RNI Regd No: APENG/2011/47294 ISSN No: 2320-3706(PRINT)
International Journal & Magazine of Engineering, Technology, Management and Research
YuvaEngineers
Transforming Young Engineers for Better Tomorrow

Computational Modeling and Comparative Analysis of Dual Bell Nozzle with Bell Nozzle

Mr.MD Khaleel
Assistant Professor,
Department of Aerospace Engineering,
MLR Institute of Technology and Management.

Niharanjan Hazarika
M.Tech IInd Year II sem,
Department of Aerospace Engineering,
MLR Institute of Technology and Management.

Abstract:

The concept of Altitude adaptive rocket nozzles recently received greater importance and interest in the space explorations and other such applications in space and rocket technology. In the recent progress of the combustion expansion system the rocket nozzles are greatly revised from both application and design perspectives. One of such development is the dual bell nozzle. Dual Bell Nozzle is an advanced rocket engine nozzle concept with an altitude-adapted capability. The main advantage of the Dual Bell Nozzle is to increase the efficiency of the nozzle. This nozzle concept is promising for application to existing and near term launch vehicle with a simple modification to current bell type nozzle configuration. The design and analysis of Dual Bell Nozzle and Bell Nozzle will be done in Catia, Hypermesh and Fluent software. The values of Mach number, pressure and temperature of Dual Bell Nozzle will be compared with Bell Nozzle.

Keywords:
Bell Nozzle, Dual Bell Nozzle, Performance, Mach, Dynamic Pressure, Velocity

Introduction:

The dual-bell altitude adaptation concept is realized by a combination of two bell nozzles via an inflection point in one structural frame. It has a number of advantages in comparison with the single-bell nozzles in addition to the fact that it provides a stable over expanded flow at low altitudes (a sea-level operation mode or OM1) and a high specific impulse at high altitudes (a high-altitude operation mode or OM2). At low altitudes, controlled and symmetrical flow separation occurs at the wall inflection, which results in a smaller effective area ratio. At higher altitudes the separation region moves downstream and the nozzle flow is attached to the wall until the exit plane thus the full area ratio is used.

Due to the higher area ratio, a better performance can be achieved in comparison with the sea-level operation. Results of tests performed by Rocket dyne on subscale nozzle have shown that some additional losses in performance are induced in the dual-bell nozzles. The pressure within the separated flow region of the dual-bell nozzle extension at the sea-level operation is slightly below the ambient pressure, inducing a thrust loss named aspiration drag. In addition, the flow transition occurs before the optimum cross-over point, which leads to thrust losses in comparison to an ideal switchover.

Bell Nozzle and Dual Bell Nozzle

The Bell-shaped or Contour nozzle is probably the most commonly used shaped rocket engine nozzle. It has a high angle expansion section (20 to 50 degrees) right behind the nozzle throat; this is followed by a gradual reversal of nozzle contour slope so that the nozzle exit the divergence angle is small, usually less than a 10 degree half angle.

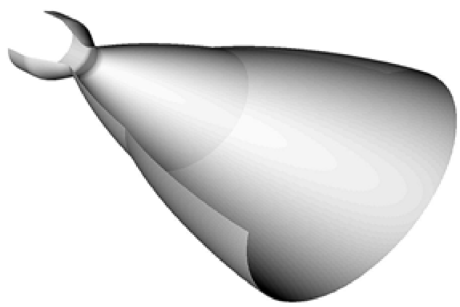


Fig1:Dual Bell Nozzle

The dual-bell rocket nozzle was first proposed in 1949, offering a potential improvement in rocket nozzle performance over the conventional-bell nozzle. 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 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.

Literature Survey:

The dual bell nozzle has been found out to be one of the most promising concepts for altitude adaption of the nozzle jet. The wall contour inflection linking the base nozzle with the ex-tension provides two stable operating modes, circumventing the area ratio limitation inherent to conventional main stage engine nozzles. During the past decade, numerous experimental as well as analytical investigations have been conducted at the German Aerospace Centre for a better understanding and the qualification of the dual bell concept for main stage engine application. Cold and hot flow tests aimed to point out the influence of the geometrical parameters on the flow behavior. Rao, developed a method for designing the wall contour of an exhaust nozzle to yield optimum thrust. K.M. Pandey , conducted studies to understand the gas flows in a conical nozzle at different degree of angle using 2 dimensional axisymmetric models. Munday et al, conducted experiments and numerical simulation on conical convergent divergent nozzles with a design Mach number of 1.56.

Nevertheless, the upgrade of existing engines with better performing subsystems, such as turbines and pumps also leads to a gain in overall performance data and is discussed. Nozzle performance of conventional rocket engines is already very high with regard to internal loss effects (friction, non-uniformity). However, for nozzles of gas-generator open-cycle engines such as the Vulcain engine, a slight improvement in performance can be achieved with turbine exhaust gas (TEG) injection into the main nozzle as realized in the F-1 (kerosene– oxygen engine first stage of Saturn-5 launcher) and J-2S, and it is foreseen for the Vulcain engine (hydrogen– oxygen engine, upgrade of Vulcain engine), and confirmed by numerical simulations and experimental results. This is mainly achieved through lower friction losses in the main nozzle and because the bypass nozzles used for the expansion of the TEGs, which have higher divergence losses, are removed. Despite the slight performance gain by TEG injection, the low-pressure near-wall stream of the injected gas favors a reduction of the critical pressure ratio at which flow separation occurs and, therefore, an earlier nozzle flow separation Furthermore, the presence of the secondary exhaust gas injection complicates nozzle-contouring methods with regard to the avoidance of uncontrolled flow separation for first-stage or booster nozzles.

Methodology:

A detailed study of concepts for the project is carried out. A procedural theoretical approach of nozzles is carried out and the models of nozzles namely the full length Dual-bell nozzle created using Catia software. The next step goes to the meshing and analysis of the dual bell model using GAMBIT and FLUENT software. The behavior of flow along the dual bell nozzle is thus obtained and comparison on the basis of Mach number is henceforth done using theoretical calculations. The material is selected as air and the density as ideal gas to make the solution simpler. Under the solve command the control is selected for limiting the pressure to a maximum of 5e+7 and Minimum of 1e+4. The initialization of value is computed from the inlet. It is also necessary to select the appropriate approximation required in the residual command under monitors and check in plot to visualize the progress of iteration. Once every parameter is described the iteration is performed till the value gets converged to required approximation. The Figures can be plotted between position in x-axis and any other function in y-axis from plot command or else to view vectors, contours or grid display command is to be chosen. A mathematical model consists of differential equations that govern the behavior of the physical system, and the associated boundary conditions.

Designing and Analysis of Bell and Dual Bell Nozzle

Bell Nozzle Design

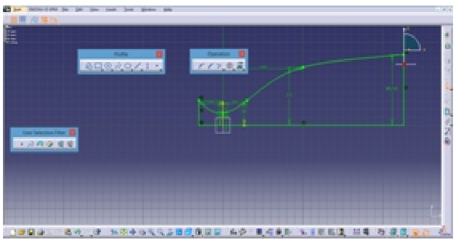


FIG 2:CONSTRAINT VIEW OF BELL NOZZLE.

The 2-D figure has been drawn as per the dimension and are to be fixed to constrains.. Then the 2-d figure is revolved in solid workbench along its longitudinal axis. A 3-D solid model is been designed.

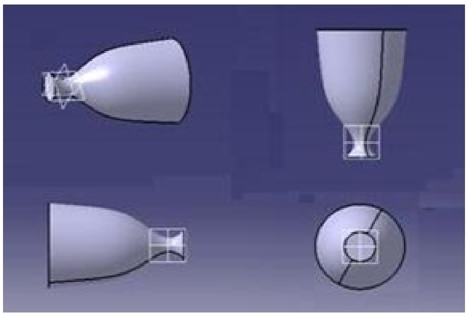


FIG 3: DIFFERENT VIEWS OF BELL NOZZLE

Dual Bell Nozzle

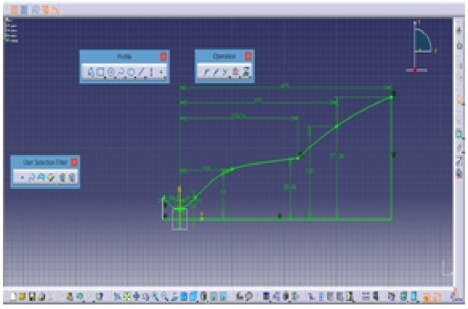


FIG 4: CONSTRAIN VIEW OF DUAL BELL NOZZLE

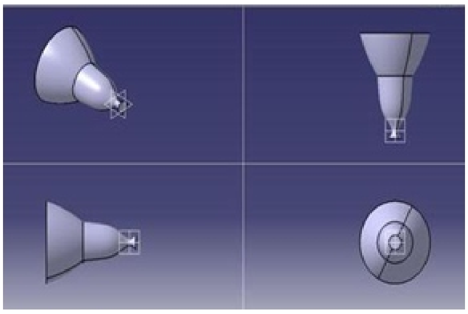


FIG 5: DIFFERENT VIEWS OF DUAL BELL NOZZLE.

Meshing in Hypermesh

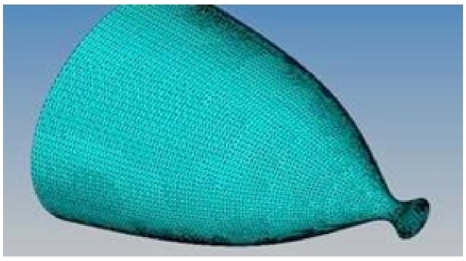


FIG 6: MAKING OF FINE TETRA MESH OVER

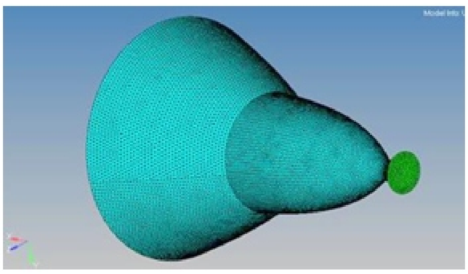


FIG 7: COMPLETE MESHED PART OF THE DUAL THE FACE OF THE BELL NOZZLE BELL NOZZLE.

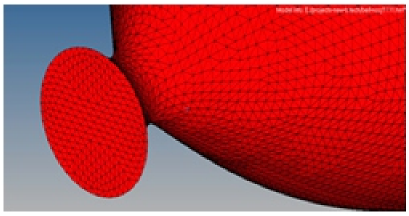


FIG 9: CREATING 3-D MESH USING TETRA MESH.

Shift F11—to move the face in required collector.
Face mesh has to done since we are considering the velocity inlet and finding the values of interior of nozzles, therefore here the outer surface of the above figure acts as interior surface of the original Nozzle.

Defining Boundary Conditions

INLET: So as to simulate the real condition of a flow entering a CD nozzle, instead of using a constant inlet temperature, a non-uniform profile was applied. In order to have hypersonic flow at the exit of the nozzles, the inlet pressure applied must be very high. The value defined as inlet total pressure was 9 bar. An initial guess had also to be input. For a subsonic inlet, as in this work, the initial guess should be the value of the static pressure. This value can be calculated from the 1D analysis. Temperature considered near the axis was 2200 K and it was decreasing radially at the inlet until 1000 K near the wall.

OUTLET:

The exit pressure was defined as 115200 Pascal. However, this value is used for subsonic flow only. Should the flow become locally supersonic, the pressure is extrapolated at the exit boundary. \

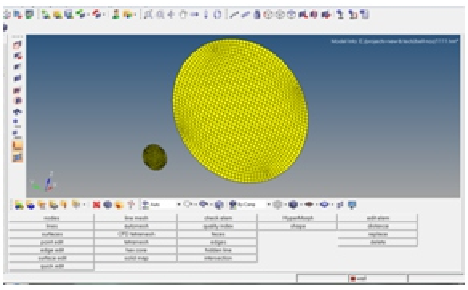


FIG 10 : INLET AND OUTLET

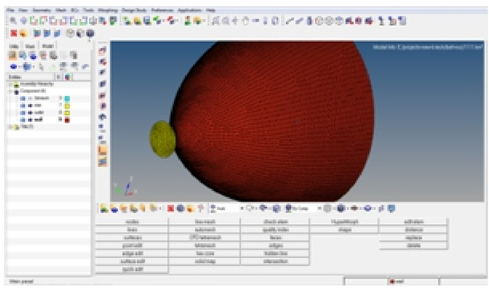


FIG 11: WALL BOUNDARY CONDITIONS.

WALL:The wall was considered adiabatic. Therefore, the heat flux is zero. After applying all settings, the simulation should be initialized. However, the discretization methods and the under-relaxations factors must be defined first. The aim is to get convergence by using the second-order upwind method for flow, turbulent kinetic energy and specific dissipation rate, in order to reduce the numerical diffusion. Higher order approximations, such as the third-order QUICK scheme is not necessary. Since the cases are 2D, the second-order provides accurate results. However, in most of the cases, it was not possible to achieve the convergence directly, using the initial guess specified in boundary conditions. Therefore, it was necessary to start with the first-order upwind scheme. Since the convergence was reached, this solution was used as initial guess for the second-order upwind.

Analysis of Bell and Dual Bell Nozzle

TABLE 1: ASSIGNING INPUT VALUES

OPERATING CONDITIONS	OPERATING PRESSURE	0
BOUNDARY CONDITIONS	INLET	PRESSURE INLET
	OUTLET	PRESSURE OUTLET
	WALL	WALL
	AXIS	SYMMETRY
TEMPERATURE	T=300k	
VELOCITY	V=640m/s	

Boundary Conditions

The following boundary conditions can be specified:
•Mach number at the inlet
•Static exit pressure
•Pressure ratio, the ratio of static pressure at the exit to static pressure at the inlet
•Static temperature at the inlet
The following boundary conditions are assigned in FLUENT:
•Boundary Assigned As
•Nozzle Wall
•Inlet Pressure Inlet
•Exit Pressure Outlet

After analyzing the designed Bell Nozzle and Dual Bell Nozzle in Fluent software, these results are been obtained for different parameters at different Mach No. or Velocities. These Dual Bell Nozzle results are further compared with Bell Nozzle to know the efficiency and advantages at all conditions. The obtained results are shown below

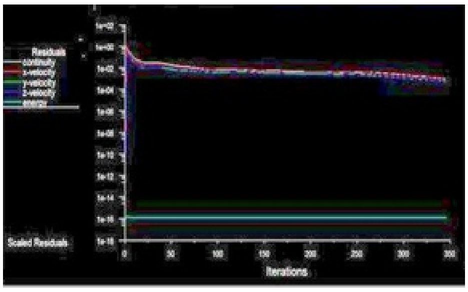
AT MACH = 2.5
A) BELL NOZZLE

```
flow in 1802 faces on pressure-outlet 6.
flow in 1805 faces on pressure-outlet 6.
flow in 1805 faces on pressure-outlet 6.
flow in 1807 faces on pressure-outlet 6.
flow in 1809 faces on pressure-outlet 6.
flow in 1810 faces on pressure-outlet 6.
flow in 1814 faces on pressure-outlet 6.
flow in 1813 faces on pressure-outlet 6.
flow in 1814 faces on pressure-outlet 6.
flow in 1815 faces on pressure-outlet 6.
! 346 solution is converged
```

Fig 12: Iterations Convergent value.

Solution is converged at 346.

Bell Nozzle Graph of iterations



PLOT 13: ITERATIONS GRAPH

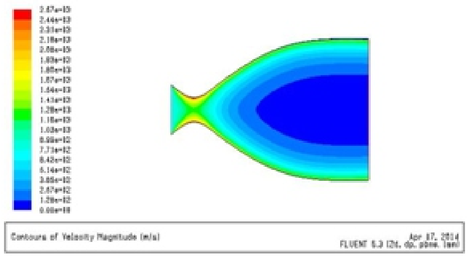


FIG 14: CONTOURS OF VELOCITY MAGNITUDE (m/s)

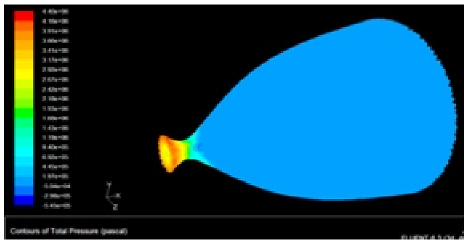


FIG 15: CONTOURS OF TOTAL PRESSURE (PASCAL) (3D)

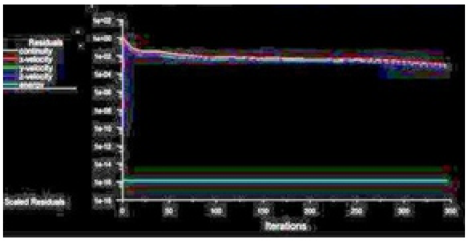
B) DUAL BELL NOZZLE:

```
flow in 1802 faces on pressure-outlet 6.
flow in 1805 faces on pressure-outlet 6.
flow in 1805 faces on pressure-outlet 6.
flow in 1807 faces on pressure-outlet 6.
flow in 1809 faces on pressure-outlet 6.
flow in 1810 faces on pressure-outlet 6.
flow in 1814 faces on pressure-outlet 6.
flow in 1813 faces on pressure-outlet 6.
flow in 1814 faces on pressure-outlet 6.
flow in 1815 faces on pressure-outlet 6.
! 346 solution is converged
```

Fig 16: Iterations Convergent value.

Solution is converged at 346.

Dual Bell Nozzle Graph of iterations



PLOT 17: ITERATIONS GRAPH

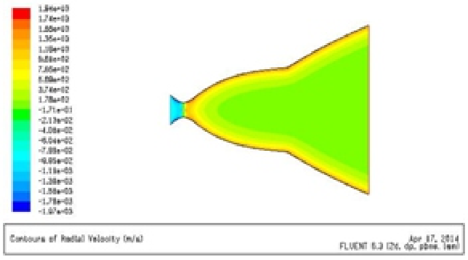


FIG 18:CONTOURS OF RADIAL VELOCITY (m/s).

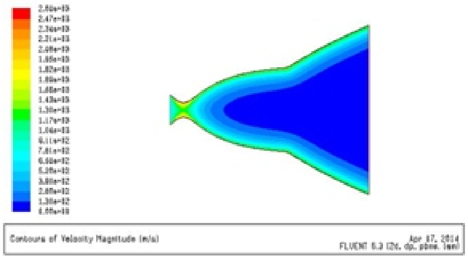


FIG 19: CONTOURS OF VELOCITY MAGNITUDES (m/s)

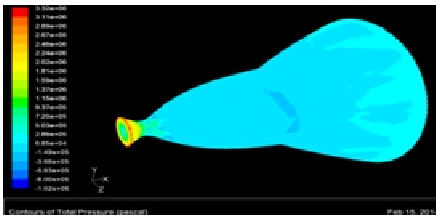


FIG 20: CONTOURS OF TOTAL PRESSURE (PASCAL) (3D)

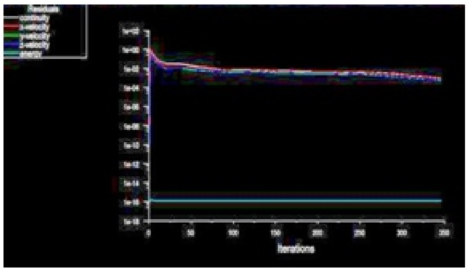
AT MACH =3,
A) BELL NOZZLE

```
Flow in 1802 faces on pressure-outlet 6.
Flow in 1805 faces on pressure-outlet 6.
Flow in 1805 faces on pressure-outlet 6.
Flow in 1807 faces on pressure-outlet 6.
Flow in 1809 faces on pressure-outlet 6.
Flow in 1810 faces on pressure-outlet 6.
Flow in 1814 faces on pressure-outlet 6.
Flow in 1813 faces on pressure-outlet 6.
Flow in 1814 faces on pressure-outlet 6.
Flow in 1815 faces on pressure-outlet 6.
! 346 solution is converged
```

FIG 21: Iterations Convergent value.

Solution is converged at 346.

Bell Nozzle Graph of iterations



PLOT 22: ITERATIONS GRAPH.

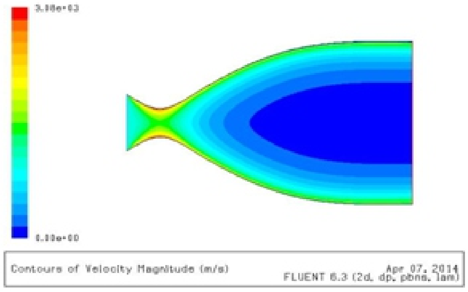


FIG 23: CONTOURS OF VELOCITY MAGNITUDES (m/s)

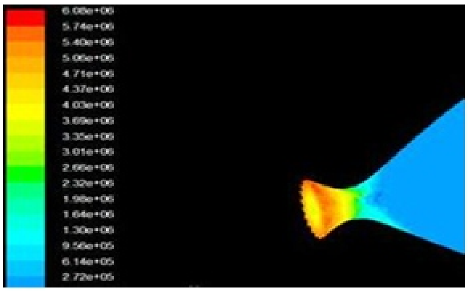


FIG 24: CONTOURS OF TOTAL PRESSURE (PASCAL) (3D)

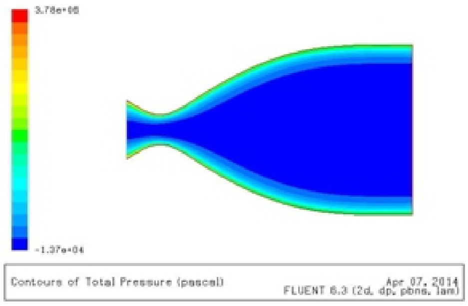


FIG 25: CONTOURS OF TOTAL PRESSURE (PASCAL)

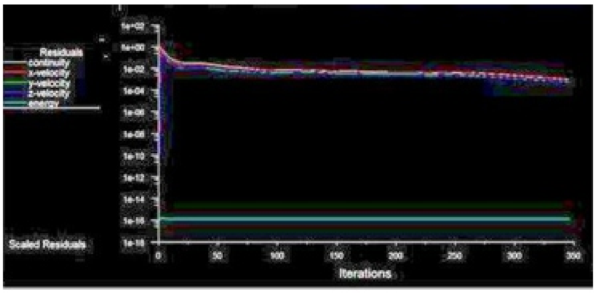
B) DUAL BELL NOZZLE

```
flow in 1802 faces on pressure-outlet 6.
flow in 1805 faces on pressure-outlet 6.
flow in 1805 faces on pressure-outlet 6.
flow in 1807 faces on pressure-outlet 6.
flow in 1809 faces on pressure-outlet 6.
flow in 1810 faces on pressure-outlet 6.
flow in 1814 faces on pressure-outlet 6.
flow in 1813 faces on pressure-outlet 6.
flow in 1814 faces on pressure-outlet 6.
flow in 1815 faces on pressure-outlet 6.
! 346 solution is converged
```

FIG 26: ITERATIONS CONVERGENT VALUE.

Solution is converged at 346.

Dual Bell Nozzle Graph of iterations



PLOT 27: ITERATIONS GRAPH.

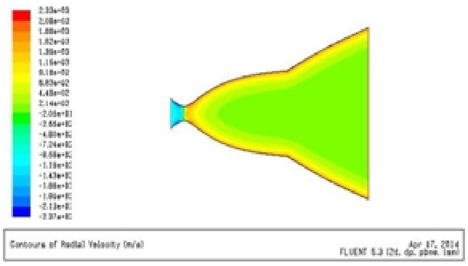


FIG 28: CONTOURS OF RADIAL VELOCITY (m/s).

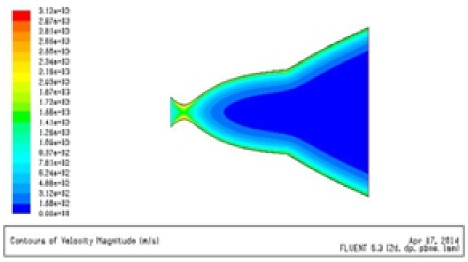


FIG 29: CONTOURS OF VELOCITY MAGNITUDES (m/s)

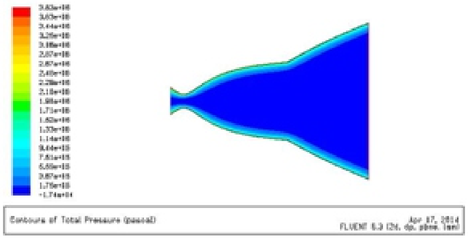
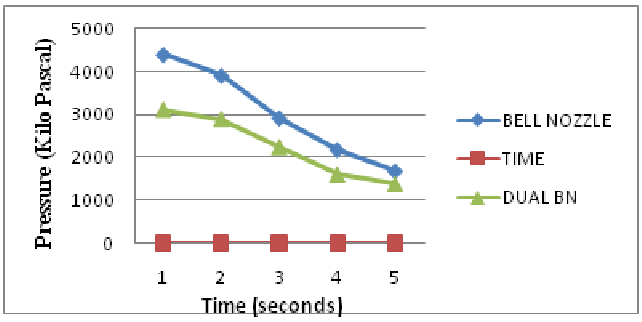


FIG 30: CONTOURS OF TOTAL PRESSURE (PASCAL)

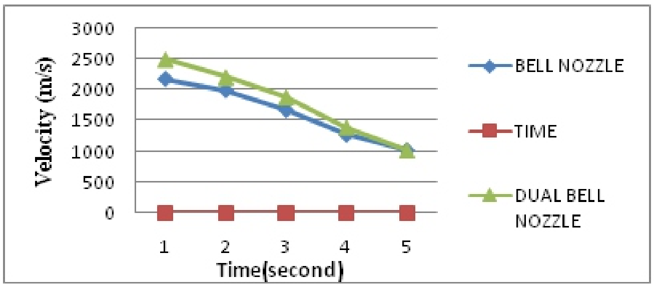
RESULTS:

In this project, the performance of both the nozzles are being analysed and the obtained values are being compared for both Bell Nozzle and Dual Bell Nozzle with respect to time. These results are shown below in graphs:-

At Mach=2.5

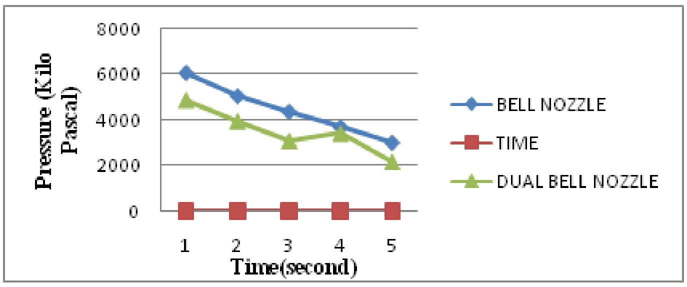


PLOT 31:- PRESSURE VERSUS TIME

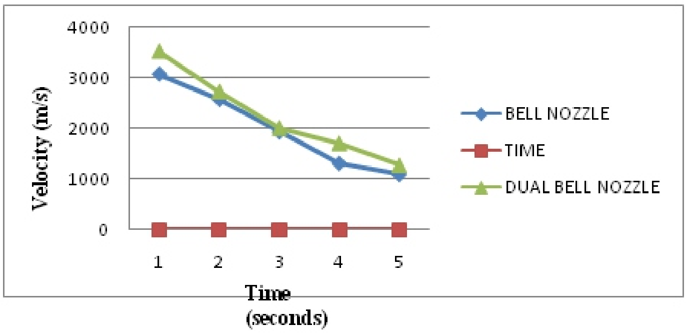


PLOT 32:- VELOCITY VERSUS TIME

At Mach=3



PLOT 33:-PRESSURE VERSUS TIME



PLOT 34:-VELOCITY VERSUS TIME

COMPARISION OF BELL AND DUAL BELL NOZZLE

TABLE 2 :COMPARISION OF BELL AND DUAL BELL NOZZLE

		Mach =2.5	Mach=3.0
PRESSURE(KP)	BELL NOZZLE	4400	6080
	DUAL BELL NOZZLE	3110	4850
VELOCITY(m/s)	BELL NOZZLE	2180	3080
	DUAL BELL NOZZLE	2400	3520

CONCLUSION:

The following observations were found in the Dual bell nozzle and bell nozzle Dynamic Pressure: The dynamic pressure value decreases at the exit section due to the expansion of the fluid towards Here pressure value is decreases inlet to exit area of nozzle. Similarly for bell nozzle as the gas travels down the expansion part of the nozzle the pressure it increases Velocity: The velocity value of bell and dual bell Nozzle increases inlet to exit the velocity at the exit . From all of the above result we can conclude that dual nozzle efficiency much more than that of the bell nozzle. 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.

FUTURE SCOPE:

The dual bell nozzle design is modified with a clustered arrangement at the throat section. It is believed that the nozzle would achieve an even higher performance by making an optimal use of the flow in future. By achieving above task mentioned, this model is further implemented into rocket model and further research is carried out. The fuel selection and gas selection is made with an most important part which falls on material selection (mostly composite materials) is carried out to obtain suitable mass fraction at each stage.

The various parameters for each stage such as dry mass, Chamber pressure, Sea level Thrust, Vacuum thrust and Separation/Burnout (for time and altitude) are identified. Today, most nozzle transient predictions are performed using empirical methods that can be refined through engine test correlations, as in the skewed plane method, or through numerical simulations. An improved analytical framework can help to guide these experimental and numerical investigations, as well as provide insight into the physical processes that affect some of the attendant phenomena. Future research efforts would include incorporation of two-dimensional effects as well as oscillatory models to account for both steady and unsteady forces observed during the blow down process. It is hoped that these effects will be further investigated, as it seems that they have been habitually avoided in the past.

REFERENCES:

1.Manski, D. and Hagemann, G., "Influence of Rocket Design Parameters on Engine Nozzle Efficiencies," Journal of Propulsion and Power, Vol. 12, No. 1, 1996.
2."Liquid Rocket Engine Nozzles," NASA Space Vehicle Design Criteria, NASA SP-8120, 1976.
3.Dumnov, G. E., Nikulin, G. Z., and Ponomaryov, N. B., "Investigation of Advanced Nozzles for Rocket Engines," Space Rocket Engines and Power Plants, Vol. 4, No. 142, NIITP, 1993, pp. 10.12 –10.18 (in Russian).
4.Nguyen, T. V., and Pieper, J. L., "Nozzle Flow Separation," Proceedings of the 5th International Symposium of Propulsion in Space Transportation (Paris, France), 1996.
5.Manski, D., "Clustered Plug Nozzles for Future European Reusable Rocket Launchers," German Aerospace Research Establishment,643-81/7, Lampoldshausen, Germany, 1981 (in German).
6.14Manski, D., Goertz, C., Saßnick, H.-D., Hulka, J. R., Goracke, B.D., and Levack, D. J. H., "Cycles for Earth-to-Orbit Propulsion," Journal of Propulsion and Power, Vol. 14, No. 5, 1998, pp. 588 – 604.
7.Foster, C. and Cowles, F., Experimental study of gas-flow separation in overexpanded exhaust nozzles for rocket motors, Progress Report, 4-103, Jet Propulsion Laboratory, 1949.
8.Horn, M. and Fisher, S., Dual-Bell Altitude Compensating Nozzles, NASA-CR-194719, 1994.
9.Hagemann, G., Immich, H., Van Nguyen, T. and Dumnov, G., Advanced Rocket Nozzles, Journal of Propulsion and Power, 1998.
10.Spalart, P. and S. Allmaras, S. A one-equation turbulence model for aerodynamic flows, Technical Report AIAA-92-0439, American Institute of Aeronautics and Astronautics, 1992.