NOZZEL OPTIMIZATION BY DUAL BELL TECHNIQUE

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ABSTRACT

The world today relies heavily on combustion of fossil fuels for its energy needs, as the major portion of energy used worldwide is contributed by combustion. Hence the scope of the combustion is very wide. Even in day to day life, we use combustion appliances directly or indirectly. The processes involved in combustion are governed by several different phenomena. This includes transport of mass, momentum and energy. We know that the driving forces such as concentration, pressure and temperature gradient can cause species transport, momentum transport and energy transport respectively.

Special attention is then given to altitude-adaptive nozzle concepts, which have recently received new interest in the space industry. The reduction of Earth-to-orbit launch costs in conjunction with an increase in launcher reliability and operational efficiency are the key demands on future space transportation systems, like single-stage-to- orbit vehicles (SSTO). The realization of these vehicles strongly depends on the performance of the engines, which should deliver high performance with low system complexity Current research results are presented for dual-bell nozzles. The main part of the paper addresses dual-bell nozzle concepts with improvements in performance as compared to conventional nozzle achieved by altitude adaptation and, thus, by minimizing losses caused by over- or under expansion.

1.INTRODUCTION

The most popular altitude-compensating rocket nozzle to date is the Dual bell nozzle, the origin of which dates back to Rocket dyne in the 1950s. This type of nozzle was designed to allow for better overall performance than conventional nozzle designs. The structure of this type of nozzle roots on its advantages of minimizing the losses encountered in the previous versions of the conventional types. The literature survey has been thoroughly studied and their researches were beneficial.

A nozzle is used to give the direction to the gases coming out of the combustion chamber. Nozzle is a tube with variable cross-sectional area. Nozzles are generally used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the exhaust stream that emerges from them. The nozzle is used to convert the chemical-thermal energy generated in the combustion chamber into kinetic energy. The nozzle converts the low velocity, high pressure, high temperature gas in the combustion chamber into high velocity gas of lower pressure and low temperature.

Flow phenomena observed in simulations during dual-bell nozzle operations are highlighted, critical design aspects and operation conditions are discussed, and performance characteristics of dual-bell nozzle are presented. The examination and evaluation of these loss effects is and has for some time been the subject of research at scientific institutes and in industry. Among the important loss sources in thrust chambers and nozzles are viscous effects because of turbulent boundary layers and the no uniformity of the flow in the exit area, whereas chemical non equilibrium effects can be neglected in H2 – O 2 rocket engines with chamber pressures above p=50 bar. Ambient pressures that are higher than nozzle wall exit pressures also increase the danger of flow separation inside the nozzle, resulting in the possible generation of side loads.

2. NEED FOR NEW DESIGN

The revolution in aerospace propulsion was increased greatly during World War 2. Faster, bigger and more efficient aerospace vehicles were required which led to the birth of Space research organizations like NASA. Speaking about the future, advanced rocket propulsion systems will require exhaust nozzles that perform efficiently over a wide range of ambient operating conditions. Most nozzles either lack this altitude compensating effect or they are extremely difficult to manufacture. Bell nozzles are currently used for all aerospace applications.

Bell nozzles are currently used for all aerospace applications. As stated earlier, the main drawback of this design is the decrease in efficiency with the increase in altitude as there is a loss of thrust in the nozzle. This occurs due to a phenomenon called “separation” of the combustion gases. For conventional bell nozzles, loss mechanisms fall into three categories:

- Geometric or divergence loss
- Viscous drag loss
- Chemical kinetics loss.

Geometric loss results when a portion of the nozzle exit flow is directed away from the nozzle axis, resulting in a radial component of momentum. In an ideal nozzle, the exit flow is completely parallel to the nozzle axis and possesses uniform pressure and Mach number. By calculating the momentum of the actual nozzle exit flow and comparing it to the parallel, uniform flow condition, the geometric efficiency is determined. By careful shaping of the nozzle wall, relatively high geometric efficiency can be realized.

A drag force, produced at the nozzle wall by the effects of a viscous high-speed flow, acts opposite to the direction of thrust, and therefore results in a decrease in nozzle efficiency. The drag force is obtained by calculation of the momentum deficit in the wall boundary layer. This viscous drag efficiency is defined as:

$$\eta_{drag} = 1 - \frac{\Delta C_{f(drag)}}{C_{f(ideal)}}$$

The third nozzle loss mechanism is due to finite-rate chemical kinetics. Ideally, the engine exhaust gas reaches chemical equilibrium at any point in the nozzle flow field, instantaneously adjusting to each new temperature and pressure condition. In real terms, however, the rapidly accelerating nozzle flow does not permit time for the gas to reach full chemical equilibrium

$$\eta_{kin} = 1 - \frac{\Delta C_{f(ODK)}}{\Delta C_{f(ODE)}}$$

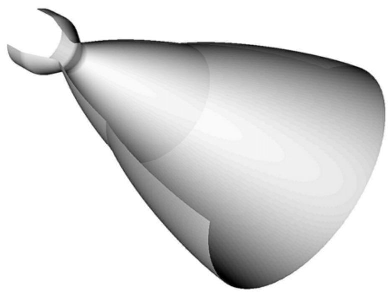
The overall nozzle efficiency is then given by the combined effects of geometric loss, viscous drag and chemical kinetics: $\eta kin = 0.99$(approximate)

$$\eta_{overall} = \eta_{geo} * \eta_{kin} * (1 - \eta_{drag})$$

A long nozzle is needed to maximize the geometric efficiency; but simultaneously, nozzle drag is reduced if the nozzle is shortened. If chemical kinetics is an issue, then the acceleration of exhaust gases at the nozzle throat should be slowed by increasing the radius of curvature applied to the design of the throat region. The optimum nozzle contour is a design compromise that results in maximum overall nozzle efficiency. Nozzle contours can also be designed for reasons other than for maximum thrust. Contours can be tailored to yield certain desired pressures or pressure gradients to minimize flow separation at sea level. A nozzle contour designed to produce parallel, uniform exit flow, thereby yielding 100 % geometric nozzle efficiency, is called an ideal nozzle.

This ideal nozzle is extremely long and the high viscous drag and nozzle weight that results are unacceptable. Some design approaches consider truncating ideal nozzles keeping in mind the weight considerations. Most companies have a parabolic curve-fit program, generally used to approximate optimum contours, which can also be used to generate desired nozzle wall pressures. For nozzles at higher altitudes, vacuum performance is the overriding factor relating to mission performance and high nozzle area ratio is therefore desirable. However, nozzle over-expansion at sea level does result in a thrust loss because the wall pressure near the nozzle exit is below ambient pressure. If the nozzles exit area could be reduced for launch and then gradually increased during ascent, overall mission performance would be improved. The ideal rocket engine would make use of a variable-geometry nozzle that adjusted contour, area ratio and length to match the varying altitude conditions encountered during ascent. This feature is referred to as Altitude Compensation.

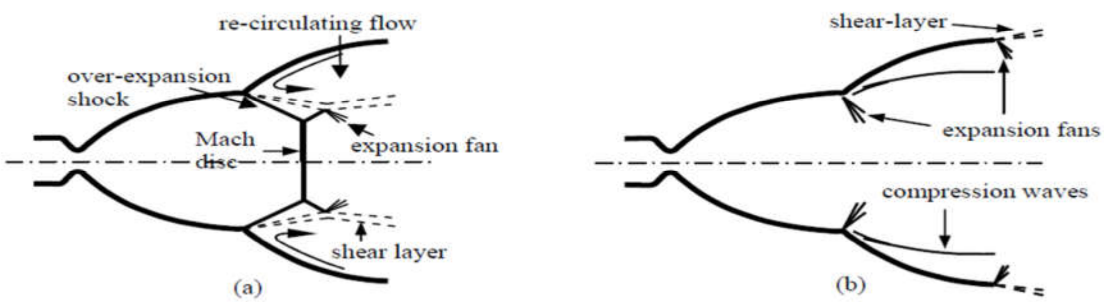
3. DUAL BELL NOZZLE



This nozzle concept was. First studied at the Jet Propulsion Laboratory in 1949. In the late 1960s, Rocket dyne patented this nozzle concept, which has received attention in recent years in the U.S. and Europe. Figure illustrates the design of this nozzle concept with its typical inner base nozzle, the wall inflection, and the outer nozzle extension. This nozzle concept offers an altitude adaptation achieved only by nozzle wall inflection. In low altitudes, controlled and symmetrical flow separation occurs at this wall inflection (Fig), which results in a lower effective area ratio. For higher altitudes, the nozzle flow is attached to the wall until the exit plane, and the full geometrical area ratio is used. Because of the higher area ratio, an improved vacuum performance is achieved. However, additional performance losses are induced in dual-bell nozzles, as compared with two baseline nozzles having the same area ratio as the dual-bell nozzle at its wall inflection and in its exit plane.

To gain insight into the performance and flow behavior of dual-bell nozzles at different ambient pressures, extensive numerical simulations with parametrical variations of contour de-sign parameters were performed. An optimized bell nozzle with equal total length and area ratio was used as the reference nozzle for comparison. As a result the vacuum performance of the dual-bell nozzles has degradation because of the imperfect contour, and this additional loss has the same order of magnitude as the divergence loss of the optimized bell nozzle.

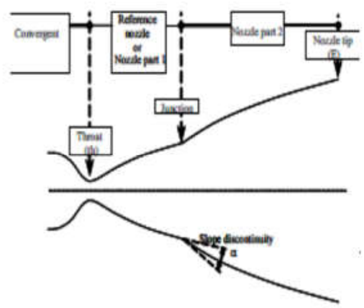
Flow transition behavior in dual-bell nozzles strongly depends on the contour type of the nozzle extension. A sudden transition from sea-level to vacuum operation can be, at least theoretically, achieved by two different extensions, with a zero wall pressure gradient (constant pressure extension), or a positive wall pressure gradient (overturned extension). But a critical analysis of the transition behavior considering decreasing ambient pressures during the launcher ascent revealed that a considerable time with uncontrolled flow separation within the nozzle extension exists even for these types of extensions. The duration of this period can be reduced drastically by throttling the chamber pressure.



Schematic of the exhaust flow pattern from a dual-bell nozzle in (a) low altitude mode and, (b) high-altitude mode

The main advantage of dual-bell nozzles as compared to other means of controlling nozzle flow separation is its simplicity because of the absence of any movable parts and, there-fore, its high reliability. It is necessary to note that the external flow over the vehicle in flight reduces the pressure in the vehicle base region, where engines are installed. The ambient pressure triggering the flow transition is the vehicle base pressure instead of the atmospheric pressure at the specific sight altitude. As the base pressure is lower than the atmospheric pressure, the nozzle flow transition occurs at a lower altitude than the one showed in which slightly decreases the efficiency of the dual-bell nozzle operation along the trajectory. During accent of the launcher, the ambient pressure decreases and at a certain altitude the flow jumps from the end of the first bell to the end of the nozzle extension, the second bell. The full flowing dual bell nozzle now works under high altitude conditions. The period of transition is sensitive to outer pressure field fluctuations and therefore of special interest. Figure below demonstrates the advantage of a **dual bell** in comparison with conventional bell nozzles with different expansion ratios.

A. Nomenclature of a dual bell nozzle



B. Nozzle Design parameters

Design parameters	Values
Throat RaidusR_{th}	15 mm
Exit area, a_e	14.3 in^2
Exit area ratio, a_e/a_b	4
Rocket flow specific heat ratio,	1.532
Nozzle exit mach number m_e	1.2
Rocket chamber pressure p_c	3200 Psia
Nozzle exit pressure p_e	3.41e+04 Pascal

Despite the additional losses induced in dual-bell nozzles, they still provide a significant net impulse gain over the entire trajectory as compared to conventional bell nozzles. The dual bell nozzle is an auto-adaptive concept, first proposed in 1949, relying on the altitude compensation. This concept uses a two section nozzle. The first part of the divergent is the reference nozzle or the base nozzle. The second part is the nozzle extension. At the junction between the two sections there exists a discontinuity of wall slope or wall inflection. In a dual bell nozzle there exists two flow regimes according to the nozzle pressure ratio (*NPR*) relatively to a critical value *crit NPR.* The nozzle pressure ratio is expressed as the ratio of the chamber pressure –or total pressure over the ambient external pressure, *t a NPR = p* as the chamber pressure of the engine is generally constant the *NPR* is continuously increasing during the ascent of the rocket.

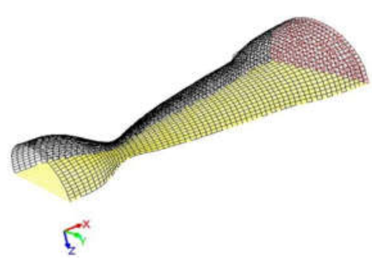
4.NUMERICAL METHODOLOGY

A numerical method adopted to approximate the governing equations, along with the relevant boundary conditions, by a system of linear algebraic equations is known as a discretization method. Thus, a problem involving calculus is transformed into an algebraic problem which can then be solved on a computer by using a solution methodology. A discretization technique and a solution methodology constitute the numerical methodology used to solve a heat transfer and fluid flow problem. There are many Discretization methods, but the most commonly used are the Finite difference method (FDM), the Finite volume method (FVM) and the Finite element method (FEM). During the early days of Computational fluid dynamics (CFD) finite-difference methods were the most popular. They are algorithmically simple, efficient, and accurate. However, they are best used on uniform grids and hence on regular computational domains. With advances of CFD, and its application to industrial problems, there is a need for methods for computing flows in complex geometries. To adapt the finite difference method to such geometries, we can map the

Complex domain into simple domains, either globally or locally, and solve the equations there. However, such transformation makes the governing equations take quite complicated forms and may lead to a loss of computational efficiency and accuracy. Alternatively, one can use schemes based on the finite volume methods directly on the physical domain (i.e. without transformation). Finite volume methods are essentially a generalization of the finite-difference method, but use the integral form of the governing equations of flow rather than their differential form. This gives greater flexibility in handling complex domains, as the finite volumes need not be regular. The FLUENT code, which is used to simulate the flow field is based on the finite volume discrtization scheme and is one of the best application software for this purpose.

5.MESHED GEOMETRY

As said above in nozzle design the spike bell nozzle is modeled and is further meshed using ANSYS 13.0GAMBIT Software. The mesh is of unstructured type.2Dmesh contains triangular elements and the 3D mesh contains tetragonal mesh elements.



E.FLOW ANALYSIS

The flow analysis for the dual bell nozzle is carried out using ANSYS 13.0 Fluent software. In this process first the models are imported, meshed and flow analysis is carried out in major three steps;

1. The first step is GAMBIT, where the meshed model is imported and boundaries are created and corresponding boundary conditions are assigned to the boundaries.
2. The second step is FLUENT-SOLVER, where the solutions are obtained by solving the equations and process is highlighted in terms of codes and graphs and once the run is over it reaches next step.
3. The third step is FLUENT, where the corresponding contours are created for following major parameters such a Pressure, Temperature and Mach number.

B. Stages in a CFD Simulation

The main stages in a CFD simulation are:

Pre-processing:

– Formulation of the problem (governing equations and boundary conditions);

– Construction of a computational mesh (set of control volumes).

Solving:

– Discretisation of the governing equations;

– Solution of the resulting algebraic equations.

Post-processing:

– Visualization (graphs and plots of the solution);

– Analysis of results (calculation of derived quantities: forces, flow rates, ...)

Nozzle Materials

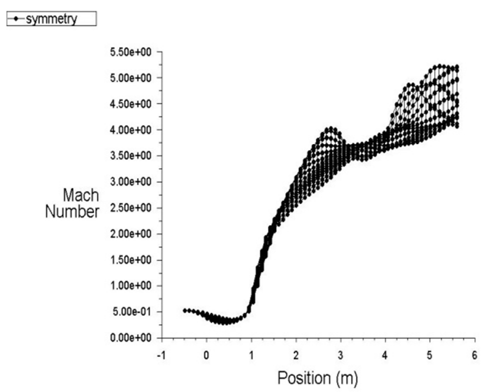
The materials used in the fabrication of solid propellant rocket motor nozzles can be divided generally into five classes: structural materials; adhesives; sealants and greases; thermal insulators; and ablative (erodible) materials.

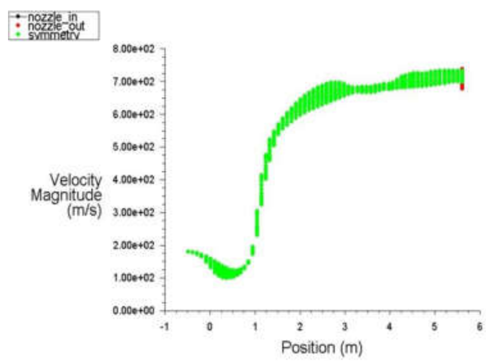
Structural materials are applied generally according to the maximum operating temperature to which they will be exposed upto 500 °F, the most used materials are aluminum alloys and fiberglass-resin composites, both of which have high-strength-to-weight ratios, are light in weight, easily fabricated, have good corrosion resistance, and are reasonable in cost. High strength steels are used when major considerations are high strength in thin sections, or operation at the higher end of the temperature range.Between 500 °and 1,900 °F-, the higher temperature iron, iron-nickel, nickel, cobalt, and iron-nickel-cobalt chromium base super alloys are used.Above 1,900 F, alloys of refractory metals (capable of resisting high heat without cracking, melting or crumbling) such as molybdenum, columbium, tantalum, and tungsten provide high strength to approximately 4,500 °F. Above 4,500 °F, about the only structural materials available are graphite and pyrolytic graphic.

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

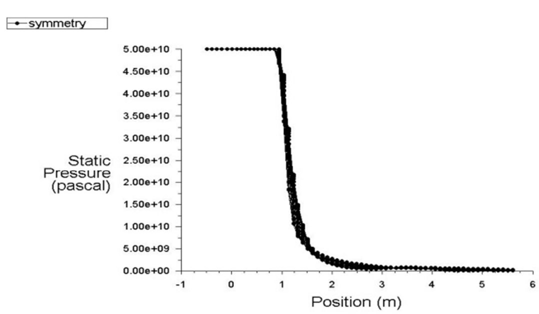
RESULTANT GRAPHS

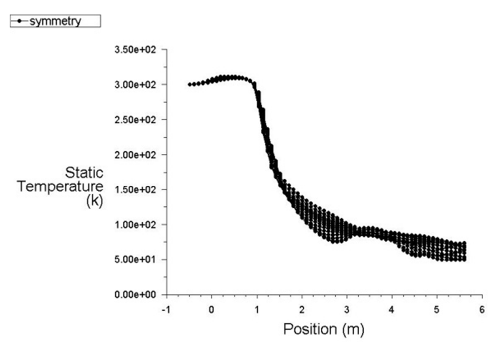
MACH NUMBER VELOCITY MAGNITUDE



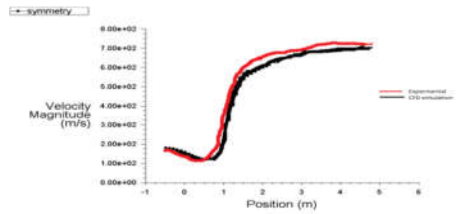


STATIC PRESSURE STATIC TEMPERATURE





Results comparison between experimental and CFD simulation



MERITS

The dual bell nozzle has 90% overall better performance than the conventional bell-shaped nozzle. The efficiency at low altitudes is much higher because the atmospheric pressure restricts the expansion of the exhaust gas. A vehicle using a dual bell nozzle also saves 25-30% more fuel at low altitudes. At high altitudes, the dual bell nozzle is able to expand the engine exhaust to a larger effective nozzle area ratio. The dual bell design is suitable for Single Stage to Orbit (SSTO) flight. Other advantages are that the dual bell nozzle makes better use of the base area, and has higher thrust efficiency and thus a higher average specific impulse.

CONCLUSIONS

The following observations were found in CFD Analysis of the **Dual bell** nozzle

Mach number

The Mach number at the exit is found to be 5.43Mach (super-sonic).

Static pressure

The Dynamic pressure value of 5.74 e+08 Pa at the exit section due to the expansion of the fluid towards the exit of the nozzle. Here pressure value is decreases inlet to exit area of nozzle.

Velocity

The velocity value of Nozzle increases inlet to exit the velocity at the exit is found to be 7.37 e+02.

Static Temperature

The **Static Temperature** of bell nozzle decreases from inlet to exit at the exit is found to be 4.61 e+01 m/s.

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