STUDY OVER DIFFERENT NOZZLE PROFILES FOR NOZZLE FLOW SEPARATION CONTROLS

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ABSTRACT

Since the dawn of the space age, flow separation issue in rocket nozzles has been an unwanted phenomenon for the engineers. So, naturally, this became a task for the engineers which is to be brought under control. But it turned out to be a daunting task; even though many were able to explain the physics behind this phenomenon, it is not fully understood even to the present day. So, there are not many methods, which explains how to control or suppress this phenomenon. This paper aims to study about two of those few methods which affectively are able to suppress flow separation in rocket nozzles.

Keywords- *Flow separation, FSS, RSS, Nozzles*

INTRODUCTION

The nozzle is the main part of the rocket, which provides the required exhaust flow to propel the rocket into space with supersonic speeds. Up to this date, different types of profiles are used based on the different requirements and applications. But all these nozzles are based upon the de-Laval nozzle; de Laval nozzle consists of a convergent section, a throat, and a divergent section.

Rocket nozzle profiles can be classified as follows; conical, Truncated Ideal Contoured (TIC), Thrust Optimized Contoured (TOC), and Thrust Optimized Parabolic bell (TOP), Compressed Truncated perfect (CTP) nozzles. Even though these nozzles are being used since the dawn of the space age, there is a concept of nozzle flow that is not fully understood to the present day, which is nozzle flow separation.

Nozzle flow separation occurs when the boundary layer gets separated from the nozzle wall; this phenomenon is quite undesirable. When exit pressure of nozzle is in the range of 0.4 to 0.8 of local atmospheric pressure [3], ambient air tries to enter into the viscous layer. Thus, due to the adverse pressure gradient, the boundary layer will get separated from the wall.

In general, overexpanded nozzles are used to obtain optimum nozzle flow pattern, which helps to attain maximum thrust at the desired altitude. But these overexpanded nozzles experience nozzle flow separation. The nozzle flow separation patterns vary which operating pressure, nozzle profile, exhaust gas properties, back pressure, etc. The nozzle flow separation patterns can be classified as follows; Free Shock Separation (FSS) and Restricted Shock Separation (RSS) [1]. Both these flow separation phenomena and then modes to suppress the RSS phenomena are discussed in detail.

LITERATURE REVIEW

Most of the works which study nozzle flow separation, concludes that the ambient pressure is the main reason why flow separation occurs. The presence of adverse pressure gradients causes the flow to separate from the nozzle wall and this separated flow inhibits several side loads on the nozzle, ultimately leading to its damage. So, a method was suggested to suppress the flow separation; this method involves adding an aerospike profile to the lip of the nozzle.

Until 2000, it was widely assumed that RSS occurs only in Thrust optimized cold flow subscale nozzles. So, no attention was paid to whether the design of the nozzle affects the occurrence of RSS. Later these subscale cold flow tests were also conducted with TIC [8-9] and conical nozzles, where no reattachment occurred, and only FSS occurred. It is due to the lack of formation of internal shocks in TIC and conical nozzles. Hence, the RSS phenomenon can be attributed to the nozzle contour based on these results [5-7]. So, by doing modifications to the existing nozzle contour, we can suppress RSS. This method involves adding a step to the divergent section of the nozzle.

DISCUSSION

NOZZLE FLOW SEPARATION PATTERNS

Free Shock Separation (FSS):

In a thrust optimized contour nozzle (TOC), when the pressure ratio is low, FSS is observed. FSS is the continuation of the flow as a free jet after separation from the nozzle wall, which implies that there is no reattachment of the flow to the wall downstream of the separation point. Besides the TOC nozzle, the FSS pattern is also seen in other nozzle profiles such as conical, TIC, and TOP.

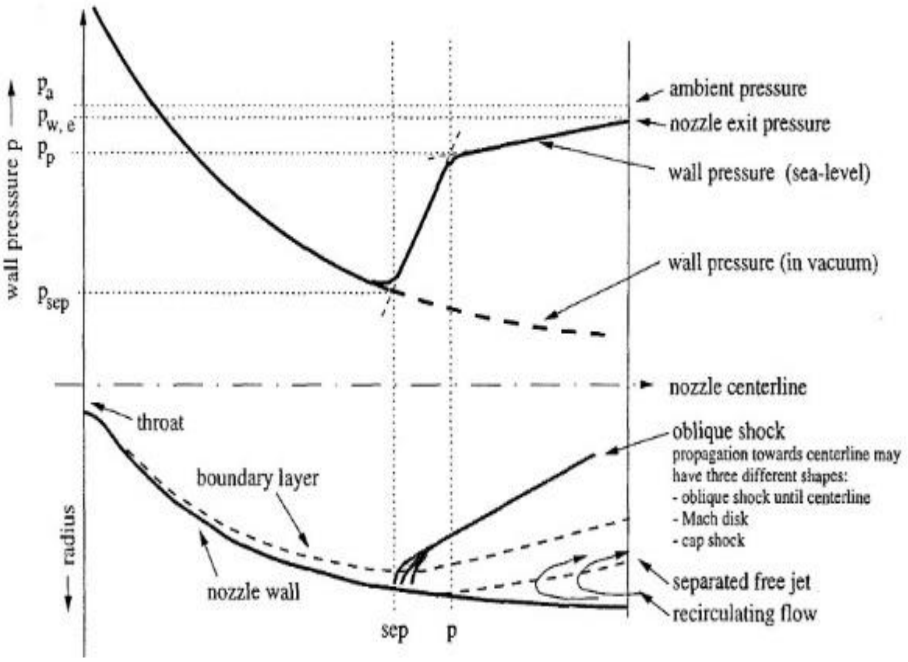

Fig 1: Free shock separation in overexpanded rocket nozzle [1]

Restricted shock separation (RSS)

RSS occurs during the startup and shut down of the engine and is only seen in the TOC nozzle. RSS is reattachment of the flow to the wall downstream of the separation point. Reattachment takes place due to the formation of cap shock in thrust optimized nozzle. A cone-shaped oblique shock is a part of a cap shock pattern that is inclined to the central axis of the nozzle. Because of this inclination of the shock, momentum is generated, which is greater than momentum induced by the separation shock, resulting in the flow getting deflected towards the nozzle wall in the radial direction [2]; this reattachment results in the formation of a recirculation bubble. RSS occurs in the TOC nozzle due to the different wall pressure profiles downstream of the reattachment point. RSS doesn't happen in conical nozzles and TIC nozzles [1]. The transition of FSS to RSS is known as the hysteresis effect. RSS causes lateral load or side load, resulting in the damage of the nozzle and its components. So, it is vital to suppress the

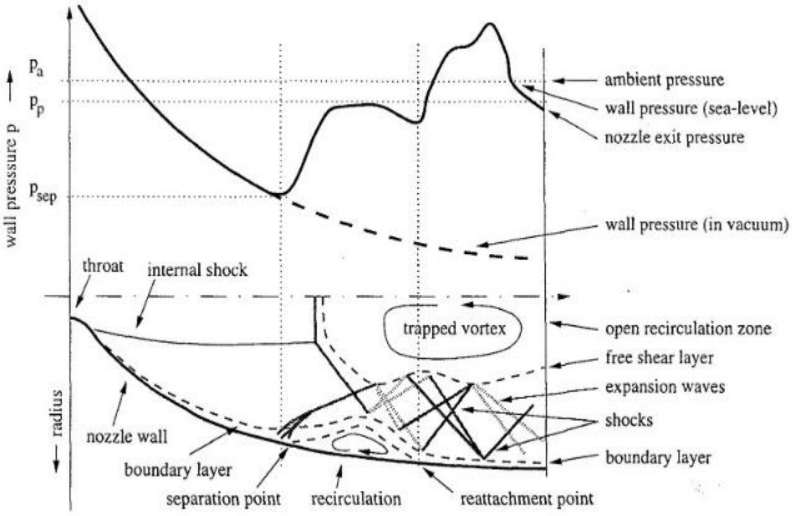

Fig 2: Restricted shock separation in overexpanded rocket nozzle [1]

FLOW SEPARATION CONTROL BY ADDING AN AEROSPIKE PROFILE TO THE LIP OF THE NOZZLE

The basic idea involved here is to prevent the action of adverse pressure gradient on the main exhaust flow. So, an aerospike profile is added to the lip of the basic bell nozzle design. The flow generated by the aerospike profile acts as a barricade to the ambient pressure gradient; So that this pressure gradient won't be able to penetrate this high momentum barricade and affect the main exhaust flow. The addition of this aerospike profile to the main bell nozzle doesn't affect the performance and efficiency. [12]

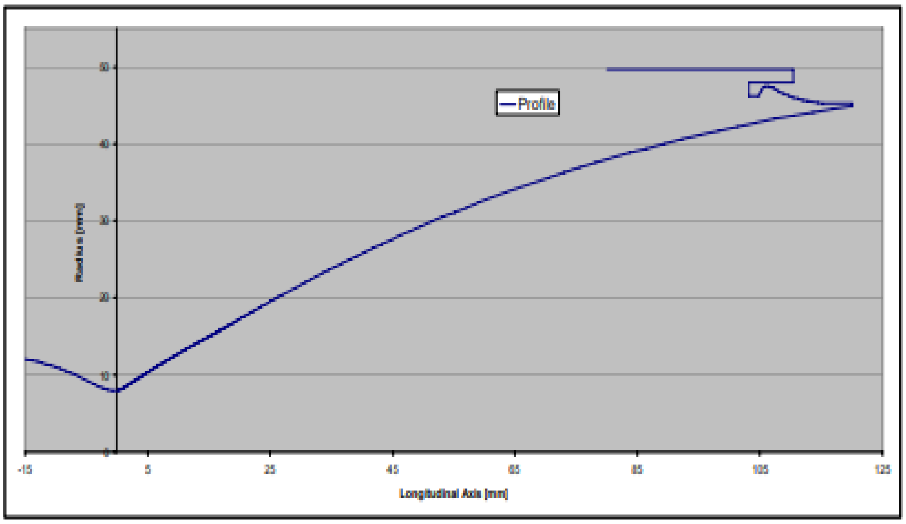

Fig 3: Bell nozzle with added aerospike structure [12]

This addition also allows for increase in specific impulse and also allows for increase in throttling range even at low altitudes without inducing any side loads.

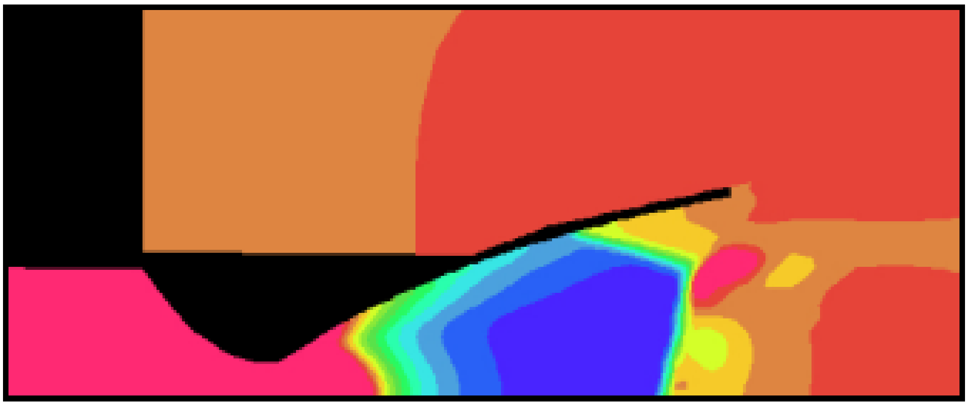

Fig 4: Pressure field for bell nozzle [12]

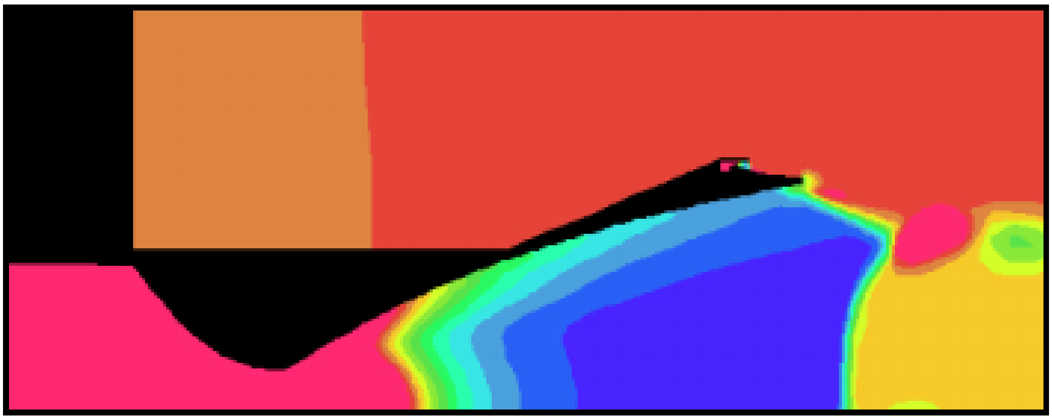

Fig 5: Pressure field for bell nozzle with added aerospike structure [12]

The numerical simulations shown above illustrates the state of flow separation in the bell nozzle with and without the aerospike profile. The fig 4 pressure contour clearly shows us the flow separation in the nozzle and the fig 5 which is equipped with the aerospike profile doesn’t show any flow separation as it is totally suppressed**.**

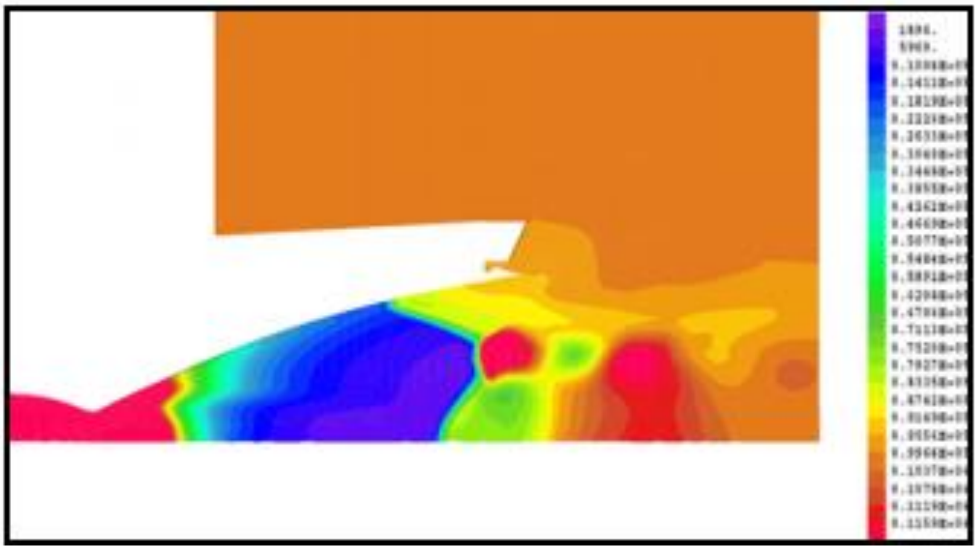

Fig 6: Pressure field for bell nozzle without aerospike flow at NPR= 37 [12]

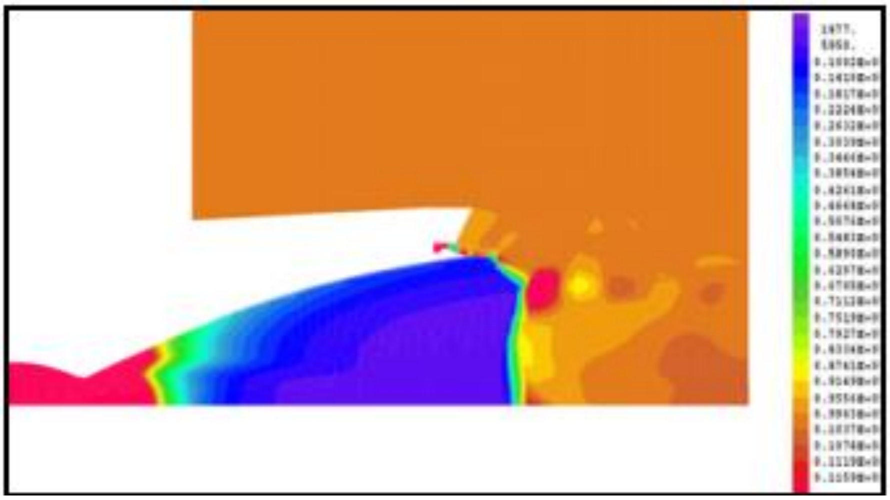

Fig 7: Pressure field for bell nozzle with aerospike flow at NPR= 37 [12]

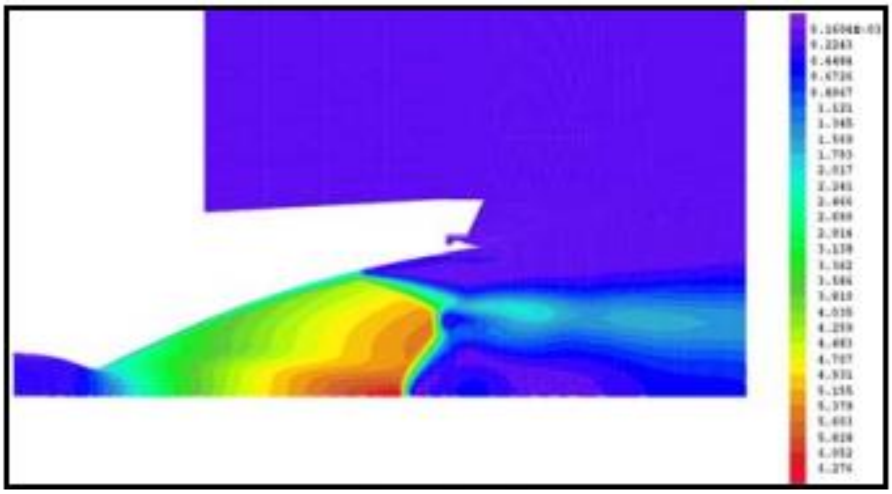

Fig 8: Mach field for bell nozzle without aerospike flow at NPR= 37 [12]

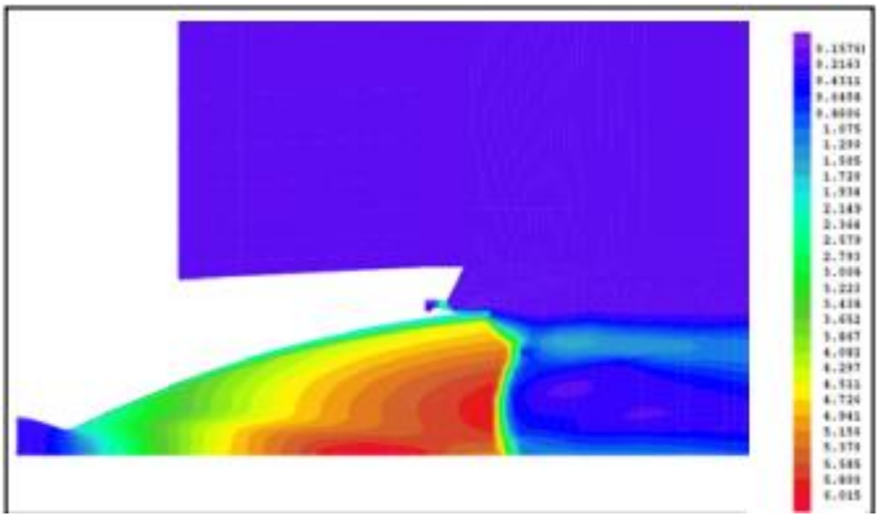

Fig 9: Mach field for bell nozzle with aerospike flow at NPR= 37 [12]

The numerical analysis was done by using turbulence model is a large range Reynolds number (k, ε) model with realizability condition. The above figures (5-8) illustrate pressure and Mach field contours at different NPRs with and without the aerospike flow.

RSS Suppression by Step Inside the Nozzle:

The step inside the nozzle contour modification was first done on the LE-7A engine. LE-7A is a Japanese engine used by JAXA on the H-IIA Launch Vehicle. It has experienced two major troubles; the large side loads and the damage of regenerative cooling tubes due to heat loads caused during startup and shut down. Later, it was found that the cause for this damage is due to the hysteresis effect. So, to counter this, a step is introduced inside the nozzle at a suitable axial location and height. It is crucial to identify the position for the step; the ideal location near the Reattachment on the nozzle inside the wall. In this case this position is at 37%L* of the nozzle inside wall axially.

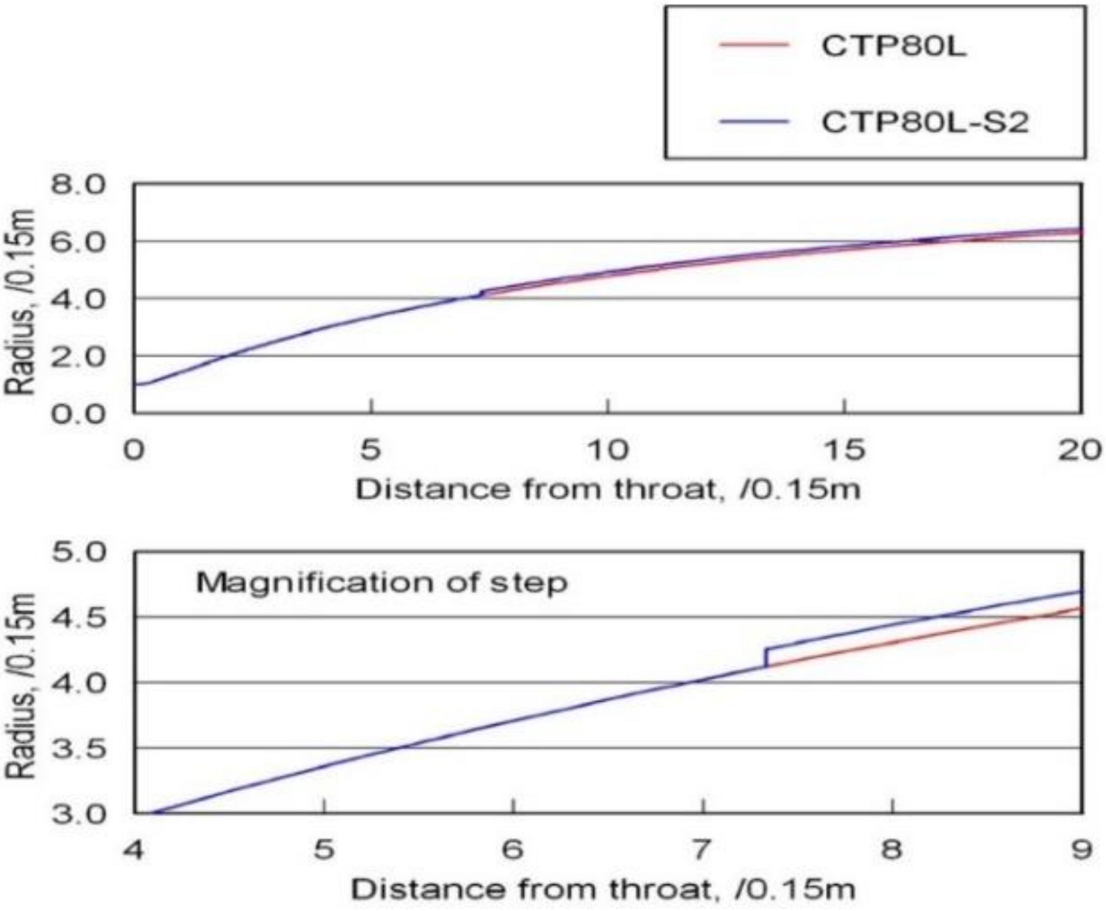

Fig 10: Illustration of nozzle profile with and without step [11]

During the shutdown sequence, the separation point moves upstream of the nozzle; the transition from FSS to RSS occurs, and the recirculation bubble starts moving upstream due to the decrease in NPR. But with a step inside the nozzle wall, when the separation point reaches the step, the reattachment flow separates from the nozzle wall, and the transition from FSS to RSS will not occur.

Numerical analysis was done using Compressible Navier Stokes equation, Spalart- Allmaras one equation Turbulence model using ideal air as working fluid. For convective terms, the AUSMDV scheme with second-order upwind biased MUSCL interpolation, and for viscous and time terms central difference scheme and three points back differencing scheme, LU-SGS are used respectively.

The nozzle is designed for a pressure range of 0.1-12 MPa at a rate of 7.93 MPa/s and a total temperature range of 300-3300 at a rate of 60000 k/s.

Fig 11 shows the numerical simulation for CTP80L and CTP80L-S2 which are nozzle configurations without and with step respectively [10]; during start-up, for CTP80L configuration, we can see that for NPR 30 to 50, the separation point moves downstream, whereas, for CTP80L-S2 configuration, RSS doesn't occur due to the presence of step.

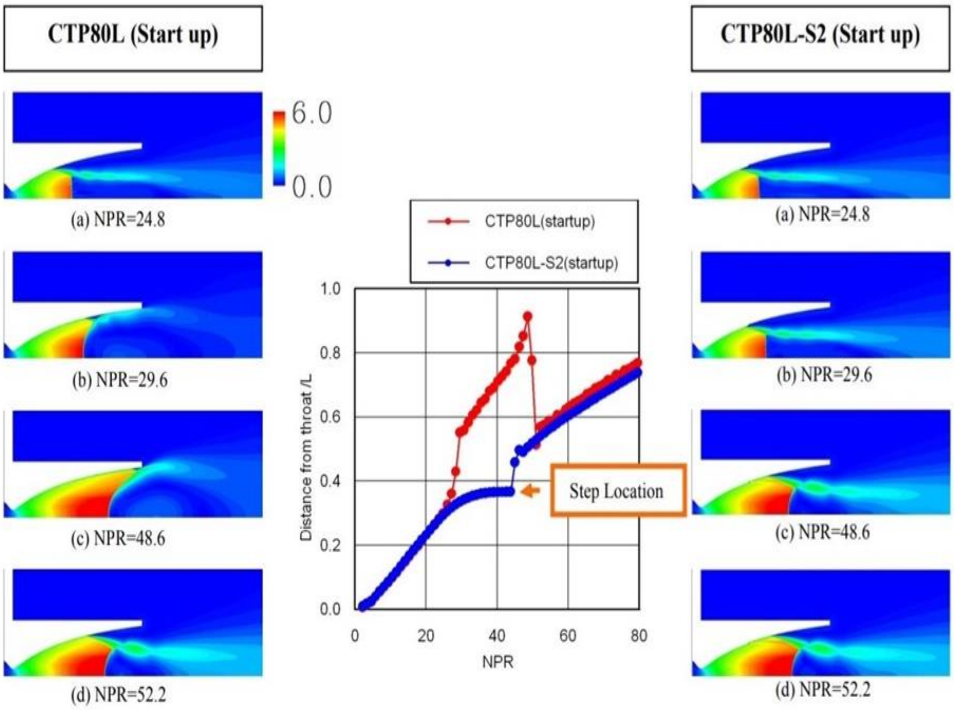

Fig 11: Comparison of Mach field for flow separation in CTP nozzle during startup [11]

Fig 12 shows the numerical simulation for CTP80L and CTP80L-S2 which are nozzle configurations without and with step respectively; during shut down, for CTP80L configuration, we can see that for NPR 30 to10, the separation point moves upstream, whereas, for CTP80L-S2 configuration, RSS doesn't occur due to the presence of step.

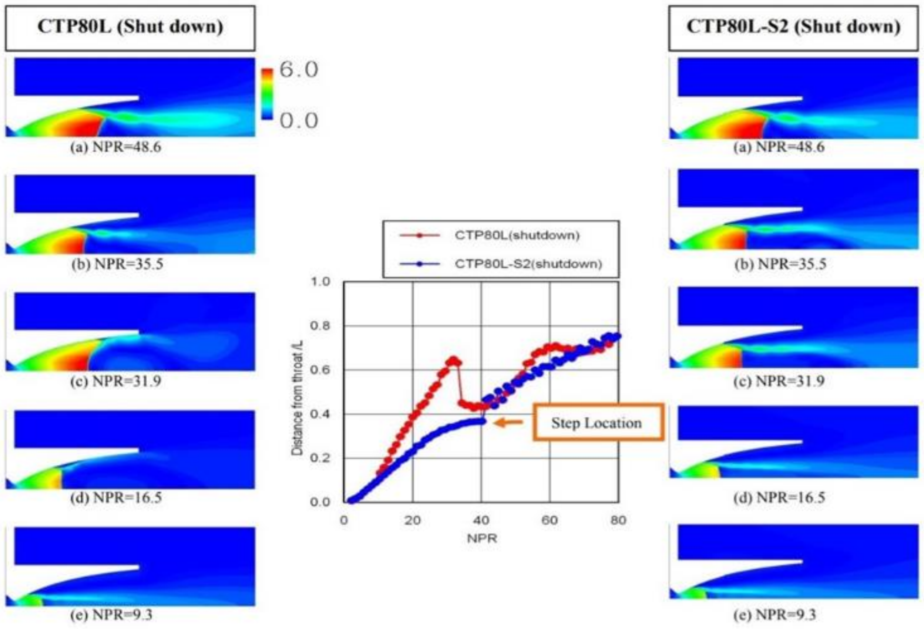

Fig 12: Comparison of Mach field for flow separation in CTP nozzle during shutdown [11]

CONCLUSION

After studying both the aforementioned methods it is evident that, flow separation in nozzles can be suppressed by making changes to the nozzle contour. With the addition of aerospike profile to the lip of the classical bell nozzle, both FSS and RSS are being suppressed. Apart from suppressing flow separation, we can also achieve higher specific impulse and the throttling range can be widened even at low altitudes. Now coming to the study on step inside the nozzle in case of the LE-7A engine, even though the complete flow separation is not being suppressed, RSS effect is getting suppressed. RSS may cause significant structural damage to the nozzle and its components, so, it is a significant leap suppressing this effect.

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