Numerical Investigation of Flow in Duel bell Nozzle

Mohammad Azis khan, Y.N.V. Santhosh Kumar, M.Venkatesh
Student, Assistant professor, Assistant professor
Department of Aeronautical Engineering,
Nimra Institute of Science and Technology, Vijayawada, India

***Abstract* - The dual bell nozzle is a concept of altitude adaptive nozzles. The flow adapts separation at the wall inflection at low altitude, and full flowing at high altitude. To understand the phenomenology of the flow by the transition from sea level to high altitude mode, a series of CFD Simulations are carried out understand the physics of flow. Its results are compared with conventional bell nozzle. ANSYS ICEMCFD and CFX are used for simulations. Parametric numerical simulations of the flow field development are performed to quantify the different losses due to flow separation. A secondary injection method is used to avoid flow separation thus the effect of side loads on nozzle. Various injection speeds are also considered in the present analysis and its effect on efficiency of nozzle. Results Has been extracted using ANSYS CFD POST with Velocity streamlines, temperature contours, Mach plots etc.**

***Keywords* – Flow separation, Shock formation ,TOP nozzle, Rao's contour, Pressure variation.**

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1. INTRODUCTION

A goal of the aerospace engineering community is to develop more efficient and reliable methods to transport payloads into orbit .As a part of that increasing the efficiency of nozzle also been focused for creating the most efficient single-stage-to-orbit (SSTO) rocket possible.

In an idealized nozzle, maximum efficiency is achieved when the gas is expanded isentropically to exasctly the same pressure as the ambient pressure just beyond the exit plane of the nozzle. However, ambient pressure is a function of altitude. Conventional nozzles, which refer to any nozzle with a single, continuous contour between the throat and the exit, are designed to be optimally expanded at one mid-range altitude. Consequently, these nozzles are over-expanded at low altitudes, since they produce an exit pressure less than ambient pressure, and under-expanded at high altitudes, since they produce an exit pressure greater than ambient in these conditions [1].

In the over-expanded case, the exhaust plume separates from the wall inside of the nozzle rather than at the nozzle lip, which occurs at the design altitude. When a nozzle is highly over- expanded, a flow separation phenomenon can occur which creates dangerous side loads. Side loads are caused by the interactions between the boundary layer of the separated flow and internal shocks. Changes in the turbulent velocity profile found in the separated region can result in unsteady shock behavior [1] in which a shock can alternate between free shock separation (FSS) and restricted shock separation (RSS)..

In the under-expanded case, the exhaust gas continues to expand after it leaves the nozzle.. Since energy is released after the gas leaves the nozzle, Thus, under-expansion results in a considerable decrease in engine efficiency at altitudes above the design altitude [3].

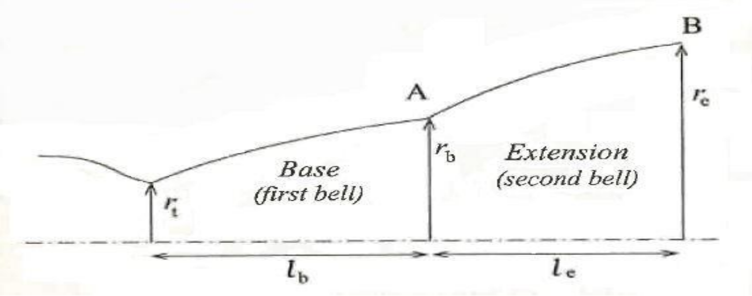

Figure 1.1:A Dual-BellNozzle[Copyright©Nasuti,F., Onofri, M.,&Martelli,E., 2005[4]]

Dual-bell nozzles have been explored as a possible solution to maximizing efficiency at high altitude while avoiding dangerous side loads at low altitudes. A dual-bell nozzle differs from a conventional nozzle in that it has two distinct contours as opposed to one between the throat and exit. A dual-bell nozzle consists of a base contour that is separated from the extension contour by an inflection in the wall (see Figure 1). The effective cross sectional "exit" area of the base nozzle is the area at the wall inflection. This area can be manipulated such that an effective exit pressure for this section is matched to a relatively low-altitude pressure condition. The inflection acts as a separation point and the separated flow is contained in the additional axisymmetric area given by the extension contour. By controlling the separated flow, side loads can be mitigated at low altitudes. As the rocket's altitude increases, ambient pressure decreases and the exhaust gases need a larger expansion ratio to approach the ambient conditions for that the flow re-attaches to the wall of the extension section . The exit area of the extension section of the nozzle is sized for high altitude operation, thereby reducing efficiency losses due to under- expansion. The dual-bell nozzle is an altitude adaptive nozzle by having a wall inflection that allows one nozzle to be matched to two different ambient pressures [2].

Dual Bell Nozzle History

The dual-bell concept was first introduced in literature in 1949 by F. Cowles and C.Foster
Horn and Fisher tested four contour combinations to find the extension contour that provided the most favorable flow transition characteristics and high altitude performance when compared to the performance of two baseline contours. In their testing, a 16:1 expansion ratio Rao optimized contour was used as the base contour for each test nozzle. The extension contours that were tested were selected based on the pressure gradients that were produced, since this gradient affects overall performance as well as flow transition characteristics. They tested conical and Rao contours, which both produce a negative pressure gradient, a "constant pressure" contour that produced no pressure gradient, and an overturned contour, which produced a positive pressure gradient. They concluded that a constant pressure contour extension provided the most beneficial combination of flow characteristics over the course of a SSTO flight. However, they also demonstrated that real dual-bell nozzles fall short of the theoretical optimum due to losses sustained from aspiration drag, earlier-than-ideal flow separation, and a non-optimal contour for high altitude flight. Even with these additional losses, Horn and Fisher found that a dual-bell nozzle could provide enough thrust to carry 12.1% more payload than a conventional nozzle of the same area ratio [9].
The Rao's method of characteristics uses the method of characteristics to design nozzles. A kernel flow, flow in the initial expansion region of the nozzle, is generated with the method of characteristics for a wide variety of flow angles [1]. Next, the curvature of the throat is defined and a nozzle curve is generated using other given parameters such as the area ratio and the length of the nozzle. The contour is created by picking points on the flow field that result in a smooth, theoretically shock less flow back to the throat. This process is rather complex, and the resulting thrust optimized contour can only be defined by a coordinate list. Rao decided to approximate this contour from the inflection point to the nozzle exit with a parabola.

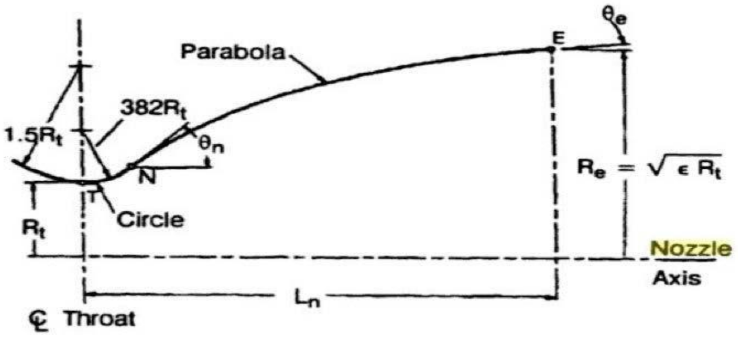

Figure 1.1.1: Rao ParabolicContour[Copyright Kulhanek 2012[6]]

2. NOZZLES DESIGN

Conventional Nozzle Design

A TOP nozzle, using Rao coefficients to define the circular curves entering and exiting the throat, equal to 1.5Rt and 0.382Rt, was used as a baseline nozzle for this project [6]. The Rao parabolic nozzle is defined by three curves, the length of the nozzle, and the throat radius. The length of the nozzle is determined by

$$L_n = \frac{K(\sqrt{\varepsilon} - 1)R_t}{\tan(\theta_e)}$$

where K is a value chosen based on the percent of the length of a conical nozzle with a 15 ° half angle, the flow deflection angle at the exit, Λe, and the throat radius, Rt. In order to define the nozzle further, a coordinate system is defined with the axial (x) axis passing through the line of symmetry and the radial (y) axis going through the center of the throat. The first and second curves define the entrance and exit of the throat of the nozzle, and are based on circular curves. The first curve into the nozzle is determined by the equation:

$$x^2 + \left(y - (R_t + 1.5R_t)\right)^2 = (1.5R_t)^2$$

which can then be solved for y. Note the curve is defining the bottom half of the circle, and therefore is negative.

$$y = -\sqrt{(1.5R_t)^2 - x^2} + 2.5R_t$$

The second curve begins at the throat where the derivative of both curves is equal to zero. The second curve is also a circle defined by the equation:

$$x^2 + \left(y - (R_t + 0.382R_t)\right)^2 = (0.382R_t)^2$$

which leads to the equation for the second circle:

$$y = -\sqrt{(0.382R_t)^2 - x^2} + 1.382R_t$$

Dual Bell Nozzle Design

The dual-bell nozzle was designed for ideal isentropic expansion with an upstream contour area ratio of 1:31.4 and a downstream contour area ratio 1:64.5. These area ratios correspond to a pressure ratio (chamber-to-ambient) of 1000 (for the downstream contour) and 148 (for the upstream contour). By comparison, the conventional nozzle had an area ratio of 11.3.
The dual-bell contour design adds a fourth curve to the conventional Rao design by adding a second parabola to connect two Rao that share the same throat area, but are optimized for different altitudes. The second parabola defines the second bell section and connects the two contours thereby achieving a greater expansion ratio. The dual-bell nozzle was defined similarly to the contour

of the Rao nozzle, with the same throat entrance and exit parameters. The parabola coefficients for the first parabola were found using the same method as the Rao contour.

3. DESIGN CONSIDRATIONS

Dual bell nozzles represent a possible solution to improve the performance of large liquid rocket engines for launcher first stages. To avoid flow separation secondary injection method is used. Simulations were performed for the full-scale dual-bell and conventional nozzles operating at various pressure ratios (chamber-to-ambient) and various secondary injection speeds as shown in below table.

Table 3.1 Pressure ratios of Nozzle

S.No	CASE	Altitude (km)	Pressure (Pa)	Pressure Ratio(Pr)	Secondary injection Speed (m/s)
1	A	2	85000	17.64	50,150
2	B	3.05	71000	21.2	50,150
3	C	10	29296.3	51.2	50,150
4	D	16.5	12000	125	50,150

4. MODELING

The following points describe the procedure of modeling:

1. File – Import geometry – Formatted point data – select .dat file.
2. Geometry – Create/Modify curve – Select key points – done.
3. Create two axis points of nozzle.
4. Surface – Surface revolution - Select two axis points – Select nozzle curve.
5. Create outer exit domain 4 times of nozzle length.

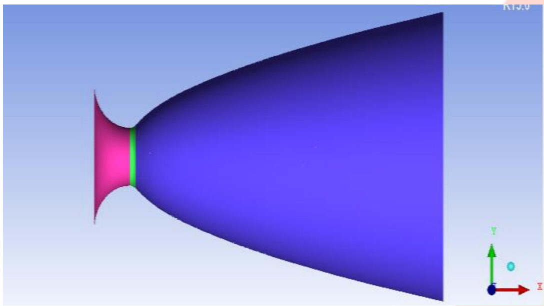

Fig. 4.1 geometric model of bell nozzle

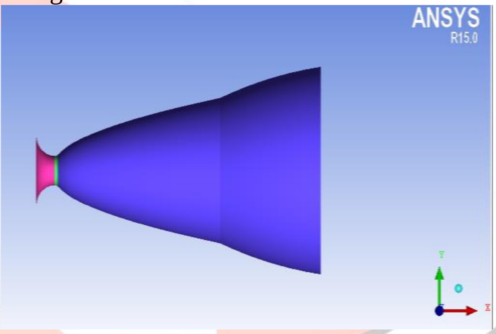

Fig. 4.2 geometric model of dual bell nozzle

5. MESHING & BOUNDARY CONDITIONS

Meshing

Hybrid mesh which is a combination of Structured and unstructured mesh. Structured mesh is created along the walls of nozzle using prismatic layers of 5 with height ratio of 1.2 to capture flow separation accurately. And also the main advantage of hybrid grid is less number of elements 6,12,649 with less computation time and more accuracy in results. Hybrid mesh for present case is shown in figure below 5.1.

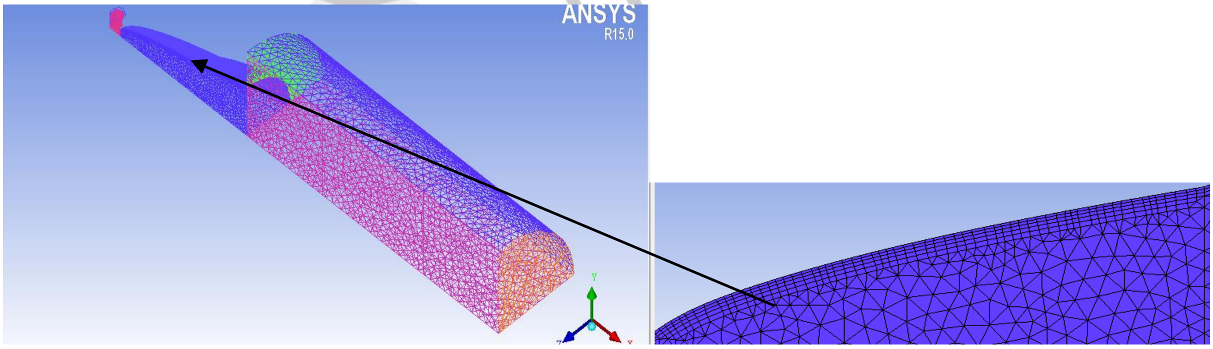

Figure 5.1 Grid 3 Hybrid mesh with prism cells of bell nozzle

Boundary Conditions

Non buoyant stationary continuous fluid having a reference pressure of 1 atm is used

At Inlet total pressure of 1.5 [Mpa], total temperature 7.000e+02[k] , for turbulence low intensity eddy viscosity ratio is considered

The walls of the nozzle are considered to be friction less i.e, it is considered as the adiabatic heat transfer

6. VALIDATIONS

To validate the CFD model dual bell nozzle experimental results of paper [16] are considered and compared with ANSYS CFX results which is used for present analysis. The geometrical conditions of nozzle are given table 6.1 below

Table 6.1 Geometrical parameters of nozzle [16]

Throat radius	R_{th}	8 mm
Base length	L_b/R_{th}	16.25
Extension Length	L_e/R_{th}	15
Area Ratio	E_b	3.95
	E_e	7.97
Inflection angle	α	15^0

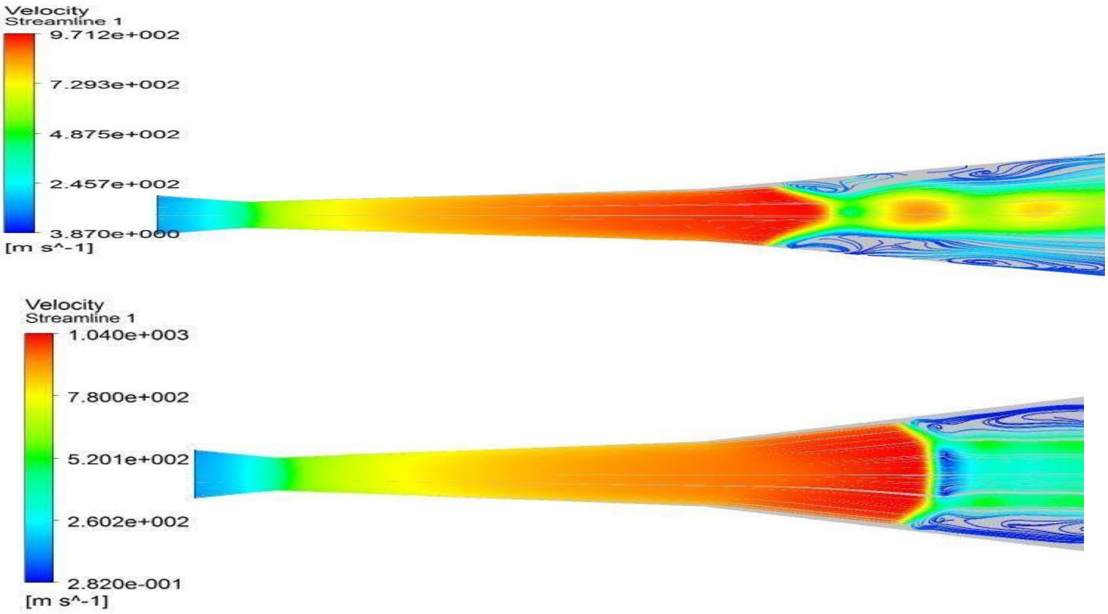

Figure 6.1 Comparison of experimental results of paper [16] with ANSYS CFX

7. RESULTS AND DISCUSSIONS

CASE A without secondary injection

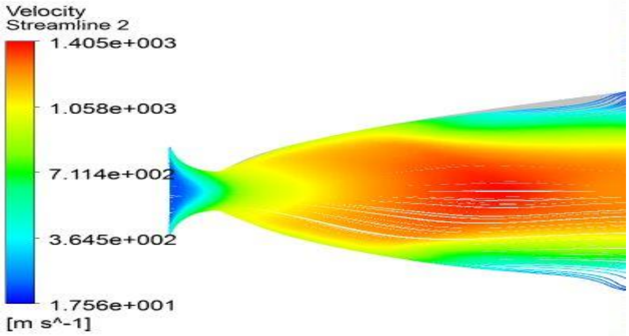

Figure 7.1.1 Velocity streamline of case-A for bell nozzle

Case A is analyzed at 2000m altitude conditions and has expanded fully in the conventional bell nozzle without any separation but at the end of nozzle there is slight variation in streamline pattern leading to separation because of design condition.

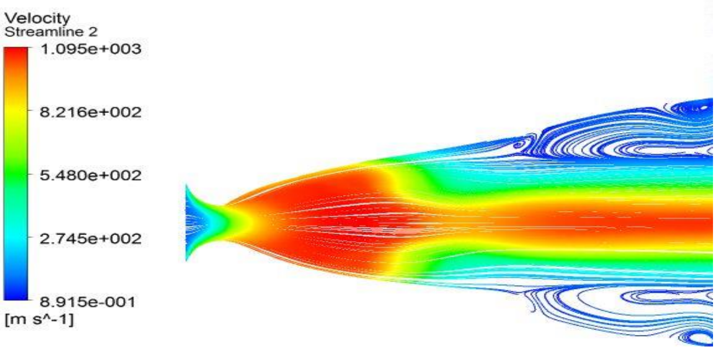

Figure 7.1.2 Velocity streamline of case A for dual bell nozzle

The figure 7.1.2 defines the streamline pattern of dual bell nozzle which shows the flow separation because of low altitude conditions as back pressure is high the flow cannot be expanded thus formation of shock and flow separation can be seen which leads to huge side loads on nozzle walls. This is the major effect of dual bell nozzle.

CASE B without secondary injection

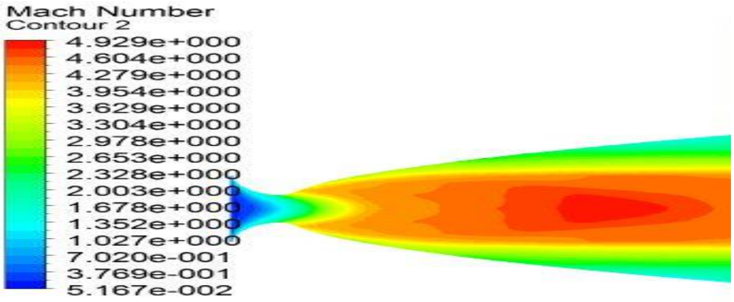

Figure 7.2.1 Mach contour of case B for bell nozzle

The flow in the above figure is fully expanded because of on design condition giving a maximum mach number of 4.9

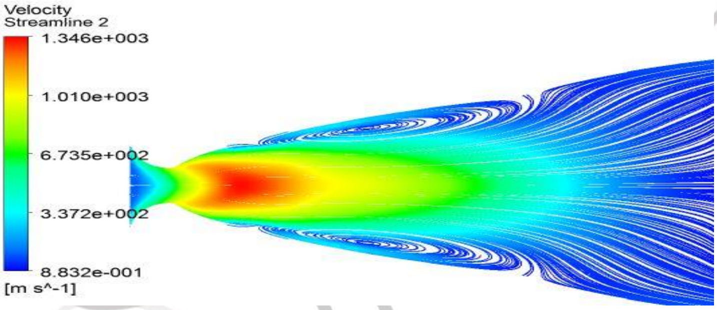

Figure 7.2.2 Velocity streamline of case B for dual bell nozzle

In figure 7.2.2 the transition point is moved towards end of nozzle compared to case A because of increase in altitude conditions and change in back pressure or ambient conditions. The size of vortex or eddy or reverse flow is lesser than case A which leads to low side loads on nozzle walls effecting the material of the nozzle

CASE C without secondary injection

Case C is analyzed based on 10km altitude condition to find the effectiveness of dual bell compared to conventional bell nozzle. As altitude increases the ambient pressure decreases and scope to expand the flow more which has added advantage with increase in effective area of nozzle by dual bell.

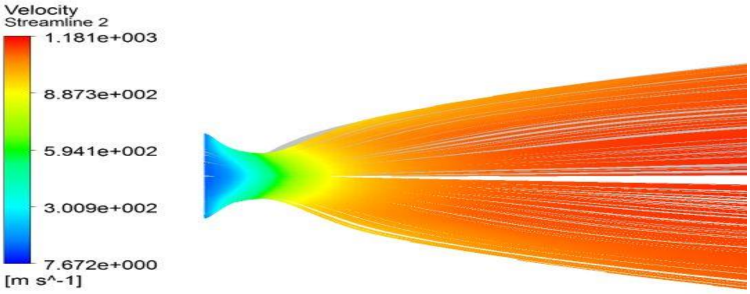

Figure 7.3.1 Velocity streamline of case C for bell nozzle

The velocity of flow decreases in conventional nozzle as altitude increases because of under expansion condition.

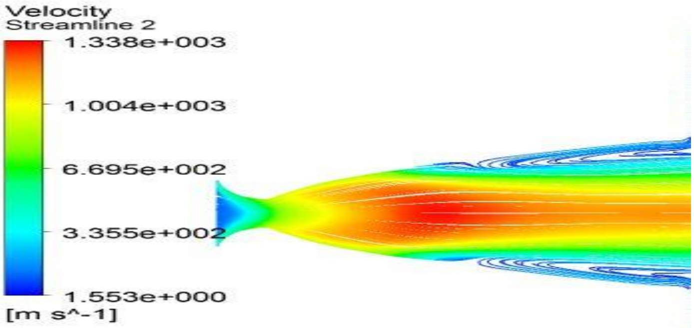

Figure 7.3.2 Velocity streamline of case C for dual bell nozzle

CASE D without secondary injection

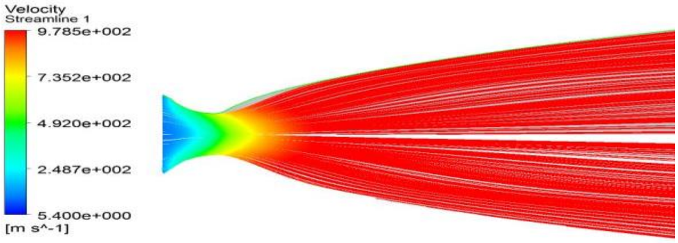

Figure 7.4.1 Velocity streamline of case D for bell nozzle

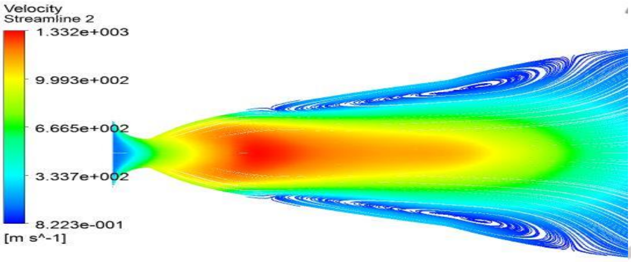

Figure 7.4.2 Velocity streamline of case D for dual bell nozzle

CASE A with secondary injection

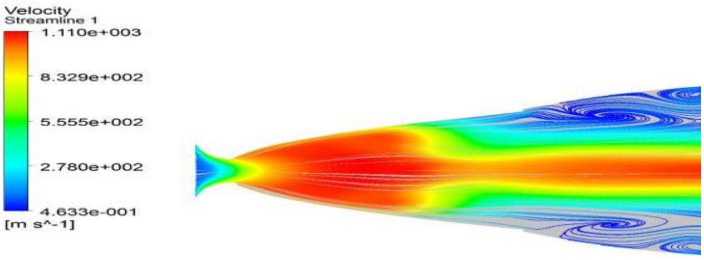

Figure 7.5.1 Velocity streamline of case A for dual bell nozzle at 50m/s injector speed

Figure 7.5.2 Velocity streamline of case A for dual bell nozzle at 150m/s injector speed

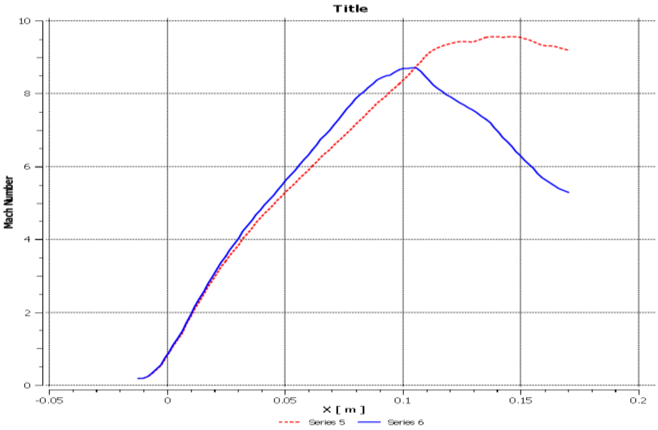

Figure 7.5.3 Mach number along axis of nozzle of case A for two speeds of injector

CASE B with secondary injection

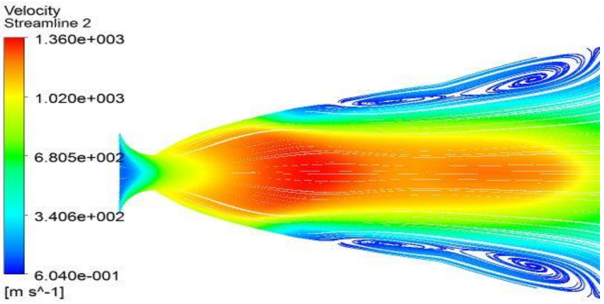

Figure 7.6.1 Velocity streamline of case B for dual bell nozzle at 50m/s injector speed

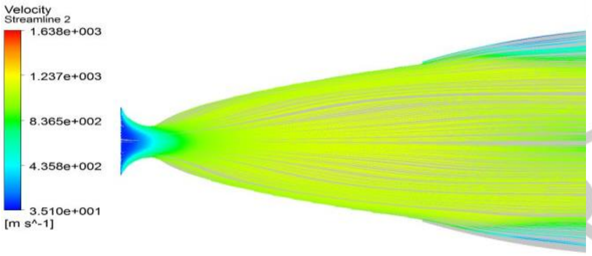

Figure 7.6.2 Velocity streamline of case B for dual bell nozzle at 150m/s injector speed

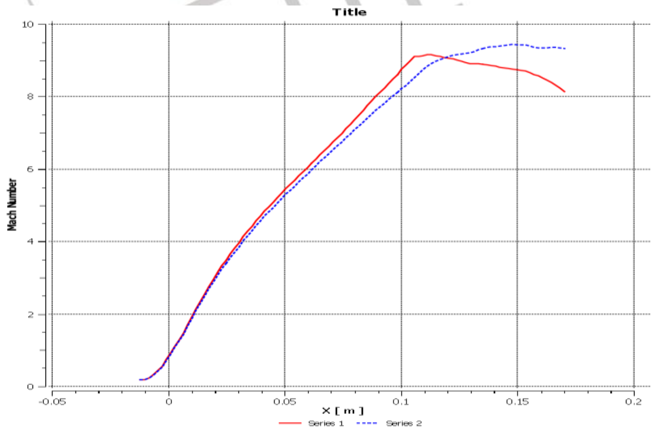

Figure 7.6.3s Mach number along axis of nozzle of case B for two speeds of injector

In the Mach number graph series 1 is for 50m/s and series 2 is for 150m/s. Injection speed effects the flow development in the nozzle. Because of secondary injection 20% of thrust is increased with respect to Mach number increment.

Because of secondary injection the bigger eddy of figure 7.2.2 has been formed into two small eddies decreasing the strength as shown in figure 7.6.1. But the flow separation has been not avoided with 50m/s of injection thus by increasing injection speed the flow separation is avoided as shown in figure 7.6.4

CASE C with secondary injection

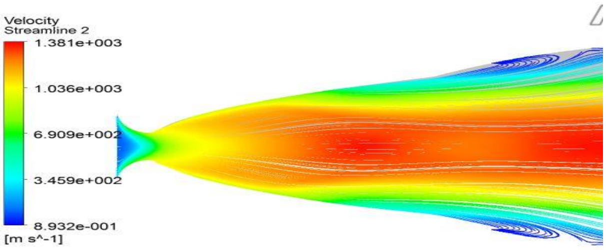

Figure 7.7.1 Velocity streamline of case C for dual bell nozzle at 50m/s injector speed

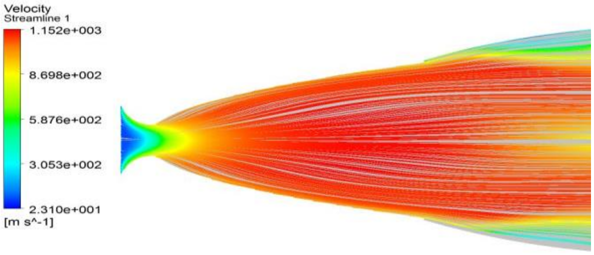

Figure 7.7.2 Velocity streamline of case C for dual bell nozzle at 150m/s injector speed

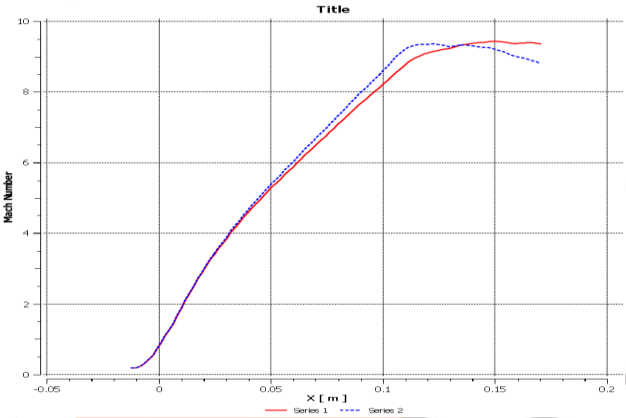

Figure 7.7.3 Mach number along axis of nozzle of case C for two speeds of injector

CASE D with secondary injection

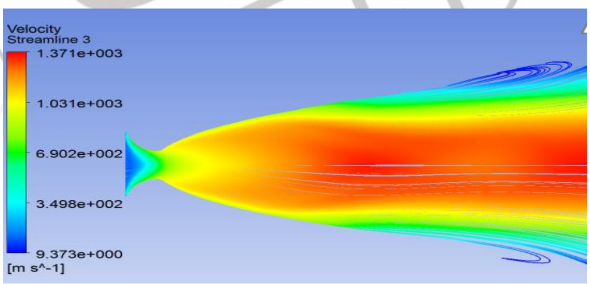

Figure 7.8.1 Velocity streamline of case D for dual bell nozzle at 50m/s injector speed

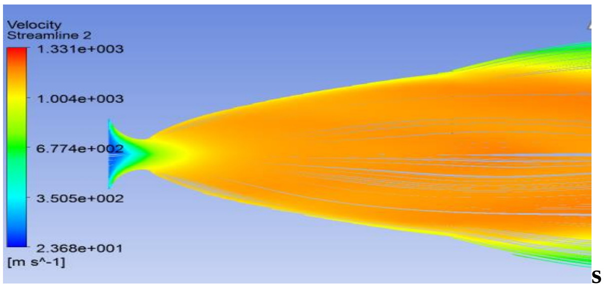

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Figure 7.8.2 Velocity streamline of case D for dual bell nozzle at 150m/s injector speed

Thus from above results dual bell nozzle can be considered as alternative for high altitude flow conditions. By using secondary injection the flow can enhanced furthermore which can be clearly observed from Mach contour graph in every case. With 50m/s of secondary injection speed the flow cannot be attached because high adverse pressure gradient which cannot be overcomes by kinetic energy of injection speed. Such that injection speed has been increased to 150 m/s to avoid flow separation and attach the flow to nozzle obtaining full efficiency of dual bell nozzle.

8. CONCLUSION

By considering the rao contour for both base and expansion for a duel bell nozzle the results at different altitudes is considered By comparing the results of different altitudes it is concluded that The conventional nozzle contour performed better than the proposed dual-bell contour over a range of backpressures upto design point. The performance of duel bell nozzle decreases At low altitude conditions ,as back pressure is high the flow cannot be expanded thus formation of shock and flow separation can be seen which leads to huge side loads on nozzle walls. The increase in performance in duel bell nozzle can be done by the secondary injection in the expansion contour with high injection speeds.After the design point i.e. at high altitudes the performance of the conventional nozzle decreases because of under expansion ,duel bell nozzle performs better at high altitudes even though without secondary injections

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