FORMATION OF CAP-SHOCK PATTERN

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ABSTRACT

Flow separation in rocket nozzles is undesirable becacuse of its unsteady and non-symmetric nature, which leads to dangerous side-loads. At the initial stages of start-up, when a thrust optimized contour (TOC) nozzle operates under over-expanded conditions, free shock separation (FSS) takes place. Under certain conditions this free separated flow reattaches back to the nozzle wall and forms restricted shock separation (RSS). The cap-shock pattern is believed to be the main cause for this flow transition from FSS to RSS. In the present study, numerical investigation of flow transition (FSS$\longrightarrow$RSS) has been performed to understand the formation phenomenon of the cap-shock pattern, which is still unknown.

1 INTRODUCTION

Flow separation takes place in a rocket nozzle when it operates under over-expanded condition. Whatever the nozzle contour, truncated ideal contour (TIC nozzle) or thrust-optimized contour (TOC nozzle), the free shock separation (FSS), i.e. a separation without reattachment on the nozzle wall, can occur when the rocket engine runs in a strong over-expansion regime. However past research [1] made it clear that another type of flow separation, called restricted shock separation (RSS), can occur in some rocket nozzles in a well defined range of nozzle pressure ratio (NPR). This special flow is characterized by a small recirculation pocket followed by reattachment on the nozzle wall. The main flow involves a special shock pattern called cap-shock followed by a trapped vortex surrounded by an annular supersonic jet. This flow separation is undesirable due to its unsteady and non-symmetric nature.

A number of studies in the past have been done to find out the origins of the side-loads [3]-[11]. It is proven that in thrust-optimized contoured (TOC) nozzles, a major side-load occurs as a result of transition of separation pattern from free shock separation to the restricted shock separation ($FSS \rightarrow RSS$) [5],[9]. The large side-load generation in the rocket nozzle during the start-up transient can induce serious launch problems and may also destroy engine hardware in sea-level tests. Apart from large side-loads high thermal stresses on the nozzle wall can be generated during the transient of the operation by non-axisymmetric behaviour of the separation line and the reattachment of the separated flow (in the case of RSS).

Transition from free shock separation to restricted shock separation is a complex phenomenon and has been an area of interest for the last few decades. Various experimental and numerical studies have been performed to understand this phenomenon [1]-[15]. The first work on these complex flow configurations was carried out by Nave and Coffey [1], who reported hysteresis loop to occur for the J-2S nozzle. Later on, Chen et al. [2] performed numerical calculations for the J-S2 nozzle and were able to capture the hysteresis flow-field for a wide range of nozzle pressure ratios (NPR). Reasons for the transition between the separation patterns have been discussed by Hagemann et al. [8] who identified the cap-shock pattern to be the cause of this transition.

In spite of various attempts to understand the flow separation in the rocket nozzles, the question about the formation of cap-shock pattern is still open and needs to be explored. In this paper we have focused our attention on the formation of cap-shock patternn and their consequences. Hence, numerical simulations are performed on a wide range of nozzle pressure ratios (NPR) to achieve flow transition from FSS to RSS regime. These simulations are performed on a thrust optimized contour (TOC) nozzle, which is experimentally investigated at Laboratoire d'Etudes Aérodynamiques (LEA), France, and is denoted as LEATOC nozzle [16].

2 NUMERICAL TOOLS

Numerical study on LEATOC nozzle has been performed by using the TGNS3D code developed at CEAT/LEA (Poitiers, France). This code solves the three-dimensional unsteady compressible Navier-Stokes equations on multiblock structured grids. The Navier-Stokes equations are discretized in space by using a cell centered finite volume method. Wilcox standard $k-\omega$ model [17] with realizability correction [18] has been used for the flow prediction. Roe's flux difference splitting scheme is employed to obtain the flux at the cell interface. The monotone upstream-centered schemes for conservation laws (MUSCL) approach has been used to extend the spatial accuracy to second order with the combination of limiters, which are minmod and van Albada, to prevent numerical instabilities in shock regions. A diagonally dominant alternating direction implicit (DDADI) approach has been used for the inversion of a large sparse matrix system for the implicit scheme.

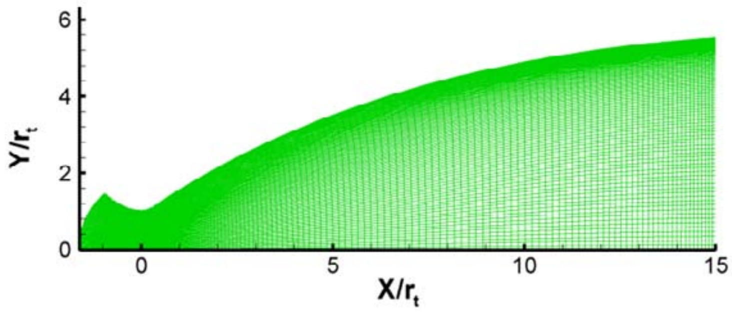

Figure 1: Mesh inside the nozzle

Mesh inside the nozzle contour is shown in Fig. 1, and is composed of 200*120=24000 nodes. Computational domain outside of the nozzle is extended 8 & 2 times the nozzle exit radius in axial and radial directions, respectively. Regarding the numerical boundary conditions, a stagnation temperature of 300 K and a time-varying stagnation pressure (P_o) have been prescribed at the nozzle inlet. Stagnation to ambient pressure ratio P_o/P_a is increased from NPR = 15 to 25 with an increment of ΔNPR = 0.5. Non-slip flow and adiabaticity are set at the walls. Static pressure $P_a = 1 \times 10^5 pa$ is prescribed as outflow condition.

3 PHENOMENOLOGY OF SEPARATED FLOWS

Adverse pressure gradient of sufficient strength can cause the boundary layer to separate. Such a condition typically occurs in the rocket nozzle when it operates under over-expanded condition (when the ratio of nozzle wall pressure inside to the ambient pressure is less than 1). Past research has made it clear that two different separation patterns exist: the classical free shock separation (FSS) and restricted shock separation (RSS) [1].

3.1 *Free Shock Separation*

In the case of free shock separation, the over-expanded flow fully separates from the wall. The resulting streamwise mean wall pressure evolution is mainly governed by the physics of the shock-wave / boundary layer interaction. The separation and the subsequent formation of the recirculation zone give rise to an oblique shock wave near the wall as depicted in Fig. 2. This incident oblique shock interacts with the Mach and consequently forms a reflected shock. This common point of interaction is called "Triple Point (TP)". The separated jet flow continues as a free jet. Fluid outside the nozzle is sucked into it and separates from the nozzle lip, yielding a counter-rotating recirculation bubble with respect to the massive recirculation zone. The exhaust jet flow is delimited by a mixing layer through a channel. This mixing layer can be considered as a "fluidic wall" in which the supersonic jet is confined.

3.2 *Restricted Shock Separation*

Appearance of restricted shock separated flow regime depends upon the nozzle contour in a defined range of NPR. This special type of separated flow exists only in the nozzles which contain an internal shock, which appears near the throat region. This internal shock interacts with the small normal shock (Mach stem) far away from the throat. Consequently a cone-shaped reflected shock (CSS) forms from this common point of interaction. This point of interaction is called triple point (TP). A quadruple point (QP) exists where the reflected cone-shaped shock interacts with the incident oblique shock, forming two reflected shocks. As a result, formation of cap-shock pattern takes place. A sketch of the cap-shock pattern is shown in Fig. 5. A free shear layer and the separated boundary layer interact with these reflected oblique shocks and consequently form two expansion waves. Downstream of the interaction, the boundary layer reflects back towards the nozzle wall, and reattaches a small recirculation zone attached to the wall. A large stabilized adverse pressure gradient vortex appears downstream of the cap-shock pattern surrounded by annular supersonic jets.

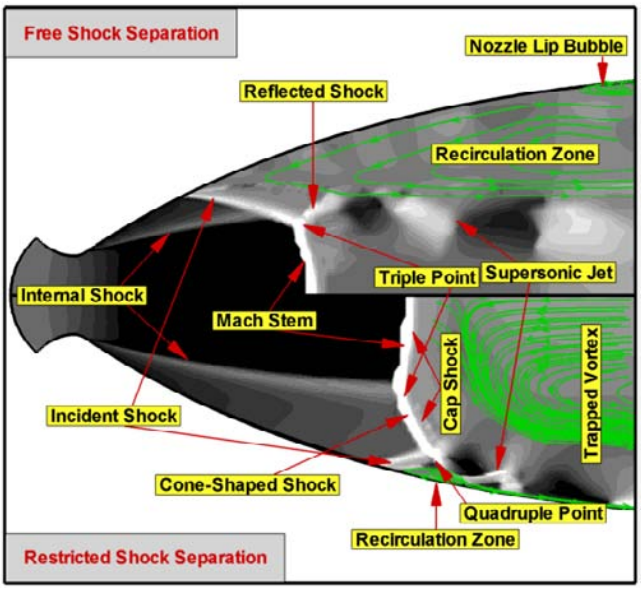

Figure 2: Free shock & restricted shock separation flow regimes.

4 RESULTS & DISCUSSION

Cap-shock pattern has been considered as one of main causes for the flow reattachment (i.e. restricted shock separated flow regime) in rocket nozzles, in a well defined range of nozzle pressure ratio (NPR). Such a condition occurs in thrust optimized contour (TOC) type nozzles, in which an internal shock appears near the throat region. To understand these complicated shock patterns and flow features, numerical simulations are performed on a TOC nozzle experimentally investigated at Laboratoire d'Etudes Aérodynamiques (LEA), Poitiers / France, denoted as LEATOC nozzle [9]. Experimental study performed by Nguyen et al. [10] on this nozzle has shown that during the start-up process of this nozzle at low NPR there exists FSS flow regime. This free shock separated flow suddenly turns into RSS flow regime when NPR reaches the value of 24. Following this, axi-symmetric flow transition has been performed to understand the flow physics and main elements which cause this sudden change in the flow behaviour. Calculations are performed in a wide range of NPR starting from NPR=15 (pure FSS flow regime) to 25 (RSS flow regime). Results and discussion on various aspects of the cap-shock pattern formation based on successfully reproduced flow transition (from FSS to RSS) at NPR=24 are presented here.

Evolution of flow structure during the whole flow transition process is beyond the scope of this paper. In the present study we are focused on the formation of cap-shock formation. Hence, a few snapshots are selected to show the evolution of flow. FSS and RSS flow regimes contains a variety of flow discontinuities. Hence, pseudo shadograph (iso contours of the density Laplacian $\frac{\partial^2\rho}{\partial^2 x} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\rho}{\partial r}\right)$) is used for fine flow structure detection.

Image 3 (Top:Left) shows the successfully reproduced FSS regime at NPR=16.5. An oblique shock is formed due to the flow separation, which interacts with the Mach disk (MD), here we call it as a Mach stem (MS). A reflected shock appears as a result of this interaction, and the point of interaction is called triple point (TP). On the other side the internal shock which forms near the throat of the nozzle interacts with the incident oblique shock from the wall. This interaction causes a small deflection in the oblique shock. A zoom near the triple point, internal and the incident shock clearly shows this deflection. A slip line emanates from triple point which is inclined towards the nozzle axis and also diverts the flow, emphasized by the streamlines.

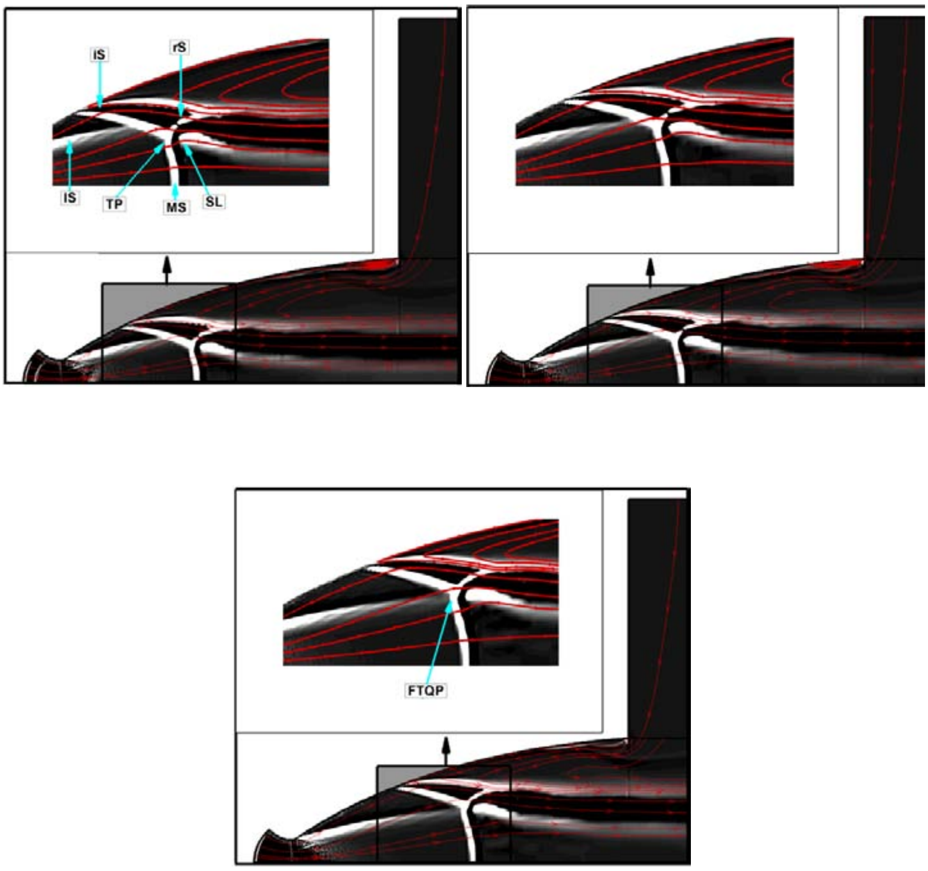

Figure 3: Time-averaged shadographs and streamlines at NPR (Top:Left) 16.5, (Top:Right) 19.5 & (Bottom) 24.0

As depicted in Fig. 3, with the increase in NPR, separation point and the Mach stem respectively moves downstream. As a consequence of this shift in the separation point location, the interaction point of the internal shock on the incident shock moves towards the triple point. Figure 3 (Bottom), shows a snapshot when this internal shock reaches the Triple point. According to our knowledge no such type of interaction has been reported or seen earlier in literature. It is interesting to note that a clean curved incident shock now interacts directly with the Mach stem along with the internal shock and a slight change in the angle of reflected shock has been observed after this very interaction. It seems that the resulting reflected shock may be the common result of internal and incident shock interaction with the Mach stem. By looking at Fig. 4, one can notice that the flow behaviour after this interaction seems to change into the RSS flow regime. Hence we have called this point of interaction (a common point for Mach stem, internal, incident and the reflected shocks) “Flow Transition Quadruple point (FTQP)”. It is worthwhile to mention here that this FTQP appears only in the nozzles in which an internal shock appears near the throat region (see Fig. 3 (Bottom). It has been observed that this FTQP point appears when the NPR is about 24, and experimentally it is shown that in LEATOC nozzle flow transition takes place when NPR=24 [9],[10]. One may conclude that the NPR at which this FTQP point occurs is the critical value for the flow transition and we have called it “Critical Nozzle Pressure Ratio (CNPR)”.

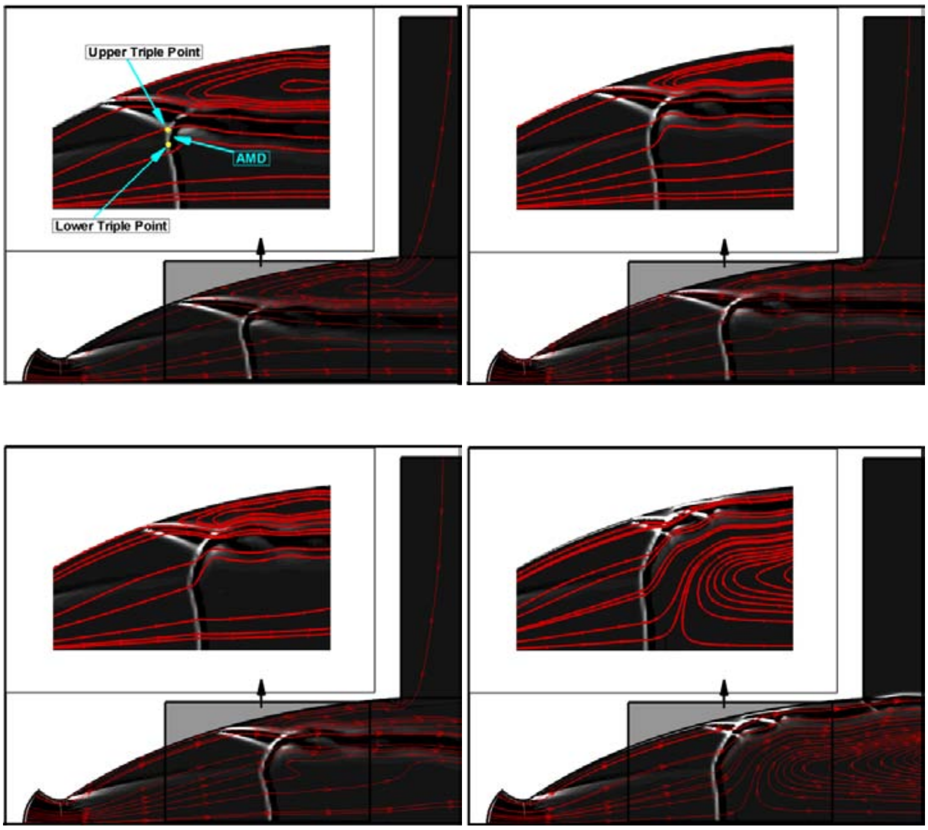

Figure 4: Evolution of flow structure during flow transition (FSS⟶RSS)

The series of snapshots in Fig. 4 shows the evolution of flow transition starting from the FSS flow regime to the RSS flow regime. With the evolution of time the FTQP turns into two separate triple points. The small normal shock that joins these two triple points is called the annular Mach disk (AMD). The upper part of the AMD makes a triple point with the incident and the reflected shock, while the lower part does so with the internal shock and the Mach stem. Later on, this AMD turns into a reflected oblique shock for the internal shock and the Mach stem interaction at the triple point. At the same time the slip line originating from this triple point is inclined away from the nozzle axis, towards the nozzle wall. The streamlines deflect away from the nozzle axis in the region of this interaction. Previously, in FSS flow configuration, it has been observed that these streamlines seem to reflect back to the nozzle axis from the triple point due to the Mach reflection. A conical reflected shock-wave (also known as cone-shaped shock) from the triple point interacts with the incident shock and makes a quadruple point with the subsequent formation of two reflected oblique shocks. Finally we see the complicated axi-symmetric "cap-shock pattern", which is a combined feature of the Mach stem, cone-shaped shock and the incident oblique shock due to the flow separation, also shown in Fig. 5.

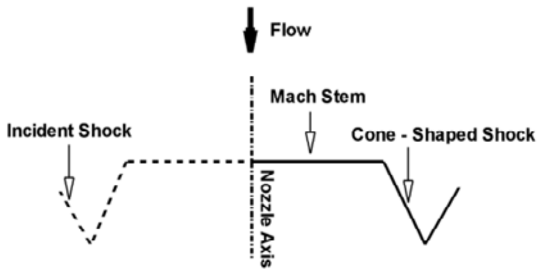

Figure 5: Sketch of cap-shock pattern.

During this process, pressure at the nozzle axis increases, and flow deflection away from the nozzle give rise to the vortical structures along the nozzle axis. A negative axial momentum (against the main flow stream) resists the movement of the Mach stem along the nozzle axis. Hence, the distance between the separation point and the location of the Mach stem in the streamwise direction decreases. Consequently, the size of the incident shock relatively decreases and on the other hand we can see the increase in the reflected shock from the triple point. The resulting radial momentum away from the nozzle axis increases and diverts the flow towards the nozzle wall. Meanwhile, a vortical structure appears downstream of the cap-shock pattern. The size of this vortical structure increases with the increase in the size of cone-shaped shock and finally combines into one large trapped stabilized vortex of an adverse pressure gradient. The annular separated supersonic separated jet reattaches back to the nozzle wall and traps a small recirculation zone between the separation and the reattachment points. Finally we can see a very complex restricted shock separated flow regime.

Pressure evolution along the nozzle wall is different for FSS and RSS flow regimes. When a separated supersonic jet reattaches back to the nozzle wall, it causes the pressure to increase even higher than the ambient pressure. The annular supersonic flow is subjected to expansion and compression waves reflected between the nozzle wall and the mixing layer separating the high speed region from the central trapped vortex. These reflected waves give an oscillatory wall pressure distribution which can lead in some cases to secondary separation, as shown by Nguyen [10].

Numerically obtained wall pressure profiles at different NPR during this transition are compared with the available experimental data. Figure 6, shows plots of the wall pressure (normalized with the inlet stagnation pressure P_0) along the nozzle axis (normalized with the throat radius r_t). Numerically obtained wall pressures are in excellent agreement with their corresponding experimental data. We see that for FSS flow regime the wall pressure suddenly increases at the incipient separation point, and reaches a plateau which gradually increases but always remains less than the ambient pressure. Whereas in the case of RSS flow regime after reaching the plateau, a sudden rise in the pressure occurs due to the reattachment of the flow. Further decrease and increase in the wall pressure is due to the successive interaction of shock and expansion waves in the annular supersonic jet.

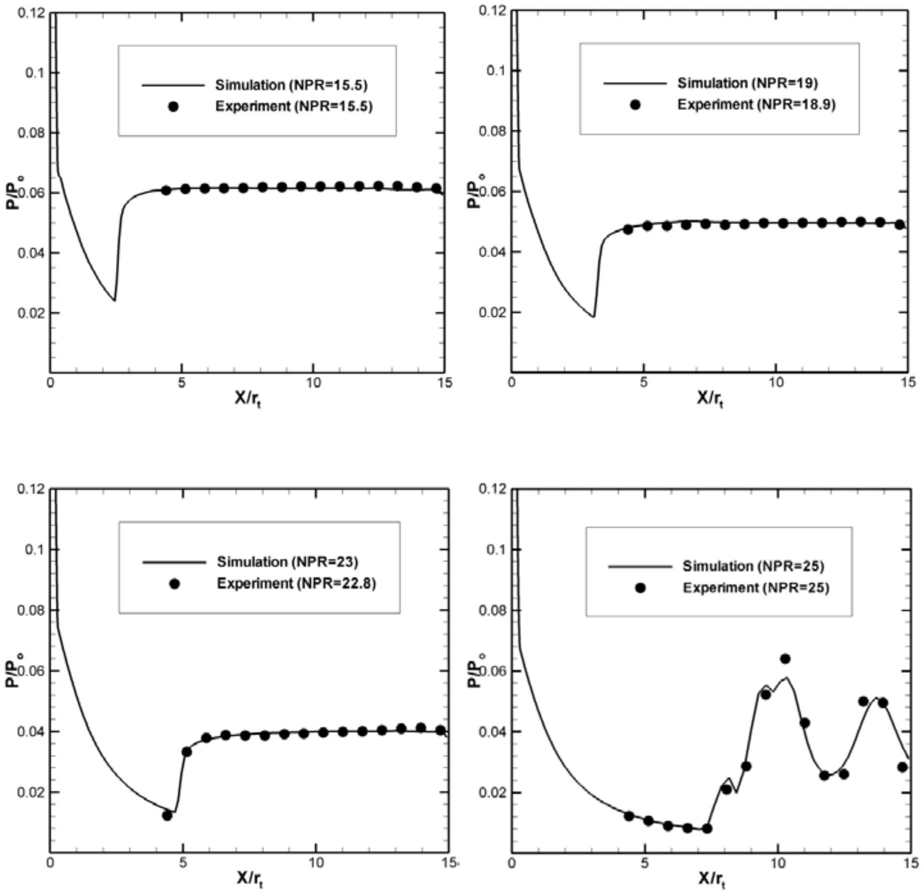

Figure 6: Evolution of mean pressure along the nozzle wall.

Based on these correctly predicted separation point (SP) locations, their relative distance with respect to the Mach stem (MS) is plotted against the nozzle pressure ratio in Fig 7. Starting from lower NPR (say 15) this relative distance of SP and MS increases and reaches to its maximum at $NPR \simeq 19$ in FSS mode. Further increase in the value of NPR towards the CNPR, this relative distance decreases. Once we reach NPR=24 (i.e. CNPR for LEATOC nozzle) a huge decrease in this difference has been observed, which is due to the rapid movement of separation point towards the nozzle exit w.r.t the slow moving MS in this very transition zone. Futhermore, in RSS mode we see a linear decrease in its value near to zero. Recently Shams et al. [19] in their detailed 3D numerical investigations on RSS flow regime has shown that for higher NPR this separation point moves downstream of the Mach stem.

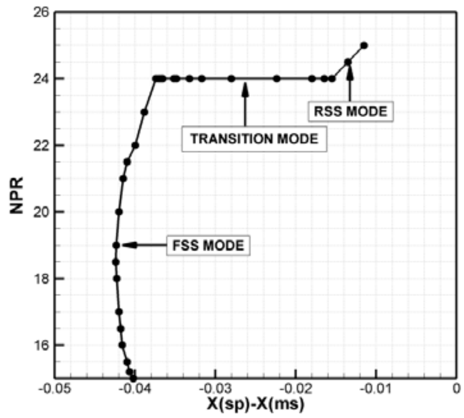

Figure 7: Evolution of relative distance between separation point and Mach stem w.r.t the NPR.

5 CONCLUSIONS

Axi-symmetric flow transition from free shock separation to restricted shock separation has been numerically reproduced in thrust optimized contour, LEATOC, nozzle. The main goal of this study was to understand the phenomenon of the cap-shock formation. This complicated pattern appears only in the nozzles which exhibit an internal shock near the throat region. The present study has shown that formation of cap-shock pattern is triggered when internal and separated shocks interact with the Mach stem and form two reflected shocks at a common interaction point. This common interaction point (which is denoted as flow transition quadruple point, FTQP) occurs corresponding to its critical nozzle pressure ratio (CNPR), which is 24 for LEATOC nozzle. As a consequence of cap-shock pattern radial momentum away from the nozzle increases and causes the separated annular supersonic jet to reattach back to the nozzle wall.

ACKNOWLEDGEMENT

The Higher Education Commission (HEC), Government of Pakistan, is acknowledged for the research grant. The first author would like to thank T. Alziary de Roquefort for many discussions related to this research work.

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