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Study of the Effect of Over-expansion Factor on the Flow Transition in Dual Bell Nozzles

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***Abstract*—**Dual bell nozzle is a promising one among the altitude adaptation nozzle concepts, which offer increased nozzle performance in rocket engines. Its advantage is the simplicity it offers due to the absence of any additional mechanical device or movable parts. Hence it offers reliability along with improved nozzle performance as demanded by future launch vehicles. Among other issues, the flow transition to the extension nozzle of a dual bell nozzle is one of the major issues being studied in the development of dual bell nozzle. A parameter named over-expansion factor, which controls the value of the wall inflection angle, has been reported to have substantial influence in this transition process. This paper studies, through CFD and cold flow experiments, the effect of over-expansion factor on flow transition in dual bell nozzles.

***Keywords*—**Altitude adaptation, Dual bell nozzle, Nozzle pressure ratio, Over-expansion factor

Nomenclature

AR	Area Ratio
COP	Constant Pressure Profile
DBN	Dual Bell Nozzle
LIP	Linearly Increasing Pressure Profile
NPR	Nozzle Pressure Ratio
PAM	Parabolic Approximation Method
PIP	Parabolically Increasing Pressure Profile

Notations

α	Over-expansion factor
γ	Ratio of specific heats
Δ_{NPR}	Difference in NPR
θ_{i2}	Angle at inlet to extension nozzle
θ_{e1}	Angle at exit to base nozzle
ϑ_{e1}	Prandtl Meyer function at base nozzle exit
ϑ_{e2}	Prandtl Meyer function at extension nozzle exit
AR_b	Exit AR of base nozzle
AR_e	Exit AR of extension nozzle
M	Mach number
P_0	Stagnation pressure
P_a	Ambient pressure
P_w	Nozzle wall pressure
R_t	Radius of the nozzle at the throat
X	Distance along the axis of the nozzle
Y	Radial distance of the nozzle wall

I. Introduction

FUTURE space transportation systems like reusable single-stage-to-orbit launch vehicles, which aim for reduction of Earth-to-orbit costs, look forward to the increase of operational efficiency and launcher reliability for success [1]. Rocket engines with high performance and low system complexity are the key for the development of such launch vehicles. The performance of existing expendable launch vehicles is also very much dependent on the performance of engines. Combustion efficiency and thrust efficiency are the two factors that contribute to the engine performance. Combustion efficiencies of different propellant combinations have reached the practical thermo-chemical limits and hence scope for more improvement is possible in the field of designing high performing nozzles.

In present booster engines, which operate in the varying pressure environment between the sea level and the near vacuum conditions, the nozzle exit area ratio (AR) is limited due to the usage of conventional nozzles. This limitation is to avoid the problems associated with flow separation that happen at the sea level. This curtails the high altitude performance of the engine. Altitude adapting nozzles offer solution to this problem and improve the performance of booster rocket engines. Being a simpler and more reliable option among the altitude adapting nozzles, Dual Bell Nozzles (DBN) and researches on the development of DBNs acquire the foremost place.

The concept of DBN appeared in the literature in 1949 [2]. Rocketdyne patented the concept in the 1960s [2]. Recently it has gained renewed interest in U.S., Japan, Europe and Russia [3] due to its suitability in the futuristic launch vehicles.

DBN is a combination of two differently designed conventional nozzles [4]. One is a base nozzle with small AR, which stabilises flow separation at the 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 larger AR, which provides for the considerable higher thrust performance in vacuum[5]. At low altitude, stably controlled and symmetrical flow separation occurs at the inflection point [6]. This controlled flow separation at wall inflection point prevents the generation of dangerous side loads commonly observed in conventional over expanded nozzles. The small effective AR of the base nozzle generates increased sea level thrust. At a certain altitude of the flight trajectory, the transition conditions to high altitude mode are reached and the flow attaches abruptly in the whole extension to the wall, up to the nozzle exit plane. The full AR is now used and leads to optimized high altitude thrust generation [2].Fig. 1 shows the schematic of a DBN subjected to the two modes of operation.

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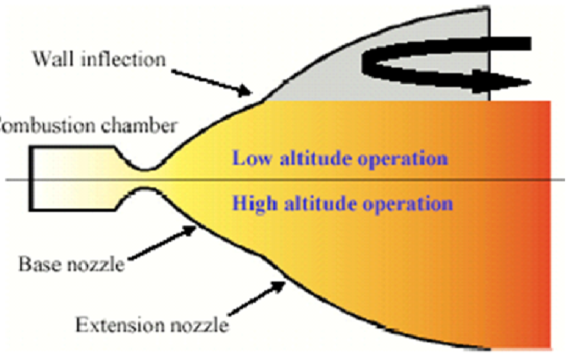

Fig. 1 Schematic of a DBN under the two modes of operation (From Fig.1 of [4])

Even though DBNs have been not introduced into flight engines, flight performance analysis of the concept has been done by substituting the nozzles of LE-7A and RD-180 engines and the trajectory-averaged specific impulse gain over the original nozzles is about 10 s for both the engines [7].

Appropriate design philosophy, reduction of side loads and vibration levels, performance prediction, timing and duration of flow transition, profile design for abrupt flow transition in the extension nozzle, heat transfer problems at the inflection, geometry of the inflection are some of the major issues related to the development of DBN.

II. Design of Nozzles

Reference [8] discusses a methodology for designing DBN profiles. It describes a parameter, named over-expansion factor (α) that amplifies the difference between the Prandtl Meyer functions at AR_e and AR_b. The exit angle of the base nozzle is added to this amplified difference of Prandtl Meyer functions to obtain the angle at the inflection point between the junction of the base nozzle and the extension nozzle. So

$$\theta_{i2} = \theta_{e1} + \alpha(\vartheta_{e2} - \vartheta_{e1}) \quad (1)$$

Where ϑ_{e2} and ϑ_{e1} are calculated using one-dimensional isentropic flow relation as shown below.

$$\vartheta = \sqrt{\frac{\gamma+1}{\gamma-1}}\tan^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)} - \tan^{-1}\sqrt{(M^2-1)} \quad (2)$$

Reference [8] brings out that the value of greater than unity ensures sufficiently instant flow transition to the extension nozzle. It cautions that there exists a ceiling value for considering the fabrication feasibility of the DBN. It also states that the ceiling value is different for different nozzle bell percentages adopted for designing the two nozzle contours of a DBN.

Reference [9] discusses the use of three different sets of profiles namely, COP, LIP and PIP for the extension nozzle of DBNs. It concludes that the nozzle extension with zero pressure gradients shows good transition behavior whereas the positive pressure gradient shows better behavior with a sudden jump of separation from the inflection point to nozzle exit. Method of Characteristics is unable to provide the description of the profile of the extension nozzle with any desired resolution because of the spreading effect of the expansion fan on the characteristic lines of the opposite family [9]. In this context, here, practically widely used parabolic approximation method (PAM) profiles, which are simpler to be designed, were used for the extension nozzle; also. This approach is quite reasonable as the aim of the study is only to compare the effect of the variation of α in flow transition.

Thus three DBN profiles were designed with α= 0.7, 1 and 1.4. The base nozzle is kept same for all the profiles. The ratio of extension nozzle length was kept same at 0.7 for all the nozzles. Fig. 2 shows the nozzle profiles studied.

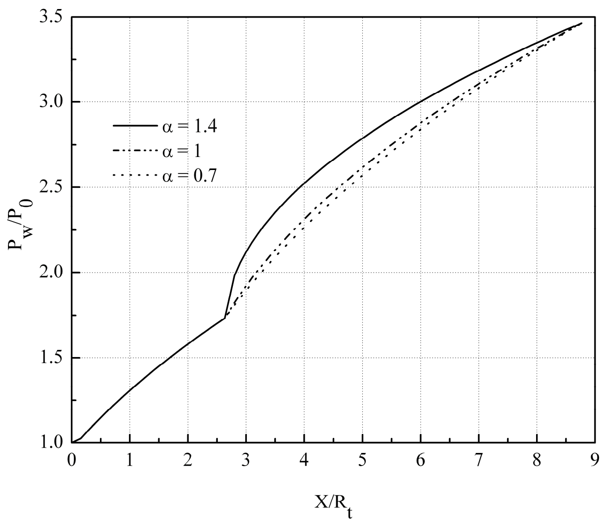

Fig. 2 DBN profiles studied

III. CFD Analysis

Numerical simulation had been performed by commercial CFD software for the cold flow conditions.30^0 sector of each nozzle variant formed the computational domain. In order to get good resolution of the boundary layer, structured prismatic elements with higher grid density were used at the nozzle wall. Tetrahedral elements were used elsewhere. k-ε turbulence model was used for the simulation. CFD analysis captured the flow transition and served as the basis for comparing the results obtained through cold flow tests.

IV. Cold Flow Tests

In the flight trajectory nozzles operate mostly at constant P_0 and gradually decreasing P_a. But in the experiments increasing the P_0 gradually and maintaining the nozzle pressure ratio (NPR) at the desired level is adopted, as the qualification of DBN looks for the NPR rather than the actual P_0 or P_a. References [2] and [3] also report such methodology for experiments. The fluid used is dry Nitrogen which gives the advantages of being cheap, easy and safe for usage [2].

Out of the nozzle profiles designed, two profiles with α= 0.7 and α= 1.4 were realized for the cold flow tests. The design NPR and the CFD analysis served for setting up reference pressures for the pressure measurements. On increase of the P_0, flow gradually developed inside the DBN and crossed each wall pressure measurement location. The wall pressures recorded gave the qualitative indication of flow crossing a particular AR and quantitative measure of the NPR for that AR to flow full.

P_0 measurement made on the stagnation chamber and four wall pressure measurements formed the major instrumentation set up. Wall pressures were measured at crucial locations along the flow direction of the DBN. These locations are just upstream of the inflection point, just downstream of the inflection point, at around 75% length of the DBN and just upstream of the nozzle exit. Fig. 3 shows the schematic of the test set up.

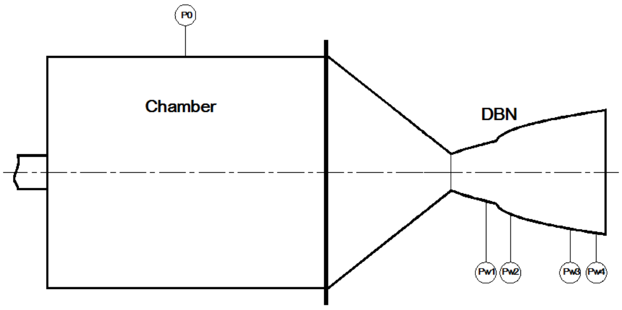

Fig. 3 Schematic of the test setup

The pressure measurements were done at the rate of 2 kHz. The values are filtered, smoothened, non-dimensionalised and compared with the CFD results.

V. RESULTS AND DISCUSSIONS

The CFD simulation done on the nozzle variants clearly captured the flow transition behaviours in the nozzle variants. Fig. 4 shows the instants just before and after the flow transition with the different nozzle profiles. The significance of higher α is underlined here. Higher the value of α, delayed is the onset of transition. The base nozzles flow full at the same NPR for all the nozzles. The delayed onset of transitions for nozzles with higher α result in anchorage at inflection points even for higher values of NPR. Consequently, the ranges of anchorage for nozzles with higher α are higher, as shown in fig. 5 Based on these results, fig. 6 summarises the flow characteristics of the DBNs studied.

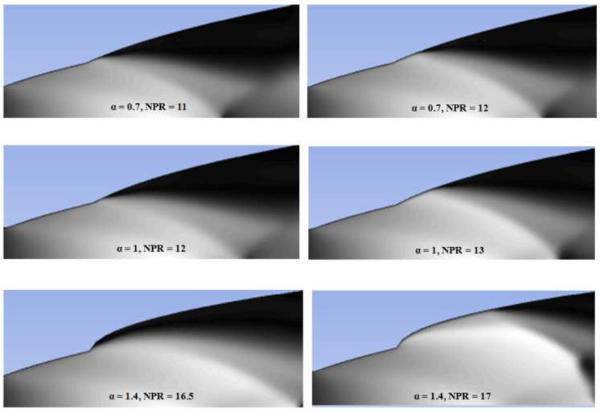

Fig. 4 Mach contours showing flow transition

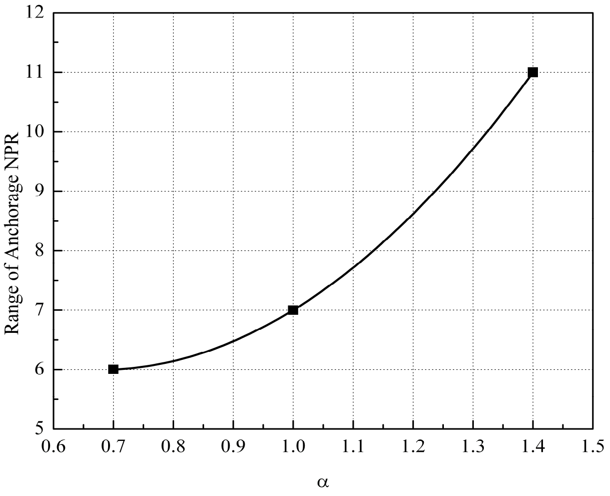

Fig. 5 Ranges of anchorage for different α

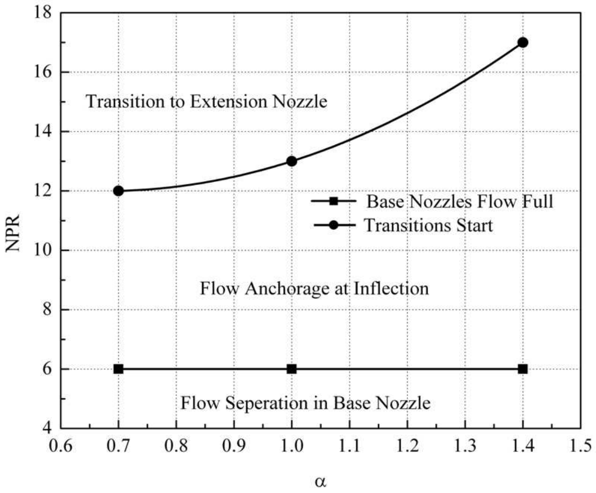

Fig. 6 Flow characteristics of the DBNs

Fig. 7 to fig. 9 show the CFD results for the salient flow behaviours in the nozzle variants with α = 0.7, α= 1 and α= 1.4 respectively. Experimental results are also included for those hardware for which cold flow tests had been carried out.

Experimental and CFD results show good agreement validating the procedures followed.

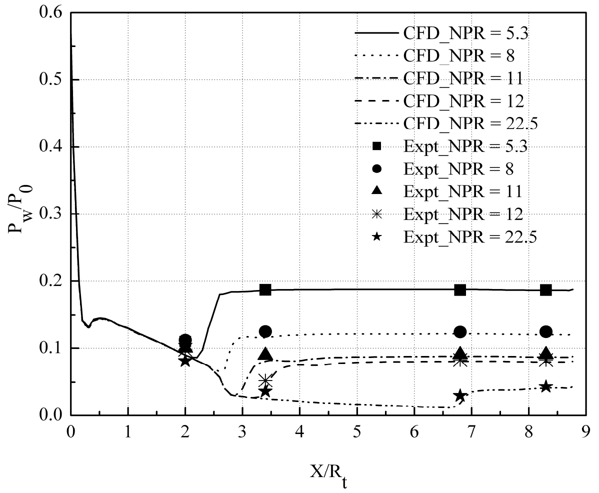

Fig. 7 Nozzle wall pressure variation in the DBN with α=0.7

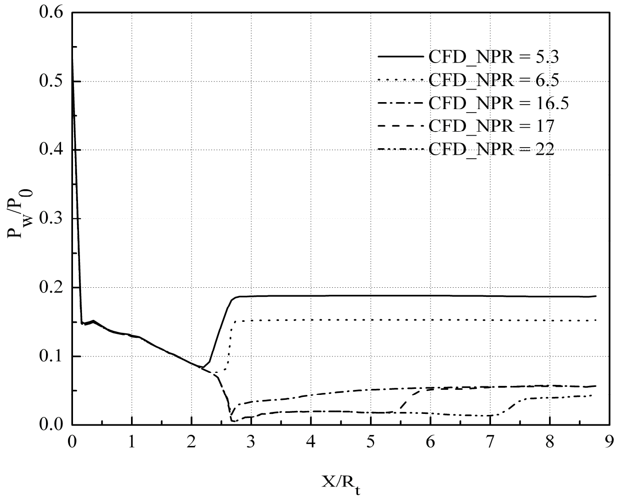

Fig. 8 Nozzle wall pressure variation in the DBN with α=1

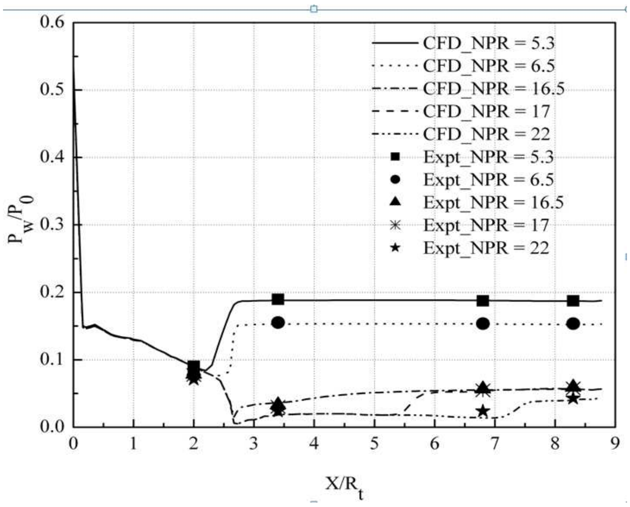

Fig. 9 Nozzle wall pressure variation in the DBN with α=1.4

The difference in NPR (Δ_{NPR}) is the measure of quickness and smoothness of flow transition. Lesser the Δ_{NPR}, quicker and smoother is the transition. From the results of the above studies the Δ_{NPR} of the three nozzles studied are estimated with the measurement location of Pw3, which corresponds to more than 75% of the length of the nozzle, as reference. Fig. 10 compares the ratio of Δ_{NPR} to the range of anchorage NPR for the different nozzle profiles studied.

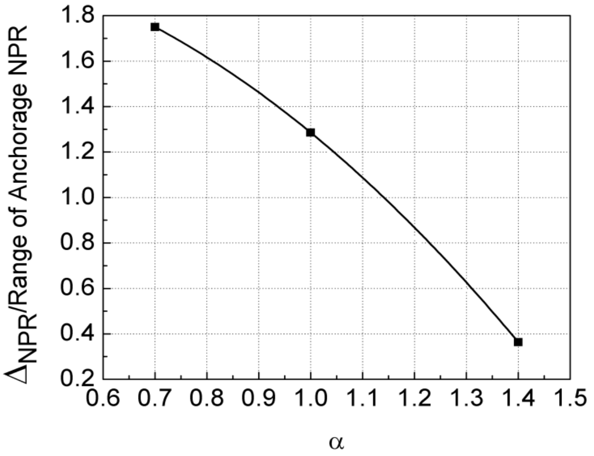

Fig. 10 Plot of ratio of Δ_{NPR} to the range of anchorage NPR

A. *Inference*

Higher the value of α delayed is the instant of transition. Hence, this factor signifies the holding potential of a DBN at its inflection point. So by manipulating the value of α, designs of DBNs that undergo flow transition at the desired altitude of the flight trajectory can be made. This guarantees improved performance, which result from selection of optimum transition altitude. Again, higher the value of the factor, quicker and smoother is the transition. It is evident from Fig. 4 that with α greater- than- unity appreciable jump happens with small rise in pressure. The fact that this effect is seen even in nozzle profiles with negative pressure gradient like those generated by PAM, signifies the crucial role that α plays in flow transition.

VI. CONCLUSION

A study had been carried out through experiments and CFD simulation about the effect of α on the flow transition phenomena in DBNs. Even from the study that used PAM profiles, which feature negative pressure gradient along axial length, it is found that transition is significantly influenced by this factor and its value above unity aids smooth and faster transition. Also higher value of the factor delays the instant of transition, it is verified. This factor thus is a good tool for practical designers who want the transition to happen at a particular altitude in the flight trajectory, for improvement in performance and for other reasons.

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