting knob, and a fixing unit. The nozzle unit includes multiple nozzle blades arranged in a circular shape to form a nozzle with one injection hole. The support plate is positioned below the nozzle unit and has rotational pins that correspond to the central hole of the nozzle blades. It supports and rotates the nozzle blades. The adjusting knob is located above the nozzle unit and has control holes that align with control pins on the nozzle blades. It allows for the adjustment of the rotational angle of the nozzle blades. The fixing unit consists of a first and second fixing unit, which are coupled together to prevent separation of the nozzle unit, support plate, and adjusting knob. The conical variable nozzle allows for the modularization of the nozzle blades and the variation of the injection hole calibre through the rotation of the adjusting knob. This enables precision adjustment in the manufacturing of 3D articles [6].

## LITERATURE REVIEW

Sreenath K Ret.al (2016) wrote that the dual bell nozzle has better overall performance than the single bell-shaped nozzle. Atmospheric pressure restricts the expansion of the exhaust gas at low altitudes so the efficiency is much higher at low altitudes. At low altitudes, a vehicle can save 25-30% more fuel by using a dual bell nozzle. It is also, able to expand the engine exhaust to a larger effective nozzle area ratio, at high altitudes[7].

Manuel Frey et.al (1999) conducted critical assessment of dual-bell nozzles. Different design aspects for the wall inflection and nozzle extension were discussed, with special regard to the dependence of the transition behaviour from sea level to altitude operation on the type of nozzle extension. A sudden transition from sea level to altitude operation is desirable, to avoid uncontrolled flow separation and side loads. Analytical and experimental results lead to the conclusion that two different types of nozzle extensions, the constant pressure extension and the overturned extension, might offer the sudden flow transition[8].

Yong Wang et.al (2022) Expansion–deflection nozzle (EDN) and dual-bell nozzle (DBN) are the designs of altitude compensation nozzles that are currently widely studied. The cold flow subscale experiments and two-dimensional axisymmetric Reynolds-averaged numerical simulations were performed to explore the flow characteristics and the altitude compensation performance of an expansion–deflection dual-bell nozzle (EDDBN), which combines an EDN and DBN[9].

Vermaet.al (2020) In this study, we perform a two-dimensional axisymmetric simulation to assess the flow characteristics and understand the film cooling process in a dual bell nozzle. The secondary stream with low temperature is injected at three different axial locations on the nozzle wall, and the simulations are carried out to emphasize the impact of injection location (secondary flow) on film cooling of the dual bell nozzle[10].

Daviset.al (2015) This project addressed a common issue in nozzle design and its effect on the efficiency of rocket engine systems. A dual-bell nozzle contour design procedure was developed and used to investigate a possible nozzle that could be implemented on a sounding rocket or nanosatellite launcher[11].

Loosen et.al (2019) The turbulent wake of a planar space launcher equipped with a dual-bell nozzle is numerically investigated to determine the influence of the advanced propulsion concept onto the intricate wake-nozzle flow interaction[12].

Beena D et.al (2017) A 2D axisymmetric flow analysis was conducted within a bell-type nozzle using computational fluid dynamics software, specifically GAMBIT 2.4.6 and FLUENT 6.3.26, at both design and off-design conditions for cold and hot flow scenarios. Several key conclusions were drawn from this analysis[13].

Nairet.al (2019) A numerical analysis has been performed on the flow through conical plug nozzle, 40% conical plug nozzle and 40% conical plug nozzle with base bleed have been carried out using ANSYS Fluent. The base pressure, shock pattern and flow structure of numerical result agree with the experimental data[14].

Khareet.al (2021) Rocket nozzle designers are always being challenged to search for the resolution to use a smaller size nozzle in harvesting a higher specific impulse while maximizing the cost saving and simplifying the structural complexity. Lesser weight, maximum performance, and ease of manufacture are some of the main desirable features of a rocket nozzle. This review paper attempts to analyse the major research work [15].

Jagmit Singh et.al (2019) In a series of single-phase compressible flow experiments aimed at optimizing nozzle geometry for maximizing critical pressure ratio and minimizing pressure drop, 27 different nozzle configurations were tested and analysed[16].

**Overview on Bell and Conical nozzle**

A nozzle is a device that is designed to regulate the direction and characteristics of the combustion gas products of jet engines. So, the nozzle performance has a significant impact on the mission achievement. This paper is concerned with the internal ballistics of the nozzle aiming to estimate pressure and thermal loads on its walls. Computational fluid dynamics is applied to analyse the effect of changing nozzle internal profile on the resulting thrust, flow energy losses, and nozzle wall structure[17].

In order to produce rocket engines with high thrust and efficiency, dual-bell nozzle design and performance optimization are essential. Using computational fluid dynamics (CFD) simulations and analytical modelling, this paper gives a thorough investigation of the design and optimization of a dual-bell nozzle. The key considerations are the geometric optimization of the nozzle contour and the performance optimization of the expansion ratio for both the primary and secondary nozzle [18]. A new contouring method for radiatively cooled nozzle extensions of orbital transfer vehicle engines is proposed. This method provides a replacement of expensive heat-resistant materials used for the nozzle extensions by an ordinary heat-resistant steel due to a contour inflection at the joint with the externally cooled nozzle part, which causes the reduction of the heat flux to the nozzle wall and, therefore, reduction of the maximum nozzle extension wall temperature[19]. Large Rocket engine nozzles performance deteriorate because of asymmetric flow separation that led to side loads. The dual-bell nozzle is a promising two operating modes nozzle which consists of a base nozzle with low area ratio and a nozzle extension with high area ratio. Although the dual-bell nozzle improves the performance of large rocket engines, it suffers from side loads that occur during the transition between the two operating modes[20].

The performance of dual-bell nozzles is affected by the aspiration drag generated in the recirculation zone during low-altitude operation. In this paper, dual-bell nozzles with different design parameters were studied by simulation to gain the aspiration drag at various flight altitudes. Results show that the aspiration drag of dual-bell nozzle with negative wall pressure gradient extension decreases with the increasing flight altitude, while the aspiration drag of dual-bell nozzles with zero and positive wall pressure gradient extensions first decreases and then increases with the increase of flight altitude[21].

Altitude adaptive nozzles have recently got more importance in the field of space science and rocket technology. For future space exploration and space tourism, the combustion system is in the refurbishment for better and robust performance. As a part of this progression, dual bell nozzle is introduced which has dual operating modes (at low and high altitude) without any mechanical activation[22].

We analytically studied the propulsion and flight performance of dual-bell nozzles. Specifically, we analysed the shock induced separation flow inside the nozzle with the help of a recently proposed separation model. Based on the nozzle flow analysis, we evaluated propulsion performance and flight performance gains to be obtained by applying dual-bell nozzles to existing rocket engines[23].

Propulsion nozzles generate the thrust needed through the conversion of thermal energy into kinetic energy. The combustion or working gases expansion takes place within the convergent, throat and divergent sections reaching supersonic velocities. The widely used contoured (or bell) geometry has been and is still popular because of its shorter length that leads to lesser mass along with its ability to direct the exhaust gases towards the axis of symmetry at the exit cross-section leading to greater thrust [24].

Computational Fluid Dynamics (CFD) is a field in fluid dynamics that incorporates numerical analysis to simulate and solve problems that involve fluid flows. The study used a two-dimensional axisymmetric model for the analysis, with the governing equations solved using the finite-volume approach in ANSYS FLUENT® software. The inlet boundary conditions are selected from the available experimental data. The oblique shock and shock travel phenomena with the divergence of 5°, 10°, and 15° are demonstrated [25].

The damping of axial instabilities by a variety of solid rocket exhaust nozzles has been determined experimentally using the modified impedance tube technique. me dependence of the damping upon the depth of the cavity and the secondary flow rate issuing from the cavity of a submerged nozzle, the geometry of the convergent section of a single ported nozzle, and the number of nozzles present in a multiple-ported nozzle cluster has been determined[26].

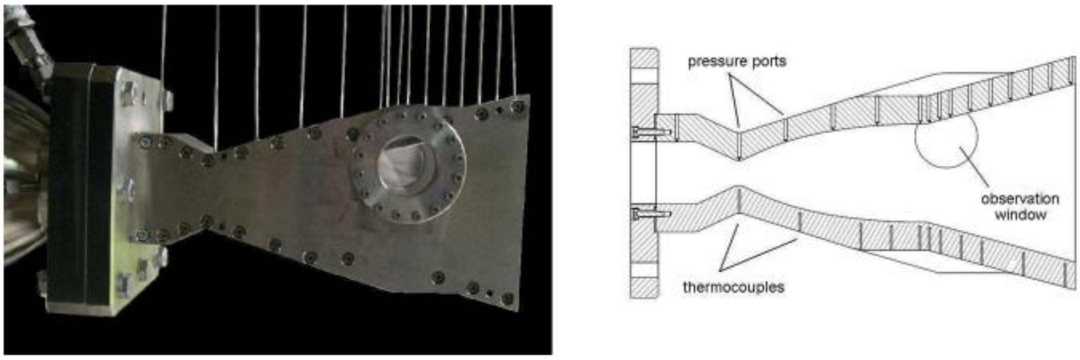

**Fig 1.Planar dual bell nozzle model [26]**

**Flow characteristics**
The observation of the flow leads to a better understanding of the transition phenomenon. The parametric study of the nozzle extension length leads to the following conclusions: the transition is more stable (higher hysteresis between transition and retransition), shorter and with higher front velocity if the relative extension length is higher. These advantages will have to be optimised with the drawbacks of a longer extension: potential higher side loads, higher sensibility to ambient pressure fluctuations in flight due to increased surface and additional weight [27]. The EDDBN is in the sea level closed mode under the experimental nozzle pressure ratios, as observed in the cold flow subscale experiments and numerical simulations. The EDDBN and the dual-bell nozzle (DBN) have different mode transition pressure ratios. The EDDBN has a higher mode transition pressure ratio than the DBN in wider ranges of nozzle pressure ratios, due to the lower wall pressure of the extension nozzle. The EDDBN can improve the thrust performance of the exhaust system during the mode transition compared to the DBN with the same design pressure ratio. This confirms the application value of the proposed nozzle design. Overall, the flow characteristics of the EDDBN indicate its suitability for altitude compensation, with improved thrust performance during mode transition compared to the DBN[28].

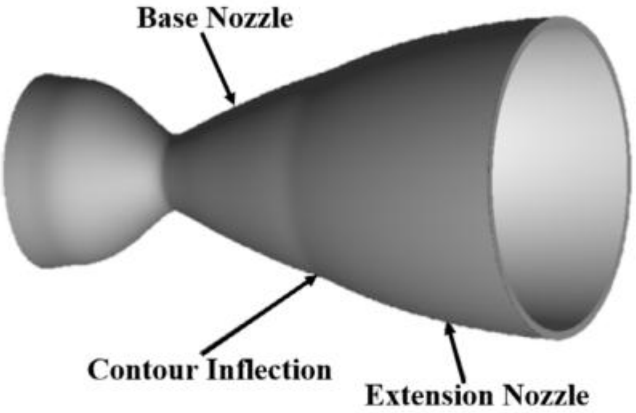

**Fig 2. Dual Bell Nozzle [29]**

The pressure measurements along the nozzle contours can be used to determine the operating mode of the nozzles. Figure 2 shows how the pressure is distributed within the axisymmetric dual bell nozzle for different values of NPR. When NPR is low (NPR $\leq 32$), the airflow separates at the contour inflection point, and the nozzle operates in the sea level mode. As NPR increases, the airflow attaches to the extension, causing a transition to the high-altitude mode[42].

## Temperature in Dual Nozzle

Graphite is one of the most common materials used in rocket nozzle throats due to its high temperature resistance, low cost, high thermal conductivity, and increasing toughness at elevated temperatures. However, the extreme operating conditions can result in cracking in graphite, as experimentally observed through laser irradiation experiments. NASA reports also indicate severe cracking and erosion during operation. While the compressive nature of the stresses might suggest that the nozzle can maintain its integrity in the presence of cracks, experience shows that the cracks can eventually lead to the disintegration of the nozzle, resulting in catastrophic consequences[30].The temperature distribution and thermal stress of a rocket engine nozzle are important factors to consider for ensuring its safe and efficient operation .The paper establishes a three-dimensional model of an L-shaped nozzle and uses numerical simulations to analyse the temperature field and stress field of the structure .The results show that the throat of the nozzle experiences the highest temperature and maximum thermal stress .The maximum temperature of the throat is found to be 1400K when the gas temperature is 2600K .The thermal stress on the throat is measured to be 158MPa at this gas temperature .Additionally, the thermal conductivity of the insulation layer also affects the thermal stress on the throat, with a value of 170 MPa observed when the thermal conductivity is 2.8 W/(m·K). These findings provide valuable insights for the thermal protection design of rocket engine nozzles, aiding in ensuring their safe and reliable operation[31].

The paper discusses the use of ultra-high temperature ceramic matrix composites (UHTCMC) for the fabrication of reusable rocket nozzles for propulsion .The UHTCMC materials are designed to withstand high temperatures, as they are tested in a hybrid rocket motor for reusability .The paper mentions the formation of a $ZrO_2$intermediate layer and a liquid $SiO_2$ layer on the surface of the nozzles during oxidation tests, which indicates exposure to high temperatures .The UHTCMC-based nozzles are shown to have no measurable erosion compared to a reference graphite nozzle, even after repeated exposure to high temperatures. The overall operating time of the UHTCMC-based nozzles in the tests is up to 30 seconds, indicating their ability to withstand high temperatures for a significant duration[32].

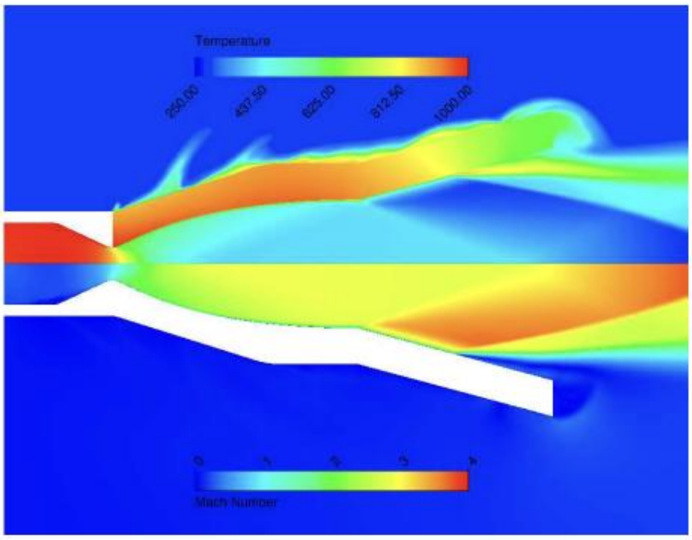

**Fig 3. Temperature repartition in the flow and in the nozzle wall (top) and Mach number distribution (bottom) [46]**

## Mach number

The Mach number is a dimensionless quantity that represents the ratio of the speed of an object to the speed of sound in the surrounding medium. It is used to describe the flow conditions of a fluid, particularly in the context of aerodynamics and supersonic or hypersonic flight[33].

The invention relates to a high-mach-number low-temperature array nozzle used for HF/DF chemical laser. The array nozzle comprises more than two nozzle assembling units which are arranged in parallel; a nozzle unit is formed between the two nozzle assembling units; the nozzle unit is a typical two-dimensional slit Laval nozzle; a row of hydrogen nozzle holes are formed in the wall surface of each of the nozzle assembling units on the two sides of the tail end of an outlet expansion section of the corresponding nozzle unit separately; a row of main helium nozzle holes are formed in the wall surface of each of the nozzle assembling units on the two sides of an outlet expansion section between the hydrogen nozzle holes and a throat-shaped channel separately; and a row of combustor helium nozzle holes are formed in the wall surface of each of the nozzle assembling units on the two sides of the inlet end of the corresponding nozzle unit separately. By adopting a high-mach-number low-temperature array nozzle design concept, the efficient fluorine atom freezing efficiency of the high-mach-number low-temperature nozzle is maintained; and by introducing a Russia novel nozzle combustor helium adding strategy, the thermal dissociation efficiency of the combustor is greatly improved[34].The maximum Mach number observed in one of the test cases was approximately 5.1, indicating high-speed flow conditions. The presence of Mach diamond-esque structures and lines of reduced Mach number downstream of inflection points in the flow pattern were also observed. The Mach number remained relatively high at certain pressure ratios, reaching approximately 3.8, which is close to the unrestricted flow in the Rao contours[44].

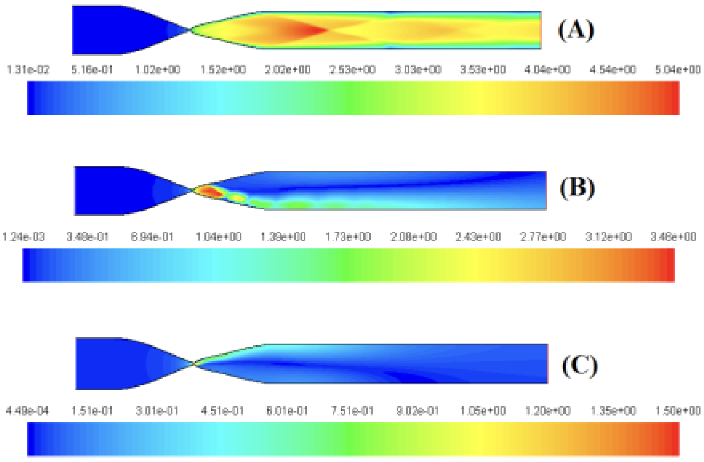

**Fig 4. Dual-bell wind tunnel Mach contours for pressure ratios of (A) 1000, (B) 10, and (C) 2 [44]**

### Heat Wall Coefficient

A numerical model of a small nozzle flow meter was developed and the simulation results showed that the numerical calculation method can effectively reveal the internal thermal characteristics. Under different inner wall temperatures, on the path from the upstream pressure tapping point to the downstream pressure tapping point, there were multiple peaks and valleys on the heat flow distribution in the Y direction, and the valley values were all reached at0.08 L. Under different inner wall temperatures, on the path from the upstream pressure tapping point to the downstream pressure tapping point, there appeared the same decreasing-increasing-decreasing trend on the heat flow distribution in the X direction, and the valley value and peak value were reached at 0.35 L and 0.73 L, respectively. Under different inner wall temperatures, on the path from the upstream pressure tapping point to the downstream pressure tapping point, there appeared the same increasing-decreasing-increasing trend on the heat flow distribution in the Z direction, and the peak values were reached at 0.42 L and 0.58 L and valley value at 0.5 L. When the inner wall temperature rose from 50 °C to 700 °C, the heat flows at the inlet and outlet of the flow meter increased significantly with the increase of temperature[35]. Thermo-structural analysis of a steel-composite rocket nozzle was conducted using the finite element method, showing that thermal loads have a significant impact on generating stresses on the nozzle structure, accounting for more than 60% of the total stresses on the nozzle .The convective heat transfer coefficient plays a crucial role in determining the temperature transferred to the nozzle wall .The composite material used in the nozzle demonstrates resistance to temperature augmentation, making it an effective thermal protection material[36].

The conventional wisdom in heat transfer analysis, which assumes that wall temperature has no influence on the Heat Transfer Coefficient (HTC) distribution along the blade surface, is not valid for a transonic High-Pressure Turbine (HPT) blading. The study shows a strong dependence of HTC on wall temperature, far above that predicted by existing correlations.

The study highlights the importance of upstream boundary layer history on the HTC distribution and also observes the influence of wall temperature on the trailing edge shock position. A new method is proposed in the paper, which allows for modelling the HTC dependence on wall temperature with much improved accuracy. The study aims to investigate the linearity between heat flux and wall temperature for external heat transfer in a typical transonic turbine Nozzle Guide Vane (NGV) geometry. The findings are independent of the turbulent Prandtl number and turbulence model used[37]. The experimental investigation focused on the heat transfer and boundary layer in conical nozzles with varying surface finishes and throat Reynolds numbers. The experiments were conducted using air at a stagnation temperature of 539 K and throat Reynolds numbers based on a diameter ranging from $6 *10^5$ to $5*10^6$. The nozzle wall surface finish was varied from a smooth machine finish to $826 \times 10^{-6}$ cm ($325 \times 10^{-6}$ in.) rms sandblasted finish. The paper provides tabulated data on measured heat transfer and wall temperatures. The results

of the experiments can be used to understand the heat transfer characteristics and boundary layer behaviour in conical nozzles, which can have implications for various engineering applications[38].
The paper presents an improved nozzle structure for engines, such as ramjets, rockets, or turbojets, that generate thrust by expelling gaseous fuel combustion products along a thrust axis .The nozzle structure consists of an annular wall with a contoured inner surface and a transverse web member at the nozzle throat .The annular wall structure is designed with a radially inwardly convergent annular ramp near the inlet and a radially outwardly divergent annular ramp near the outlet, with a nozzle throat at the juncture of the ramps .The transverse web member, located at the nozzle throat, has a double wedge-shaped cross-section and defines two symmetrical passageways through the nozzle .The surface of the web member features radially divergent ramps on the leading edge, extending from the inlet to the throat, and radially convergent ramps from the throat to the trailing edge .Both the annular wall structure and web member are made of a heat resistant material, such as a composite of carbon yarn within a carbon matrix, with a temperature resistant coating of pyrolytic graphite[39].The coupling simulation of heat transfer and transient temperature of the rocket nozzle wall was carried out in this study. The results showed that plume heating on the throat section is the most serious, with the wall temperature in that place being much higher than the average temperature. Heat insulation of the throat is crucial for the rocket nozzle's safety performance.

The transient temperature on both the internal and outside walls of the rocket nozzle steadily increased with time after start up of the rocket engine, with the internal wall temperature increasing rapidly. The temperature also decreased along the thickness from internal to outside of the wall, with a difference of over 1000 K due to the heat insulating layer in the nozzle material. The coupled simulation method used in this study can be used to predict the safety performance of the rocket nozzle during the startup stage. The results of the coupling simulation method were compared with available results in references, showing reasonable agreement[40].

## Velocity Characteristics

The dual bell nozzle design aims to enhance performance based on auto-adaptation with altitude, without mechanical activation. The design process involves using a transonic flow approach to determine the starting line for supersonic calculations and the method of characteristics to draw the base nozzle profile. The study includes an analysis of the evolution of thermodynamic parameters such as pressure and Mach number, which indirectly relate to velocity characteristics[41]. The wake flow of the generic space launcher with a dual-bell nozzle was simulated at transonic and supersonic freestream conditions. The wake flow dynamics were analysed using classical statistical analysis, power spectral density, and dynamic mode decomposition (DMD). The wake flow exhibited shear layer instabilities, causing turbulent structures to grow in size and intensity. At a streamwise position of xD = 0.15, the power spectral density revealed enhanced frequencies at Sr D = 0.04 and Sr D = 0.2, indicating periodic behavior of the wake flow. Downstream at xD = 0.4, the spectrum was dominated by a single peak at the buffet frequency of Sr D = 0.2, consistent with similar space launcher configurations. Flow control by injecting air jets reduced the buffet frequency and pressure fluctuations at Sr D = 0.2. Overall, the wake flow exhibited turbulent structures and periodic behavior, with the buffet frequency of Sr D = 0.2 being a significant characteristic. Flow control through jet injection was effective in reducing the buffet frequency and associated pressure fluctuations[45].

## Density

The decrease in gas density/reduced mass flow is accompanied by a significant decrease in the amplitude of wall pressure fluctuations in the region of separation due to a decrease in shock strength. As the gas density decreases with decreasing feeding pressure, the process of flow transition gets delayed, which may be related to the delay in movement of separation in the vicinity of wall inflection. For very low values of the driving pressure ($P_o$), transition did not occur at all. The delay in the dual-bell transition process to higher nozzle pressure ratio is primarily attributed to the increase in the width of the inflection region with a decrease in Reynolds number. The observations indicate that as the gas density decreases, the flow transition also gets delayed, and the separation location remains only in the vicinity of the wall inflection. Gaseous nitrogen at ambient temperature is used as the test gas due to its advantage over compressed air[43].

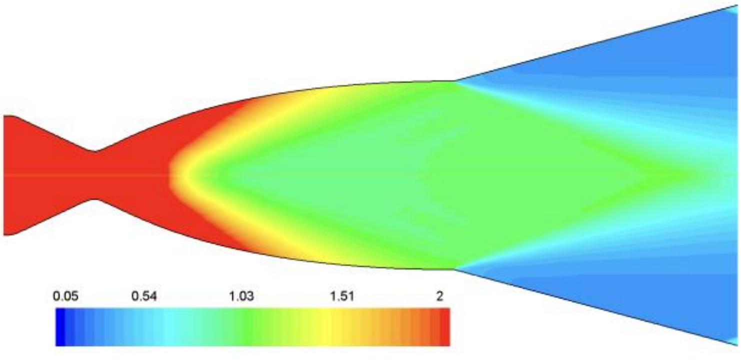

**Fig 5.Pressure repartition in the planar nozzle calculated with CFD [42]**

The wake flow density characteristics were analyzed using the instantaneous and time-averaged absolute density gradient in the zonal RANS/LES computations. The wake topology of the supersonic configuration was visualized, showing the turbulent supersonic boundary layer separating and forming a supersonic shear layer. The density gradient contour also revealed the presence of jet shock cells in the wake flow. The numerical data of the wake flow density compared well with experimental and design pressure distributions. In summary, the wake flow density characteristics were examined through the density gradient analysis, which revealed the presence of a supersonic shear layer and jet shock cells. The numerical data of the wake flow density showed good agreement with experimental and design pressure distributions [45].

## CONCLUSION AND FUTURE SCOPE

Throughout the review, we explored the flow characteristics, temperature distribution, Mach number profiles, heat wall coefficients, and velocity characteristics associated with dual nozzle systems. The exploration of dual nozzle configurations, such as the bell and conical nozzles, in rocket propulsion has opened up a realm of possibilities for future research and development in aerospace engineering. This review paper has laid the foundation for understanding the principles, advantages, and challenges associated with these dual nozzle systems. Looking ahead, several exciting areas emerge as potential future directions for this field. One of the most promising avenues is the continued refinement of nozzle design. Engineers and researchers can delve into the intricate details of nozzle geometry, materials, and manufacturing techniques to further optimize efficiency and adaptability. Computational simulations, wind tunnel experiments, and advanced manufacturing processes will play pivotal roles in shaping the next generation of nozzle designs. A particularly intriguing area of exploration involves the development of hybrid nozzle systems. These systems would combine elements of both bell and conical nozzles, harnessing the strengths of each configuration for specific mission phases.

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