A CFD study on the Supersonic Flow through a Dual Bell Nozzle

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ABSTRACT

Dual bell nozzle is one of the most promising choices among the altitude adaptation nozzles. This facilitates having a forced, steady and symmetrical separation at lower altitudes and a controlled flow separation at the wall inflection point which prevents the generation of dangerous side loads. In order to ensure the attached flow in the second bell, a clear understanding of the flow transition is required. Hence the motivation of our study is to arrive at an optimum profile for the second bell, which allows a sudden and controlled transition. In this work, we designed the first bell using the conventional MoC and the second bell using an inverse MoC, imposing a pressure gradient constraint. A CFD analysis is also carried out. It is found that the separation point is near the inflection point within one fourth of the extension length or it is near the exit.

Key Words : Dual Bell nozzle, Flow Separation, MoC, Supersonic Flow, Flow Transition.

1. INTRODUCTION

The reduction of Earth-to-orbit launch costs along 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.

The overall performance of the conventional bell type rocket nozzle is limited due to their fixed geometry during ascent of the launcher. They operate at optimal efficiency only at one point along the flight trajectory. Below this point the nozzle flow is over-expanded and at high altitudes, the nozzle flow is under-expanded. Thus a compromise must be made between sea level and vacuum performance in order to maximize the payload for the demands of the mission. For the booster engines, area ratio of conventional bell nozzle is limited based on the ratio of chamber pressure and sea level ambient pressure. Throughout the flight trajectory, the maximum performance can be attained using altitude adaptation capability nozzle.

Although the ideal propulsion device would be an engine with adapted nozzle during its

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whole operating phase, a nozzle with a high adaptation altitude [1] would be sufficient to provide high engine performance as most of the operation of the main stage engines take place at high altitudes. Dual-bell nozzle is one of the promising choices of the altitude adaptation nozzle. Recently it has gained renewed interest in U.S., Japan, Europe and Russia.

A dual-bell nozzle is a combination of two differently designed conventional nozzles [2]. One is a base nozzle with small area ratio, which stabilizes flow separation at wall inflection point. The profile for the base nozzle is equivalent to that of a conventional bell nozzle. The other is an extension nozzle with a large area ratio, which provides for the considerable higher thrust performance in vacuum. During low altitude operation flow will separate from the first bell exit. Unlike the conventional flow separation, the flow will be anchored at inflection point. This will reduce the vibration levels as well as side loads [3]. Also, in the controlled flow separation at wall inflection point prevents the generation of dangerous side loads commonly observed in conventional over-expanded nozzles.

When the flow is separated at the inflection point, due to the recirculation that takes place along the second bell, a pressure lower than the ambient pressure acts on the extension wall, thus generate an ‘aspiration drag’. Then what is required is maximum performance of base nozzle and minimum aspiration drag. A “safe” transition [4] can occur only when the wall pressure distribution is designed such that no possible steady solution exists with the separation point located within the second divergent bell, and its movement from one flow structure to the other is as fast as possible. Flow transition in dual-bell nozzles strongly depends on the contour type of the nozzle extension and the type of gas [5]. 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) [6]. The contour of the nozzle has to be carefully designed for achieving these conditions. The use of method of characteristics has long been established to design such nozzle contours [7].

Hence the primary objectives of this study are the development of a code for the design of dual-bell nozzle profiles using MoC and inverse MoC imposing the constant pressure gradient conditions and the computational fluid dynamics study of dual bell nozzles with different inflection angles and finding out the inflection angle for which the performance is maximum.

It is planned to design the first bell of the nozzle using the MoC methods and the second bell will be designed using an inverse MoC imposing the constant pressure gradients. A CFD analysis is also planned to study the supersonic flow characteristics of the newly designed dual bell nozzle.

2. METHODOLOGY

2.1 Method of Characteristics

The philosophy of direct Method of characteristics is well known and it is commonly being used to design supersonic nozzles.[8]. In the direct MoC, the shape of the boundary is specified and the pressure distribution will be found. But in the case of a free boundary, the pressure distribution

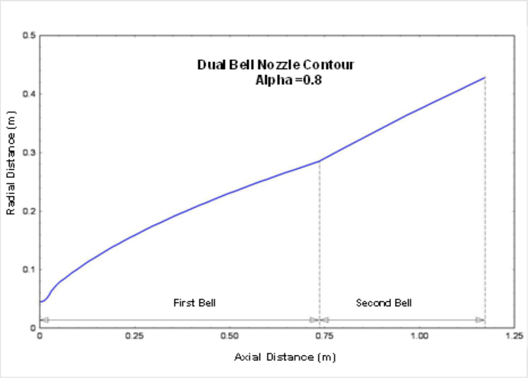

Fig. 1 Dual bell nozzle designed using direct and inverse MoC (α = 0.8 is the multiplication factor which corresponds to the degree of over expansion at the inflection point)

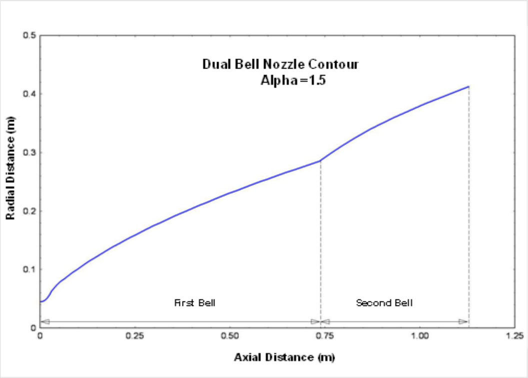

Fig.2 Dual bell nozzle designed using direct and inverse MoC (α = 1.5)

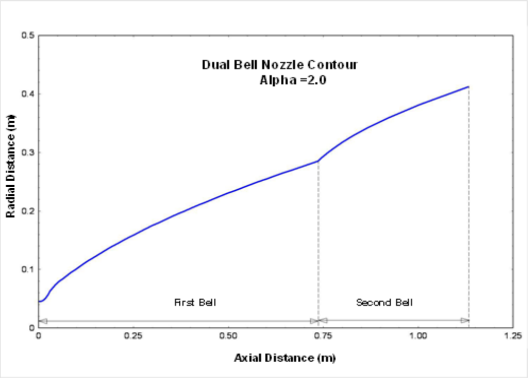

Fig.3 Dual bell nozzle designed using direct and inverse MoC (α =0.2)

must be specified and its shape will be found.

This is known as the Inverse MOC. This method is applied in a Coanda jet nozzle [9] discharging a supersonic flow with the upper boundary free and the other lower boundary solid. The flow through the nozzle exit need not be uniform or parallel. The procedure would be to specify the exhaust flow by specifying the free boundary shape (and possibly the pressure distribution) and the solid wall shape. From these the nozzle exit distribution could be calculated by an upstream running characteristics grid. The internal contour of the nozzle which will give such a flow may be calculated by continuing upstream running characteristics solutions. For the points outside of and upstream from that zone the shape of the walls must be specified.

It appears that a wide range of solutions is possible for the boundaries within an implied assumption that the goal upstream is M=1 at the throat. In this work, MOC is used for the design of first bell of dual bell nozzle and inverse MOC is used for the design of the second bell of dual bell nozzle.

The designed dual bell nozzles are shown in Figs. 1-3

2.2 CFD analysis

Viscous losses in the flow will not be computed in MOC. Hence the selected profiles were subjected for the CFD simulations. Numerical simulations are carried out using a commercial CFD code, FLUENT. It is based on a second order finite volume discretization and the SIMPLE pressure correction technique for enforcing the divergence-free condition of the velocity field; the time integration is three-level fully implicit. An axi-symmetric steady state analysis has been carried out to study the flow properties and predict the flow separation in the dual bell nozzle designed using the method of characteristics. The turbulence model used is k-◆. The computational domain and the boundary conditions are shown in Fig.4

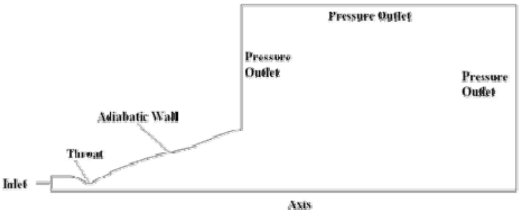

Fig.4 Computational domain and boundary conditions

3. RESULTS AND DISCUSSION

3.1 Flow characteristics inside the dual bell nozzle

Figure 5 shows the Mach number contours inside the nozzle for low altitude mode.

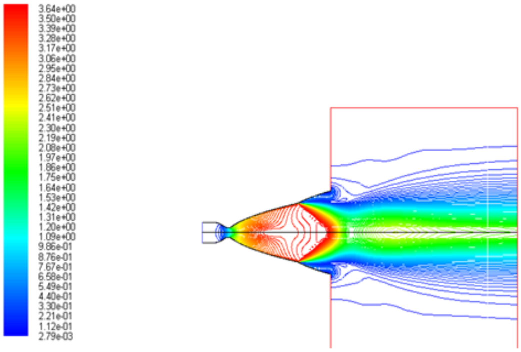

Fig. 5 Mach number contours in the dual bell nozzle for low altitude (α=1.5)

Chamber pressure used for simulation is 70 bar and the temperature used at the inlet is 3485 K. When the ambient pressure is relatively high at ground level, which corresponds to the low altitude mode, the flow separation occurs at the inflection point.

In the low altitude mode, the effective area ratio is limited to the area ratio at the inflection point i.e; primary nozzle exit. The normal shock and the triple point occur near the extension nozzle exit. Fig.6 shows the Mach number contours when the transition starts where the back pressure is 0.59 bar. Fig. 7 shows the Mach number contours when the ambient pressure is relatively low (0.2 bar),which corresponds to high altitude mode and flow separation occurs at the extension nozzle exit. This means that the effective area ratio is the area ratio at the extension nozzle

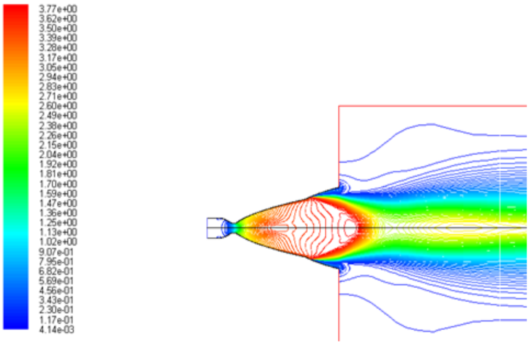

Fig. 6 Mach number contours in the dual bell nozzle (α=1.5) when transition starts (back pressure =0.59 bar)

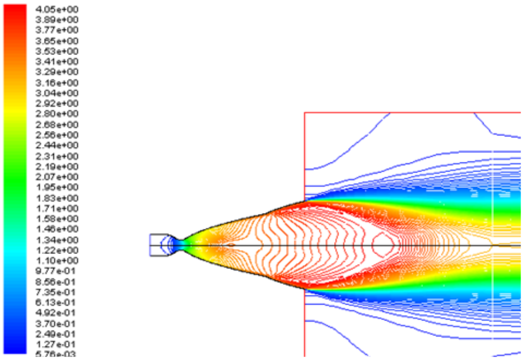

Fig. 7 Mach number contours in the dual bell nozzle (α=1.5) at high altitude (back pressure =0.2 bar)

exit in the high altitude modes. From these figures we can see that the flow pattern inside the nozzle changes drastically according to the change of ambient pressure due to the shock induced flow separation. This shows that the ambient pressure where the flow pattern changes is one of the key properties to estimate the dual bell nozzle design.

3.2 Effect of over expansion on transition

It is seen that the effect of over expansion factor α, (the degree of over expansion) at the wall inflection should be larger than 1.0 to ensure sufficiently fast transition. However excessively large factors may introduce difficulty in manufacturing the nozzle wall near the inflection point. Hence the effect of the over expansion factor in the transition is studied. The pressure distributions along the nozzle wall with various back pressures have been plotted in Figs. 8-10 for various α.

It is seen that the separation point is near the inflection point up to 0.65 bar. Flow separation from the second bell exit is observed 0.45bar which is not desirable for the dual bell nozzle. However the normal flow separation with back pressure is not observed in the second bell nozzle due to the constant pressure profile up to 0.03 bar. Full flow Wall condition is observed below 0.3 bar.

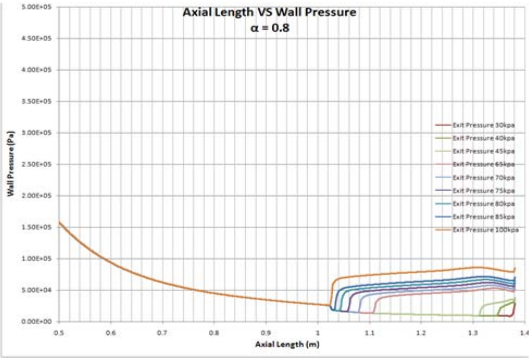

Fig. 8 Wall pressure distribution (α = 0.8)

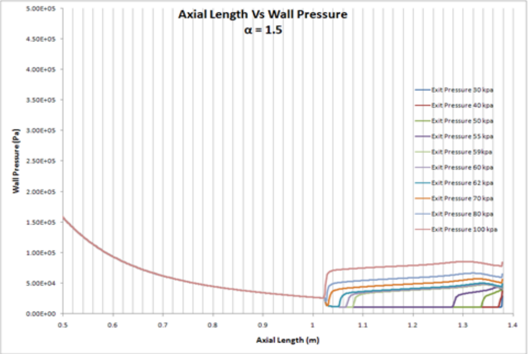

Fig. 9 Wall pressure distribution (α = 1.5)

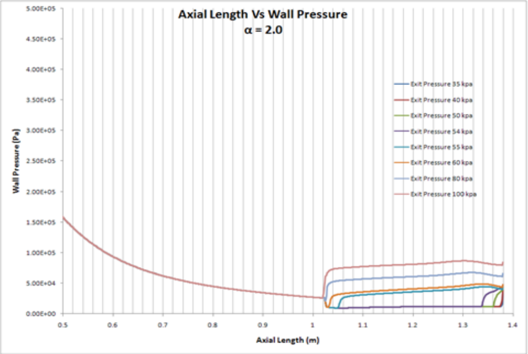

Fig. 10 Wall pressure distribution (α = 2.0)

pressure distribution for different back pressure conditions for α = 1.5 is shown in Fig.8. It is seen that the separation point is near the inflection point up to 0.59bar. The transition occurs at 0.55 bar here compared to the 0.65 bar in the case of α = 0.8. One thing is noted here is, a stable flow separation is observed from the second bell for different back pressure conditions. This is not likely to happen for a constant pressure profile contour and needs to be investigated further. Full flow is observed for back pressure less than 0.3 bar.

The wall pressure distribution for α = 2.0 is plotted for various back pressures in Fig.9. Here the separation point is near the inflection point up to 0.55bar, and it is near the exit at 0.54 bar. This indicates that for higher fraction of Prandl-Meyer angle, back pressure required for flow transition is similar. However flow behavior is totally different. In the case α = 2.0, no flow separation is observed in the second bell nozzle during flow transition. Here it is also observed that the transition is very fast and within a pressure difference of 0.01 bar in the back pressure, the separation reaches at the exit. Full flow condition is achieved below 0.3 bar exit pressure.

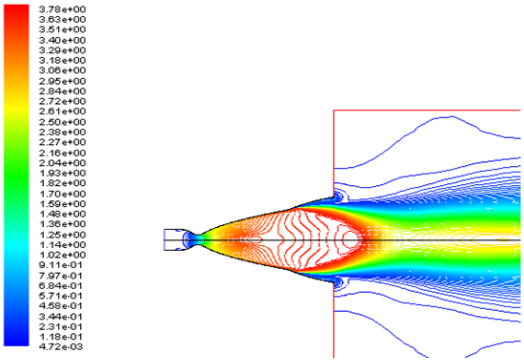

Fig. 11 Mach number distribution inside the dual bell nozzle with constant pressure profile at 0.54bar, the separation is at the inflection point (α=2.0)

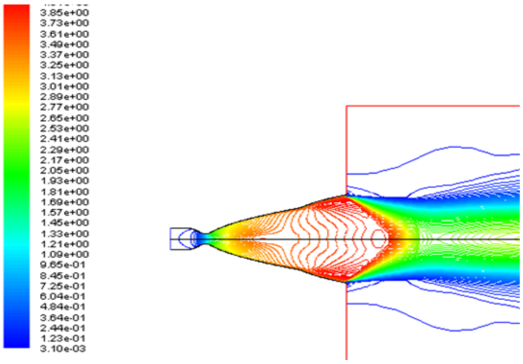

Fig. 12 Mach number distribution inside the dual bell nozzle with constant pressure profile at 0.54 bar, the separation is at the inflection point (α=2.0)

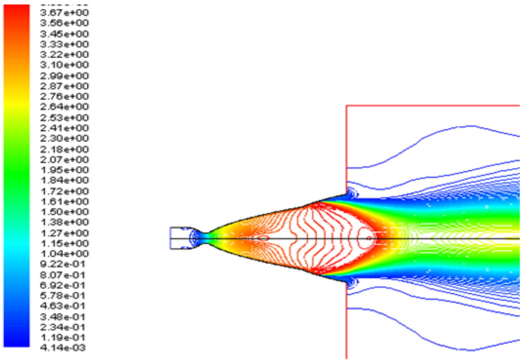

Fig. 13 Mach number distribution inside the dual bell nozzle without constant pressure profile at 0.57 bar. It shows at constant separation

The Figs. 11 and 12 show the quick transition of the separation point from back pressure 0.55 bar to 0.54 bar for the dual bell nozzle where constant pressure constraint is imposed on the second bell, while Fig.13 shows the stable separation inside the second bell for a dual bell without a constant pressure profile.

4. CONCLUSIONS

A study is carried out to study the flow features inside a dual bell nozzle transition. For this MOC code is developed to design the first bell and an inverse MOC code is developed to design the second bell with a constant pressure profile. Different Nozzle profiles are generated for various expansion factors α. All the generated profiles were subjected for CFD analysis and the role of nozzle profile on flow transition were studied. It is observed that, a constant pressure profile on the second bell will yield a quick and stable transition of the flow to the exit of the dual bell nozzle. It is also seen that for a constant pressure profile the separation point is near the inflection point within one fourth of the extension length or it is near the exit.

It is also observed that as the over expansion factor increases the transition time decreases. Studies revealed that for avoiding flow separation from the second bell during flow transition, a minimum overexpansion factor of 2 is required.

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