REST Journal on Advances in Mechanical Engineering
Vol: 2(1), 2022
REST Publisher; ISSN: 2583-4800
Website: http://restpublisher.com/journals/jame/
DOI: https://doi.org/10.46632/jame/2/1/2

Review Study on Thermal Characteristics of Bell Nozzle used in Supersonic Engine

Sejal Guram, Vidhanshu Jadhav, Prasad Sawant, *Ankit Kumar Mishra
Astroex Research Association, Deoria, Uttar Pradesh, India.
*Corresponding author Email: **ankitkumarm1998@gmail.com**

Abstract: *The nozzle is an important component of the rocket motor system, and a rocket's overall performance is highly reliant on its aerodynamic design. The nozzle contour can be meticulously shaped to improve performance significantly. The design and shape of rocket nozzles have evolved over the last several decades as a result of extensive research. The nozzle design is composed of two components, an integrated throat, an entry and an exit cone, and a thermal protection system. The Bell Nozzle is designed to provide clearance space for placing the ITE and exit cone, with a cone inflection angle of 16 and a thermal protection system. This paper intends to review and summarize all such developments. Small-scale engine testing allows for the analysis of rocket nozzle materials, but the history of nozzle surface temperature and thermal stress may be adversely affected by side effects. The review focuses primarily on the nozzle shape which has the largest radiative flux past the neck, but the nozzle shape has the highest heat flux in the throat 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. Finally, future development possibilities are suggested.*

Key words: *Rocket Nozzle, Bell Nozzle, Heat Flux, Thermal, Mach number, Wall Pressure, ITE.*

1. INTRODUCTION

In recent years, advanced nozzle configurations have been investigated. Bell and plug nozzles, either linear or axisymmetric, nozzles with extended exit cones (EEC), and dual-bell nozzles are currently being researched by aerospace agencies and companies. F. Cowles and C. Foster first introduced the dual-bell concept in literature in 1949, and Rocketdyne patented it in the 1960s. In the 1990s, research efforts were resumed as a result of the development of current CFD capabilities [1]. A rocket nozzle's primary goal is to improve the combustion products at the combustion chamber's end by converting internal potential energy into kinetic energy. It is assumed that the performance of vacuum nozzles improves inexorably as the expansion ratio increases, with the mathematically best performance observed at an infinite expansion ratio. The current method for optimizing nozzles designed to perform optimally at a specific altitude is based on determining the optimal expansion ratio multiple times [2].

$$KL = \frac{L\,tan15^0}{R_t\sqrt{\epsilon}-1} \quad \ldots\ldots\ (1)$$

A nozzle is a variable cross-sectional area tube used to increase the velocity of an outflow while also controlling its direction and form. In the simplest case, a rocket nozzle generates relative motion by ejecting mass from a chamber backward through the nozzle, with reaction forces acting primarily on the opposite chamber wall and a minor contribution from nozzle walls. The pressure distribution within the chamber is asymmetric. The outside environment does not compensate for the force on the chamber's bottom caused by gas pressure. A nozzle is a device that controls the flow direction or properties of a fluid (particularly when it escapes an enclosed chamber or pipe). A nozzle is typically a pipe or tube with varying cross-sectional area that is used to guide or alter the flow of fluid [3]. The flow downstream (i.e., external to the nozzle) is free to grow to supersonic velocities, yet Mach 1 can be a very high speed for a nozzle Although the solar thermal system is conceptually simple, major design challenges must be addressed. These challenges include concentrator design, absorber/heat exchanger development, and nozzle optimization to efficiently produce the required thrust. Research efforts are increasingly been developed to investigate each of these component challenges [4]. In an assumed nozzle, maximum efficiency is achieved when the gas is expanded isothermally to precisely the same pressure as the ambient pressure just beyond the nozzle's exit plane.

Conventional nozzles, which have a single, continuous contour between the throat and the outlet, are intended to expand optimally at a single mid-range height. As a result, these nozzles are over-expanded at low altitudes because their exit pressure is less than the ambient pressure, and under-expanded at high altitudes because their exit pressure is greater than the ambient pressure. Dual-bell nozzles have been investigated as a means of improving efficiency at high altitudes while avoiding harmful side loads at low altitudes [5]. The Bell shape imparts a wide expansion angle immediately after the throat. It is then curled back, resulting in a nearly straight gas flow from the nozzle hole. These two sets of shock waves coincide and cancel each other out in a properly constructed bell nozzle. The term "Bell Nozzle" refers to the fact that the parabolic form converges and diverges in the shape of a bell. It begins with a high-angle expansion segment just behind the nozzle throat and progresses to a progressive expansion section. Following this, the nozzle contour slope gradually reverses, resulting in a small nozzle exit divergence angle. The parabolic form's increased thrust optimises the axial component of exit velocity, resulting in a high specific impulse. The most important design consideration is contouring the nozzle to reduce oblique shocks and improve performance [6]. The study of high-temperature gas flow in a nozzle has resulted in the formulation of several parameters, which serve as a basis for analyzing a rocket motor as well as evaluating different systems. A lower emissions rocket and a higher specific impulse will result in reduced fuel film cooling, which will minimize launch costs and extend the duration of the rocket [44].

2. LITERATURE REVIEW

Navinprabu et.al (2022) discussed the axisymmetric altitude adaptive dual bell nozzle was evaluated to comprehend the regenerative cooling process in semi-cryogenic propellant rocket engines under unsteady thermal conditions. They have designed the dual bell nozzle model and incorporated them into a Computational Fluid Analysis (CFD) code for further analysis of the flow phenomena at the throat of the nozzle [7]. Felix et.al (2022) have designed an ED nozzle using the Angelino method and a MATLAB code, for upper-stage applications. To determine the best-performing ED design, the performance of the ED nozzle design was evaluated using numerical computations and compared to conventional TIC nozzles [8]. Yahiaoui et.al (2021) investigated the contours of a supersonic nozzle were designed using a numerical computation programme. The mathematical calculations of the convergence ratio at the critical section demonstrate the validity of the results. This study looked at the impact of rocket engine efficiency and created an SBN contour design procedure to look at a possible nozzle for supersonic rocket engines. [9]. Génin et.al (2021) studied the flow separation in the dual-bell nozzle and the various methods to reduce the ambient pressure during the launcher's ascent and at some point, the nozzle pressure ratio required for the flow transfer is reached. It is concluded that the wake flow seen has a significant impact on flow behavior [10]. Aabid et.al (2021) observed that a nozzle without an expanding part cannot produce supersonic air. The continuity equation can be used to calculate the Mach number velocity and local area in any other region of the nozzle [11]. Shustov et.al (2022) examined The NPR range was calculated using the location of the turbulent layer separation point in the enhanced supersonic part of the rocket engine nozzles. As mass (m) and Reynolds number (Re) increase, the stationary character of the pressure distribution along the nozzle wall in the flow separation region changes to unsteady, which is associated with a change in the mode of separation of the turbulent boundary layer from free to restricted [12]. Patidar et.al (2022) developed the method of designing a Minimum length C-D nozzle with a steady flow at the diverging part of the nozzle for the designed exit Mach number. As the velocity shoots up in both sections of the c-d nozzle due to Bernoulli's principle in the divergent part, and the area increases with the velocity in the convergent part [13]. Bhaskar et.al (2022) performed the simulations of the combustion chamber for pentane/liquid oxygen as fuel/oxidizer injected at a constant temperature. To interpret the results, the essential contours for parameters such as pressure, temperature, and velocity are plotted and compared [14]. Decher et.al (2022) encountered The total pressure losses associated with the inlet and nozzle flows are ignored because they are assumed to be reversible. Some total pressure losses would occur in practise, particularly in the inlets of supersonic flight aeroplanes [15]. Saleh et.al (2021) studied the various designs of bell nozzles used to control the direction and characteristics of engine combustion gas products. They discovered that 3-angle profile design is not a potential candidate profile due to poor ballistic performance by simulating the flow of gases in CFD. The highest PI modified bell profile also has the lowest thermal and mechanical load [16]. Nigar et.al (2021) researched the mechanical failure and thermal stresses on the graphite rocket nozzle. On Simulating thermomechanical stress on the composite steel nozzle, they found that thermal shock-induced stresses account for more than 60% of the nozzle’s total stress. the research helped to design the rocket nozzle using graphite and analysis of failures in graphite throats [17]. Sun et.al (2021) carried out an Experimental investigation of the gas film cooling efficiency of the cylindrical holes near the injector region, experiments conducted with and without gas film cooling in a bell nozzle design engine, found perform the combustion gas cooling shows the result that rapid temperature increases in nozzle wall and with gas cooling temperature increases uniformly and steady after specific time [18]. Govardhan et. al (2021) studied the modeling and analysis of combustion instability using fuel injection. using various simulating software, they found the high temperature in the combustion chamber helps the burn cryogenic fuel efficiency and increases the engine efficiency hence, fuel burn without high soot emission and engine life increases in dual bell nozzle design the expansion of a high-temperature exhaust gases decreases the pressure and temperature after the expansion [19]. Wang et.al (2020) research on Numerical analysis of combustion instabilities in end-burning-grain solid rocket motors utilizing pressure-coupled response functions. By simulating the combustion of fuel in solid rocket motors, they found when the fuel tank is nearly empty and the last remaining fuel starts to burn instability occurs in the burning of solid fuel because of changes in fuel tank pressure and temperature. the deep analysis is described by Roberts's burning rate law [20]. Sella et.al (2020) Develop and research on Nytrox-Paraffin Hybrid Rocket Engine. After the development of the hybrid rocket engine, they fired with the cold flow and then hot flow and found during the cold flow the nozzle metals degrade slowly compared to the hot flow and the also efficiency and thrust are steadier compared to the hot-fired test [21]. Zuo et.al (2020) researched the Effects of combustion on supersonic film cooling using gaseous hydrocarbon fuel as a coolant. Without the supersonic film cooling the wall temperature of the bell nozzle at starting is reduced but it increases rapidly after some time compared to the supersonic film cooling [22]. Verma et.al (2020) investigated flow characteristics inside a dual bell nozzle with and without film cooling. The transition altitude for each engine in dual bell nozzle results in the thrust imbalance in each engine because of the variation in the transition altitude of a different engine. For overcoming this problem investigated the result of using the film cooling and conclude the injection of the secondary flow into the nozzle at a different location. The result was carried out by various simulations and experiments [23]. Schneider et.al (2020) investigate the numerical study of a film-cooled dual bell extension on its operation mode transition behavior. The result was carried out by unsteady Reynolds-averaged Navier– Stokes simulation and found the effect of cooling film mass flow on separation position and also found the effect of changing in the combustion mixture ratio changes the flow separation velocity and position [24]. Samantra et.al (2020) a theoretical simulation is carried out to study different dual bell nozzle designed with different inflection angles and expansion ratios. The separation flow position changes with temperature and inflection angle and the injection of secondary cold flow affect the separation flow velocity and position. The result got from a numerical study and CFD analysis of DBN [25]. Choudhary et.al (2018) analyzed that the bell is designed to impart large-angle expansion for the gases right after the throat. The most important design issue is to contour the nozzle to avoid oblique shock waves and minimize the weight while maximizing performance. According to the study, film cooling is used to understand the mass flow rate of coolant got a significant effect on mixing, the nozzle flow moves up to the exit of the extension part of the nozzle at a high- altitude [26]. Barklage et.al (2018) studied that the bell nozzle is a very promising alternative to conventional nozzles. The main objective of this paper states about implementing actual parameters to evaluate and formulate the design for a rocket nozzle. The result was carried out by the various simulation, experimental and numerical setups stating that the transition depends on the pressure distribution of outer flow, and free-stream pressure due to expansion results nozzle exit for expanded flow [27]. Hamitouche et.al (2019) studied the idea of bell nozzle concepts which are based on the principle of forcing the flow to separate from the nozzle between sea level and high- altitude. The conception method of bell-nozzle is analyzed by calculations by describing the divergent section of an axisymmetric bell nozzle. By studying two models: Kw-SST and Spalart-Allmaras, nozzle pressure ratio (NPR) variation over nozzle for operating mode [28]. Schneider et.al (2019) researched on dual bell nozzle consisting of the base nozzle and extension linked by an abrupt change in wall angle, film cooling is particularly identified if the film is injected in the nozzle base an overview of thermochemical modeling of nonequilibrium is used in DLR-TAU Code [29]. Zebbiche et.al (2019) studied the gain of performance of self-adaptation in altitude the flow suddenly attaches throughout the nozzle, allowing a greater expansion for higher thrust corresponding to the high-altitude Mach number when atmospheric pressure fall below a certain altitude calculation Procedure in the Kernel Region B is determined numerically. The conventional nozzle is used to provide an adaption to a single altitude, usually at sea level [30]. Zimijanovic et.al (2018) studied the designed DBN test model built for experimental testing in a super/hypersonic wind tunnel, while numerical simulations in CFD-FASTRAN were conducted using the same model geometry. This study focuses on transition DBN aspects including transition persistence such as buffeting and flip-flopping, and sneak transition intervals, which are inherited properties of DBN stepped design [31]. Bensayah et. al (2018) analyzed that axisymmetric nozzle flows with MacCormack's technique, a parallel implicit finite volume algorithm based on the entire Navier-Stokes unsteady equations is developed. The effects of various parameters on the thermal and dynamic properties of flow via a cooled convergent-divergent nozzle are discussed in the current results [32]. Akib et.al (2019) The density gradient is determined using the shadowgraph imaging method. The k-epsilon turbulence model was used to do the simulations. The design of a dual-bell nozzle contour and a study of the performance of fluid parameters including pressure, temperature, Mach number, velocity vector, and others, are presented in this research [33]. Kumar et.al (2019) In the study, numerical research is carried out to depict the fluid flow and thermal properties from a realistic nozzle shape, as well as to compare different flow and thermal properties using a CFD tool. The research gives insight into the flow patterns of helium and nitrogen inside the nozzle; it has been found that in all situations, the temperature drops and Mach number at the output are greater for the helium [34]. Anugrah et.al (2019) research on the effects of secondary injection on both extending and non-expanding supersonic flows was conducted in this study on rocket nozzle thrust augmentations. The secondary injection causes a rise in wall static pressure, which has a positive association with injection pressure When there is a secondary injection, thrust augmentation occurs. In the current research, it has also been proven to be effective in delaying flow separation toward the outlet [35]. The bell outperforms the linear nozzle by just 3%, despite having a 10% bigger subsonic layer at the nozzle output plane than the 30° linear expander [51].

3. OVERVIEW

Salient Features: The nozzle wall deformation effectively makes the altitude change of this nozzle design possible. Two parts make up the nozzle hardware: a combined throat and entrance and an exit cone. The nozzle is made to offer the correct amount of clearance room so that the ITE may be inserted into the counterbore. Buttress threads are used to join the exit cone to the ITE. 50 mm has been set as the throat diameter. The exhaust is propelled to a M = 5.021 by tuning the cone inflection angle to a certain degree in order to attain an area ratio of 16. A carbon-phenolic liner that serves as a backup to the ITE and exit cone (until the threaded part) and reduces the temperature increase of the metallic portion makes up the only component of the thermal protection system. [5]. Due to the bell-shaped convergence and divergence of the parabolic form, that occurs right behind the nozzle throat, this shape is called as a bell nozzle. The nozzle contour slope then gradually reverses, producing a little nozzle exit divergence angle. A high specific impulse is produced by the parabolic form's improved thrust, which enhances the axial component of exit velocity. The nozzle's contouring is the most important aspect of design in order to reduce oblique shocks and improve efficiency. [6].

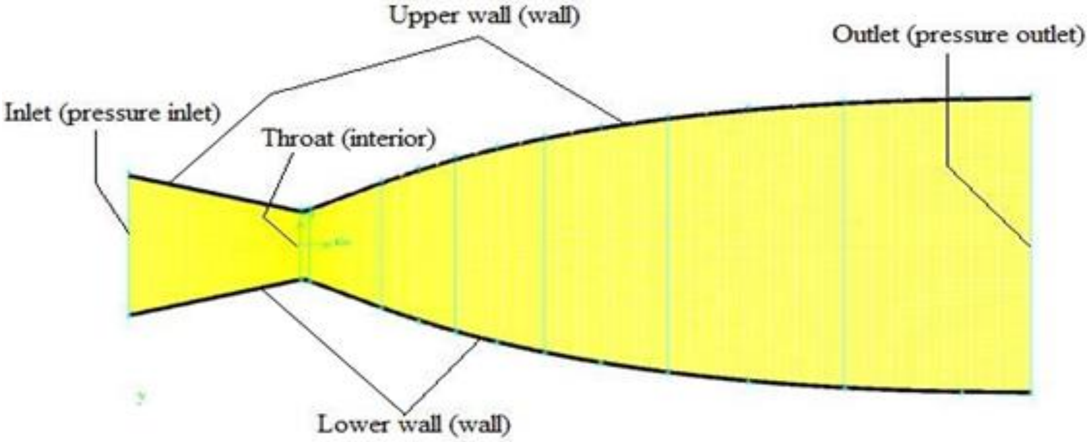

FIGURE 1. The fluid domain with boundary conditions of the bell nozzle [50]

By altering the proposed second-order diffusion solution, it is possible to arrive at a much simpler but also more limited solution to the nozzle heat-transfer issue. The aerodynamic flow in electric rotor bell systems is comparable to naturally occurring rotating annular flow. Using a Pitot tube, the mean airflow velocity was calculated. Although not allowing for the exploration of recirculation zones, pitot tubes provided an accurate and affordable way to detect the turbulent flow mean velocity. Using pitot tubes, the mean velocity of turbulent annular flows has previously been successfully determined.[46]. A solution may be determined by hand using this technique, but the Monte Carlo solution requires a high-speed digital computer. The nozzle increases thrust by accelerating the combustion gas to a high supersonic velocity by using the pressure generated in the combustion chamber. In contrast to most nozzles, which have a parabolic bell form, the American, European, and Japanese engines' nozzles have a thrust-optimized nozzle design. For radiation cooling, the right high-temperature materials, such as tungsten, rhenium, or other refractory metals, must be used.[45]. An optimization method is utilized to determine where to truncate the entire nozzle shape to optimize thrust while staying within a certain bound. Point b, the tile point at which the line is perpendicular to the constant surface area line, represents the optimum of maximum thrust for a given surface area. The group of nozzles shown by the point is both shorter and smaller in diameter with the same thrust. After this point, a negative contribution to thrust results from the wall friction forces becoming stronger than the pressure forces[49]. The inlet condition serves as a pressure intake, and the outlet condition serves as a pressure outlet. The nozzle shape is separated into zones and boundary conditions. For the conservation equations, the second-order upwind technique was applied, and grid adaptation was employed to precisely capture flow discontinuities [50].

4. NOZZLE DESIGN METHODOLOGY

The shape of the nozzle is the most essential design consideration for reducing oblique shocks and increasing efficiency [6]. A considerably simpler, but also more constrained, solution to the nozzle heat-transfer problem could be obtained by modifying the provided second-order diffusion solution. To find a solution, this technique can be performed by hand, but the Monte Carlo technique requires a high-speed digital computer. The Ideal Contour (IC) nozzle is constructed using the Method of Characteristics (MOC) to provide a homogeneous flow field with a constant velocity distribution at the exit. It delivers the best results but is too long and heavy to be practical. A Truncated Ideal Contour (TIC) nozzle can save significant weight and length while sacrificing only minor performance losses [6].

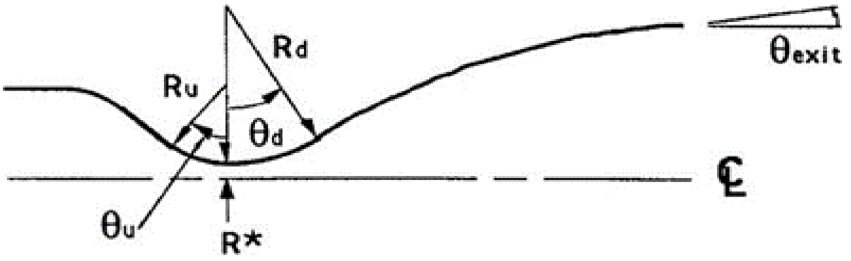

FIGURE 2. Nozzle Geometry Parameters [4].

However, for a given length and expansion ratio, the best performance is obtained with a Thrust Optimized Contour (TOC) nozzle, which may be generated using the MOC [2]. The chamber conditions, nozzle throat diameter, contraction area ratio, and expansion area ratio were all kept constant in a baseline nozzle design using baseline area ratio geometric parameters for the TDK model and chamber circumstances. The length and angle of the convergent area cone and the divergent section form might both alter as a result of fixed and variable factors. The boundary layer was permitted to shift from laminar to turbulent using Reynold's Number limit of 400 and a turbulence transition criterion based on momentum thickness. For all circumstances investigated in this study, the boundary layer remained laminar [4].

$$L_n = \frac{K(\sqrt{\epsilon}-1)R_t}{tan(\theta_e)} \qquad \ldots\ldots\ldots\ldots (2)$$

As a potential possibility, large liquid rocket engines for launcher first stages might perform better with dual bell nozzles. Using a secondary injection method keeps the flow separated. For the full-scale dual-bell and conventional nozzles, various pressure ratios (chamber-to-ambient) and secondary injection rates were simulated [36]. A TOP nozzle is made up of three curves: a large circle at the intake, a smaller circle at the throat, and a parabola to extend the approximate bell form to the exit plane. The length of the nozzle is derived using the flow deflection angle at the exit, e, and the throat radius, Rt, where K is a quantity computed as a percentage of the length of a conical nozzle with a 15° half angle. To further characterize the nozzle, a coordinate system is developed with the axial (x) axis traveling via the line of symmetry and the radial (y) axis passing through the Centre of the throat. The first and second bends, as well as the exit of the nozzle's throat, are indicated by circular curves [6].Based on load factors and safety variables that have been found after four decades of experience, a design approach known as "parametric design" is used. Safety factors must be lower than the strength or permissible fatigue based on previous hardware failures to assure safe operation. Nonetheless, comprehensive ground testing is still necessary since partial over-design cannot be avoided [45].The goal of the work is to identify the optimum divergence angle for a nozzle using CFD, an advanced strategy for predicting the outcomes of a problem before investigation [48].

5. MATERIAL

The current fascination with swift and high-altitude aircraft, missiles, and rockets has resulted in a demand for structural components that exhibit the necessary structural strength and dimensional stability to withstand the extreme stresses and strains experienced during operation in the high-temperature environment. Generally, integrated motors, combustion chambers, and rocket nozzles are made of composite materials reinforced with two-dimensional fibres. The fibres can be deposited using a variety of techniques, such as flat wrap and tape wrap, in which woven fabric structures are positioned perpendicular to the nozzle/motor axis. The Dixie cup wrap is a different technique that cants the fabric shapes to the axis. A technique that inserts randomly cut cloth to a mould before crushing it and shaping it into a matrix substance. Moreover, traditional filament woven or braided structures were used. [4]. In developing rocket nozzles, high-performance solid propellants provide a variety of material problems due to the wide variety of temperature, chemical, and mechanical conditions they generate. The correct design configurations are only incorporated following full-scale prototype test firings with typical big solid-propellant rocket nozzle materials. Rocket nozzle materials study is possible through small-scale engine testing; however, side effects may have a negative impact on the history of the nozzle surface temperature and thermal stress. The majority of the significant factors found in full-scale engines, however, may be duplicated in small-scale engine testing. Constants like gas velocity, flame temperature products, and combustion rate are easy to duplicate. Tungsten is a material that appears to be resistant to nozzle erosion and thermal stress cracking, we have been able to determine the size of the aluminized propellant despite the difficulties caused by the accumulation of aluminum on the nozzle insert throat during firing [3]. The four major composite materials used in solid propellant rocket nozzles are graphite, aluminum 7075, silica-phenolic, and carbon phenolic [37]. High-temperature, high-strength alloys like CuCrNb have been proposed to replace the common CuAgZr material, but results of high-thrust engine test programs are not published due to issues with identification, measurement, and control of process variables. Consolidated tungsten for fabrication has been produced by plasma spraying, but its impurity content has drawn criticism. [42]. The most likely materials to erode were refractory metals, with Arcite 368 and HDBM propellants causing failures in low-density tungsten nozzles. Using HDBM, ZT graphite exhibited improved erosion resistance. than the usual molded ATJ graphite, suggesting mechanical abrasion [43]. The material used to make a rocket nozzle must be able to withstand extreme pressures and temperatures while maintaining structural integrity. Carbide tungsten is a useful material due to its high melting point, superior hardness, and resistance to wear, but its performance and durability can be affected by fluid properties, operating temperature, pressure, and velocity.

6. THERMAL CHARACTERISTICS OF BELL NOZZLE IN SUPERSONIC ENGINE

Thermal Properties: The radiative component of the problem's second-order diffusion solution may be modified, and then combined with the pipe flow equation for convection, to solve the nozzle heat transfer issue considerably more efficiently. Convective and radiative fluxes were individually estimated. As each heat-transfer process tends to reduce the overall propellant temperature, which in turn affects the static temperature and the characteristics, there is substantial debate over whether adding the results together would precisely represent the total heat transfer. The radiative transmission also drastically drops off just downstream of the nozzle throat. The static temperature is quickly falling to the fourth power because hydrogen propellant becomes virtually transparent at lower static conditions downstream of the throat. [38]. The local heat transfer q can be determined using the one-dimensional Fourier's law and thermal measurement information from the nozzle wall.

$$\text{Where,...} \quad qy = \frac{-KdT}{dy} \quad \text{.....(3)[38].}$$

Under testing conditions, heat-resistant steel does have a material conductivity, K, of 19 $Wm^{-1}K^{-1}$. The distance dy, which is 2 mm, the flow, solid body, and the temperature gradient all represent the radial distance between the thermocouple sites. The nozzle flow's Mach number dispersion may be seen in (bottom). The temperature of the flow rises close to the separation point. The total temperature is identical when the flow is estimated using both experimental and numerical wall temperatures. The heat flux in the base nozzle wall rises towards the contour inflection during extension, with the inflection area benefiting more than the rest of the nozzle wall. The area of the extension that includes the separation point is greater. Yet, the lack of thermocouples in this region could be to fault. Once more, the initial value is used to normalize all succeeding values (corresponding to the axial position of the first temperature measurement point). A thermography temperature measurement of the nozzle's outside was achieved thanks to the thin structure. The temperature distribution around the outer wall can be estimated using this thermography image that was taken in altitude mode. The base nozzle temperature of both methods is high and decreases as the nozzle wall approaches. Prior to the contour inflection, the temperature at sea level decreases [39]. The transitional dual bell nozzle . When the flow separates towards the end of the nozzle extension, NPR offers a one-step transition from sea level to altitude mode. It should split at the end of the nozzle, though, for maximum thrust. To maximize the nozzle's thrust when operating at high altitudes, the flow shouldn't split before the end of the nozzle. The secondary flow is injected at various axial locations along the nozzle wall as part of a systematic parametric analysis for supersonic cooling inside the dual bell nozzle to identify the most effective and promising injection site. The major flow happens within the nozzle when the intake temperature is 2842 K and the pressure is 40 bar. The primary flow develops inside the nozzle. The injection of secondary flow occurs at 500K, Mach2, 1 mm of film cooling slot height [41].

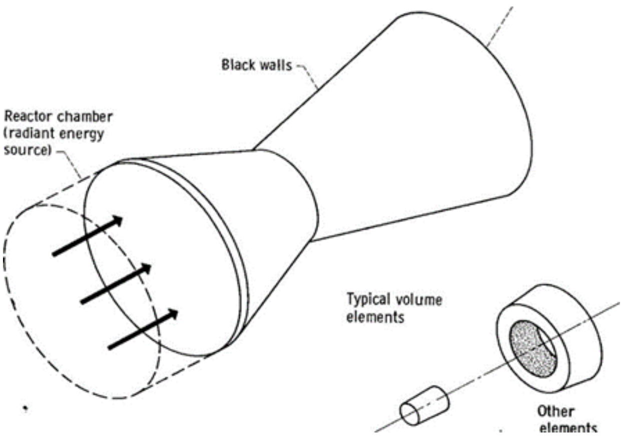

FIGURE 3. Model for Nozzle Heat-Transfer [3]

The Influence of Nozzle Shape on Flux Distribution: The radiant flux has a parameter that depends on the nozzle shape. The absorption coefficient in this case is likely entirely influenced by the local static pressure. Nozzle I have the least static pressure and temperature drop due to the greatest throat diameter and smallest convergence angle. The local static temperature and absorption coefficient remain extremely high, so the radiative flow past the neck is at its highest. In addition, geometric shielding is lessened. convective heat transfer as well as the effect of nozzle shape. The nozzle has the smallest throat diameter, the lowest propellant flow rate, and the greatest convergence angle. The throat nozzle has the highest heat flux due to its high mass-flow rate per unit area, while the convective flux in the convergent and divergent regions of nozzles is smaller than in the other nozzles. [38]

The Effect of Treating Total Heat Flux as an Additive: There are variations in total energy fluxes calculated by adding up radiative and convective fluxes and those determined by computing the coupled effect, making it questionable whether just aggregating the data would adequately anticipate total heat transfer. Each heat-transfer methodology helps to lower the overall propellant temperature, which impacts the static temperature and features. Each additive solution is based on an incorrect propellant temperature distribution, which significantly underestimates the overall flow. The energy loss in the propellant stream is incredibly low at the high flow rates found in these nozzles, therefore regardless of the method used to calculate heat transfer, the total temperature of the stream is almost constant. Therefore, coupled computations are not required for the particular circumstances given here, since an additive method produces appropriate accuracy. [38]

The Influence of Injection Location on Boundary Layer and Thermal Profiles: The boundary layer profiles and the near-wall temperature profiles are displayed at six different axial positions downstream of the secondary flow-inlet to illustrate how the cold and hot flow are mixed inside the dual bell nozzle. Three different injection locations are identified by these profiles.

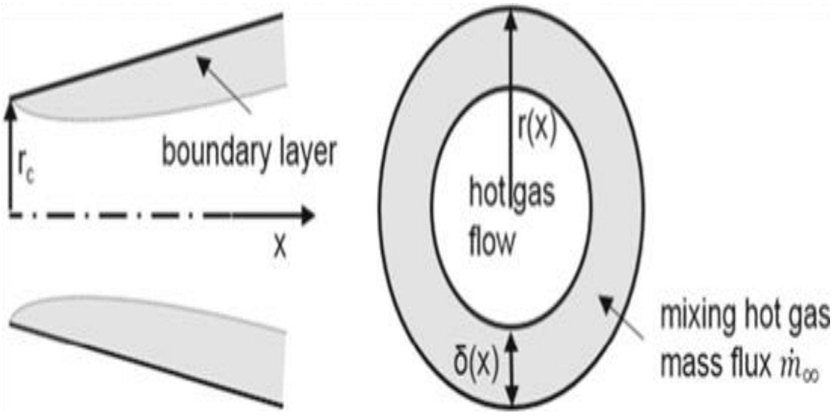

FIGURE 4. Axisymmetric mixing model [40].

The radial separation from the symmetry axis at that axial position is modified proportionally to the nozzle contour radius. Each temperature profile is scaled by 500 K for clarity, whereas each profile of the Mach number is scaled by 0.5 Mach. When an injection occurs at the nozzle throat, secondary flow is seen mixing with the primary flow and secondary flow according to the Mach number and near-wall temperature profiles [38].

The Effect of Secondary Flow Injection Mach number on Wall Pressure, Wall Temperature, and Boundary Layer Profile: To investigate whether Mach number affects flow, the secondary flow is injected at the point of inflection with the secondary flow at four different Mach numbers (Mf). The Mach number is changed while maintaining a steady input temperature by varying the injection velocity. To keep the momentum flux ratio constant, the injection pressure can also be altered. To assess the effect of the Mach number, the standardized wall pressure and wall temperature distribution over the nozzle wall are evaluated. The Mach number (Mf) of the injected secondary flow has a significant impact on how the nozzle wall pressure is distributed. When Mf is equal to 1, the flow separation reaches the nozzle upstream and causes flow separation at the inflection point. Pressure oscillations begin to build up over the nozzle wall during the transition phenomena with modifying the Mach number of the injected secondary flow, which may cause significant quantities of unfavorable side loads. [35]

Film cooling theory: The investigation of tangential, supersonic film cooling in a nozzle flow under supersonic conditions The following assumptions are also presumed to be true: In terms of temperature, Mach number, and velocity, the coolant, which is gas, differs significantly from the hot gases. Its composition also differs from that of the nozzle hot gas. The coolant and hot gas are first mixed in the mixing layer, also known as the shear layer, which begins to form close to the tip of the splitter plate. Since there is an area of pure coolant gas below this layer, it is believed that the ratio of the obtained wall temperature drop to the cooling efficiency in the case of coolant injection is dominant here.

$$\eta = \mathbf{1} - \frac{\alpha_\infty q_m}{mq} \qquad \ldots\ldots \text{(4) [41].}$$

$$\alpha\infty = xm\lambda\infty Pr\infty 0.43 Re\infty 0.8$$

$$\alpha m = x\infty\lambda m Prm 0.43 Rem 0.8 \qquad \ldots\ldots \text{(5) [41].}$$

When the mixing layer is a given distance from the injection point, the heat transfer coefficients become quite significant because they have an impact on both the overall value of cooling efficiencies and the specific cooling efficiency of the coolant in contrast to other gases. As a result, there is a method for figuring out the heat transfer ratio in the mixing of hot gas and coolant at the wall for the axisymmetric film cooling mode. This model accounts for the amount of hot gas coupled with cooling as the mass flow in a hypothetical boundary layer that begins to thicken at the injection point. A diagram of the boundary layer growth in the nozzle may be seen in Figure 1. [41]

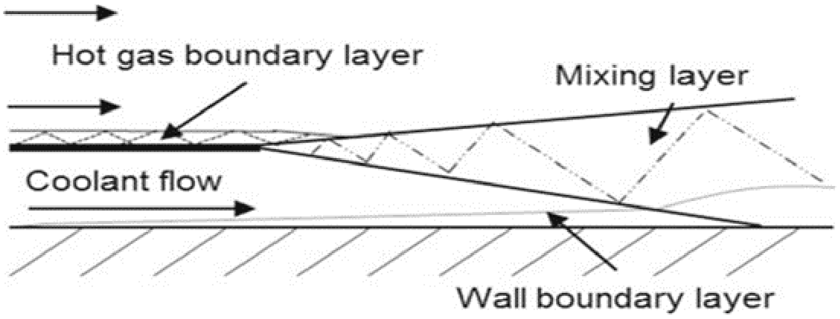

FIGURE 5. Schematic interaction of hot gas and overexpanded coolant at the injection position for tangential injection, shocks, and expansion waves are not shown.[40].

Supersonic flow regime: In the High-Speed Aerodynamics Laboratory, tests were conducted. There was a connection between the open jet facility and a sizable capacity of cylindrical storage tanks. Dry air under pressure from the storage tanks is directed into the settling chamber by a mixing length and a pressure control valve. Using a two-wire mesh, the air is filtered before being directed to the nozzle. The temperature within the settling chamber was practically ambient, and the back pressure was the ambient pressure into which the flow is released. For all of the NPRs that were looked at, where NPR stands for nozzle pressure ratio, the settling chamber pressure was kept under 3%. Pressure measurements were taken on planes perpendicular to the jet stream at numerous axial positions far from the nozzle exit.[47]. It is discovered that the magnitude of velocity increases with an increase in divergence angle at the exit section. Similar to this, when the divergence angle increases, throat section velocity increases. When the diverging angle increases, the static pressure decreases. As the diverging angle of the nozzle is increased up to a certain point, the efficiency of the supersonic engine nozzle rises [48].

7. CONCLUSION AND FUTURE SCOPE

Rocket nozzle designers are continuously challenged to find a solution for using a smaller size nozzle to extract a higher specific impulse while maximizing cost savings and simplifying structural complexity. Some of the most desirable characteristics of a rocket nozzle are its lightweight, high heat flux, film cooling, high performance, materials, and ease of manufacture. The purpose of this review paper is to examine the major research work done in the field of rocket bell nozzles over the last 60 years. The following are some of the key points from the current review work.

1. The features, design, and components of the rocket bell nozzle for supersonic flow have all been carefully examined. To analyze the design, several simulation approaches have been applied. It is found that carbide-tungsten is efficient in comparison to other materials.
2. The key components required for thermal analysis and the characterization of the particular thermal effects were covered in the discussion of the bell nozzle's thermal characteristics.
3. A constant radial temperature is assumed in thermal analysis, and it is predicted that radial mixing will remove convective and radiative energy from each radial element in proportion to the radial distribution of flow.
4. The investigation of the film cooling behavior at the dual-bell nozzle's inflection point revealed a distinct impact on the heat fluxes along the wall.
5. The exhaust plume is thought to be transparent to radiation because of the convergent-divergent geometry, which means that the nozzle upstream of the throat contributes very little radiant energy to the system.
6. To choose the components for the warm and cold zones, the heat transfer coefficient on the length of the rocket nozzle was estimated as part of the thermal study of the nozzle.
7. One of the most promising materials for high-temperature structural applications, such as rocket nozzles, is carbon fiber matrix composites.
8. Other types of nozzles, such as dual-bell nozzles, plug nozzles, etc., should be examined in terms of such features to improve the performance over diverse flows, especially because the properties of bell nozzles on supersonic flow have already been covered.
9. Investing in state-of-the-art high-temperature materials for propulsion can quickly pay for itself since it offers significant performance. But the problems with the new designs need to be clearly defined in terms of all features and fatigue qualities as a function of fabrications.

Acknowledgement: The authors would like to express their heartfelt appreciation to all of the authors of classic and popular publications that served as the foundation for the current review work. All figures and data sources used in this review are appreciated. A list of these sources is included in the references, and the authors apologise if due credit is not given to any source inadvertently.

REFERENCES

[1]. Yeasir Mohammad Akib, Asif Kabir, Mahdi Hasan,” Characteristics Analysis of Dual Bell Nozzle using Computational Fluid Dynamics” International Conference on Mechanical, Industrial and Materials Engineering 2017.

[2]. B.T.C. Zandbergen, Louis Souverein “A Procedure for Altitude Optimization of Parabolic Nozzle Contours Considering Thrust, Weight and Size” 5 TH European Conference for Aeronautics and Space Sciences (EUCASS), 2013.

[3]. Gedlu Solomon and Yeshurun Alemayehu Adde (Kibret), “Design and Analysis of Rocket Nozzle”, IOSR Journal of Engineering (IOSRJEN) Vol. 10, Issue 5, 2020.

[4]. J Boise Pearson, D. Brian Landrum, and Clark W. Hawk.,” Parametric Study of Solar Thermal Rocket Nozzle Performance”, J. Sol. Energy Eng., 118(3): 194-195, 1996.

[5]. K Shiva Shankar, S Shailesh babu, A Sai Kumar, “Thermo-Structure of Dual-Bell Nozzle”, International Journal of Engineering and Innovative Technology (IJEIT) Volume 4, Issue 11,2015

[6]. Sreenath K, Mubarak A, “Design and analysis of contour bell nozzle and comparison with dual bell nozzle”, IJRE Vol. 03 No. 06, 2016.

[7]. Navinprabu, Karthikeyan, Tamilselvan, Balakrishnan, Unsteady Thermal Modelling of Altitude Adaptive Dual Bell Nozzle with Regenerative Cooling of Thrust Chamber in Semi-Cryogenic Engine, International Journal of Scientific Research in Mechanical and Materials Engineering, 6(3), 2022, pp. 87-95.

[8]. Weber Felix, Bianchi Daniele, Nasuti Francesco, Advanced nozzle concept trade-off and selection criteria based on launcher mission constraints, 9^{TH} European Conference for Aeronautics and Space Sciences (EUCASS), 2022, DOI: 10.13009/EUCASS2022-4855.

[9]. Toufk Yahiaoui, Toufk Zebbiche, Supersonic Several Bells Design of Minimum Length Nozzle Contours for More Altitudes Level Adaptations, Arabian Journal for Science and Engineering, 2021, https://doi.org/10.1007/s13369-021-05725-1.

[10]. Chloé Génin, Dirk Schneider, and Ralf Stark, Dual-Bell Nozzle Design, Future Space-Transport-System Components under High Thermal and Mechanical Loads, Volume 146, 2021, pp. 395–406.

[11]. Abdul Aabid, Sher Afghan Khan and Muneer Baig, A Critical Review of Supersonic Flow Control for High-Speed Applications, Applied Sciences, 11(15), 2021, 6899, https://doi.org/10.3390/app11156899.

[12]. S A Shustov, I E Ivanov, and I A Kryukov, Numerical study of the separation of a turbulent boundary in rocket engine nozzles with an optimized supersonic part, Journal of Physics: Conference Series, Volume 2308, 2022, DOI: 10.1088/1742-6596/2308/1/012015.

[13]. Hariom Patidar, Mr. Parveen Sharma, Design of a Minimum Length Super Sonic Nozzle, International Research Journal of Modernization in Engineering Technology and Science, Volume 4, Issue 8, 2022.

[14]. Arun Bhaskar, Mithilesh K. Sahu, Numerical investigation on the performance of convergent-divergent nozzle with a multi-inlet combustion chamber of a rocket engine, 2022, pp. 5-21, https://doi.org/10.1002/htj.22296.

[15]. Reiner Decher, More Components: Inlets, Mixers, and Nozzles, The Vortex and The Jet, 2022, pp 137–154.

[16]. M Saleh, S Saleh, A Zayed, M Y M Ahmed, "Impact of nozzle profile on ballistic performance and structural loads", IOP Conference Series: Materials Science and Engineering, 2021 IOP Conf.

[17]. Barış Nigar, Serhan Dönmez, DemirkanÇöker, "Understanding the mechanical failure of graphite rocket nozzle throats under thermal stresses", Aerospace Science and Technology, Volume 119, 2021. https://doi.org/10.1016/j.ast.2021.107152

[18]. Xingyu Ma, Bing Sun, Taiping Wang, Di Liu, Experimental investigation of the gas film cooling efficiency of the cylindrical holes near the injector region, International Journal of Thermal Sciences, 2021. https://doi.org/10.1016/j.ijthermalsci.2021.106928

[19]. P. Naga Naveen, Mr.V. Phaninder Reddy, Dr. D. Govardhan, modeling and analysis of combustion instability using fuel injection, International Journal for Advanced Research in Science and Technology, Volume 11, 2021.

[20]. Shixiang Ji, Bing Wang, Dan Zhao, Numerical analysis on combustion instabilities in end-burning-grain solid rocket motors utilizing pressure-coupled response functions, Aerospace Science and Technology, 2020. https://doi.org/10.1016/j.ast.2020.105701 .

[21]. Vignesh Sella, Andrew Larkey, Abhiraj Majumder, Avinash Rao, Zavar Abidi, Aasheesh Randeo, Myron Liu, Avery K. Moore, Development of a Nytrox-Paraffin Hybrid Rocket Engine, AIAA Propulsion and Energy Forum, 2020. https://doi.org/10.2514/6.2020-3729 .

[22]. Jingying Zuo, Silong Zhang, DingyuanWei, Linghui Meng, Jiang Qin, Wen Bao, Oskar J.Haidn, Aerospace Science and Technology, Volume 106, 2020. https://doi.org/10.1016/j.ast.2020.106202

[23]. Mayank Verma, Nitish Arya, Ashoke De, Investigation of flow characteristics inside a dual bell nozzle with and without film cooling, Aerospace Science and Technology, Volume 99, 2020. https://doi.org/10.1016/j.ast.2020.105741.

[24]. Dirk Schneider, Ralf Stark, Chloé Génin, Michael Oschwald, Active Control of Dual-Bell Nozzle Operation Mode Transition by Film Cooling and Mixture Ratio Variation, Journal of Propulsion and Power, 2020. https://doi:org/10.2514/1.B37299

[25]. Ashish Kumar Samantra, Santhosh K S, Khalid Rashid, Jayashree, Study of expansion ratio on dual bell nozzle of LOX-RP1 engine for replacing the existing bell nozzle to dual bell nozzle, IOP Conference Series: Materials Science and Engineering, 2020.

[26]. Siba Prasad Choudhury Abhilash Suryan. J.C.Pisharady. Parametric study of supersonic film cooling in dual bell-nozzle for an experimental air-kerosene engine. Aerospace Science and Technology, Volume78,2018, page364-376.https://doi.org/10.1016/j.ast.2018.04.038

[27]. Barklage, R. Radespiel, Afterbody Jet Interaction of a Dual-bell Nozzle in Supersonic Flow. AIAA 2018-4468 German SFBTRR-40 I- Nozzles and Afterbody flow. Published Online- 2018. https://doi.org/10.2514/6.2018-4468

[28]. T. Hamitouche, M. Sellam, H. Kbab and S. Bergheul. Design and Wall Fluid Parameters Evaluation of the Dual-Bell Nozzle. International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 12, (2019), pp. 1064-1074. http://www.irphouse.com

[29]. Dirk Schneider, Ralf Stark, Chloe Genin, and Michael Oschwald, Active Control of Dual-Bell Nozzle Operation Mode Transition By Film Cooling And Mixture Radio Variation, 2019, Journal of Propulsion and Power 36(2):1-12. https://doi.org/10.2514/1.B37299.

[30]. Toufik Zebbiche, Supersonic Dual Dell Nozzle Axisymmetric Minimum Length Nozzle Conception for High Propulsion Thrust. International Journal of Aerospace and Space Sciences 20, 673-687. (2019) https://link.springer.com/article/10.1007/s42405-019-00164-7

[31]. Vladeta Zmijanovic, LucLeger Mohamed Sellam, Amer Chpoun, "Assessment of Transition Regimes in a Dual-Bell Nozzle and Possibility Of Active Fluidic Control", Aerospace Science and Technology, Volume 82-83. 2018. https://doi.org/10.1016/j.ast.2018.02.003.

[32]. Khaled Bensayah and El-Ahcene Mahfoudi, Numerical Prediction of Compressible Heat Flow with Complex Wall Temperature In Supersonic Rocket Nozzles. Thermal Science 8, Vol. 22, No. 6B. 2018. https://doi.org/10.2298/TSCI160616270B

[33]. Yeasir Mohammad Akib, Asif Kabir, and Mahdi Hasan. Critical Assessment of Altitude Adaptive Dual Bell Nozzle using Computational Fluid Dynamics. International Journal of Engineering Materials and Manufacture (1)15-21.2019. https://doi.org/10.26776/ijemm.04.01.2019.02

[34]. Manoj Kumar, R.K.Sahoo, S.K.Behera, “Design and Numerical Investigation to Visualize the Fluid Flow and Thermal Characteristics of Nom-axisymmetric Convergent Nozzle. Engineering Science and Technology”, an International Journal. Volume 22, Issue 1, pg 294-312. 2019. https://doi.org/10.1016/j.jestch.2018.10.006

[35]. G. Anugrah, P. Raja, M. Deepu and R. Sadanandan, “Experimental and Numerical Studies of Secondary Injection in Nozzle Divergence for Thrust Augmentation”, Journal of Applied Fluid Mechanics, Vol. 12, No. 5, pp. 1719-1728, 2019. https://doi.org/10.29252/jafm.12.05.29842

[36]. Mohammad Azis khan, Y.N.V. Santhosh Kumar, M. Venkatesh., “Numerical Investigation of Flow in Dual bell Nozzle”, IJEDR Volume 3, Issue 4, 2015.

[37]. Mohan Banoth., “Structural Analysis of Rocket Nozzle”, International Journal of Science and Research (IJSR), 2016.

[38]. John R. Howell, Mary K. Strife, and Harold E. Renket., “Analysis of Heat-Transfer effects in Rocket Nozzles Operating with very High-Temperature Hydrogen”, National Aeronautics and Space Administration, 1965.

[39]. Chlo´e G´enin, Andreas Gernoth, and Ralf Stark.,” Experimental and numerical study of heat flux in dual bell nozzles”, American Institute of Aeronautics and Astronautics, 2013.

[40]. Sandra Ludescher and Herbert Olivier., “Film Cooling in Rocket Nozzles”, Part of the Notes on Numerical Fluid Mechanics and Multidisciplinary Design book series (NNFM, volume 146), 2020.

[41]. Mayank Verma, Nitish Arya, Ashoke De.,” Investigation of Flow Characteristics inside a Dual Bell Nozzle with and without Film Cooling”, Aerospace Science and Technology, Volume 99,105741, 2020.

[42]. R. I. Jaffee, D. J. Maykuth, and V. D. Barth, “Fabrication of Tungsten for Solid - Propellant Rocket Nozzles”, Battelle Memorial Inst. Defense Metals Information Center,1961.

[43]. James R. Johnston, Robert A. Signorelli, and John C. Freche, “Performance or Rocket Nozzle Materials with Several Solid Propellants”, NASA Technical Note, 1966.

[44]. Len Schoenman, “4000°F Materials for Low-Thrust Rocket Engines”, JOURNAL OF PROPULSION AND POWER Vol. 11, No. 6,1995.

[45]. Oskar J. Haid, “Advanced Rocket Engines”, Advances on Propulsion Technology for High-Speed Aircraft (pp. 6-1 – 6-40),2008.

[46]. Ch. Stevenin, Y. Bereaux, J.-Y. Charmeau, J. Balcaen, “Shaping Air Flow Characteristics of a High-Speed Rotary-Bell Sprayer for Automotive Painting Processes”, *J*. Fluids Eng 137(11), 8pg, 2015.

[47]. Mohammed Faheem, Aqib Khan, Rakesh Kumar, Sher Afghan Khan, Waqar Asrar, Azan M. Sapardi,” Experimental study on the mean flow characteristics of a supersonic multiple jet configuration”, Aerospace Science and Technology, 2020.

[48]. Karna S. Patel, “Flow Analysis and Optimization of Supersonic Rocket Engine Nozzle at Various Divergent Angle using Computational Fluid Dynamics”, IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) Volume 11, Issue 6 Ver. IV, 2014.

[49]. J. L. Tuttle and D. H. Blount, “Perfect Bell Nozzle Parametric and Optimization Curve”, NASA Reference Publication 1104, 1983.

[50]. Beena D. Baloni, Sonu P. Kumar, S. A. Channiwala, “Computational Analysis of Bell Nozzles”, Proceedings of the 4th International Conference of Fluid Flow, Heat and Mass Transfer, 2017.

[51]. William F. Louisos and Darren L. Hitt, “Numerical Studies of Supersonic Flow in Bell-Shaped Micronozzles”, Journal of Spacecraft and Rockets Vol. 51, 2014.