Analysis and optimization of Dual secondary fuel injector for Thrust vector control

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Abstract. The motive of this analysis is to compare the performance parameters of a single secondary fuel injector and performance of Dual Secondary fuel injector system for Thrust Vector Control (SITVC) in a supersonic nozzle for different distances between the two ports. With the help of Computational Fluid Dynamics (CFD) the performance characteristics of SITVC has been analyzed. Experimental and numerical investigations have been done with various circumstances to examine the performance augmentations of the 2-D nozzle.

1. Introduction

Maneuvering of rocket nozzle can be a very difficult task to perform and to make things various methods are used, one of them is secondary fuel injector system for thrust vectoring control (SITVC). Thrust vectoring system of a rocket system is a method of controlling the vehicle's thrust by diverting the primary force of the rocket engine's flow away for the primary axis in order to produce a defined force in the required direction [4]. Because of the imbalance generated by the secondary flow force, a side force emerges that may be employed to regulate the moving vehicle's altitude and direction. Thrust vectoring significantly improves maneuverability, particularly at low thrust and high angle of attack, where traditional control surfaces are ineffective. Thrust vectoring control system (TVC) will work independent of the aerodynamic force as far as the engine is concerned. It's also employed in extreme atmospheric situations where the effect of aerodynamic forces are negligible to be utilized for control. In front of the supersonic flow, secondary flow functions as an object [5-6]. Due to boundary layer separation in front of upstream of the injection spot formation of bow shock was analyzed which causes asymmetry and a mild separation in the shock.

Dual secondary fuel injector thrust vectoring control system is an updated version of a single secondary fuel injector thrust vectoring control system. In this two ports are used for injection of fluid for thrust vectoring control system. For the analysis, one port is left fixed and the other port is varied with specified distances [7-9]. Dual secondary fuel injection thrust vectoring control system gives better results as compared to usual one under certain circumstances, having same inlet conditions as usual SITVC it provides the better amount of thrust and stable control of the flow of fluid. A few strategies have been developed to increase SITVC performance. Multiple injections are one of the approaches which can be used to increases thrust vectoring capabilities without decreasing thrust performance. The purpose of this research was to gather basic information on the parameters of Secondary injector of fuel for thrust vector control system (SITVC), namely injection site, nozzle diverging cone angle, and injection flow rate. The parametric research of SITVC propulsion efficiency's validation details and findings are listed below. The performance of the dual secondary fuel injector for a 2-D nozzle having a steady state flow as well as viscous flow were investigated using Fluent. The outcomes are compared to the results of a single injection approach. The effects of injectant port distance and position on SITVC performance are investigated [11-12],
Subanesh Shyam Rajendran et.al showed causes of secondary jet installed at 20% of the nozzle length from the exit boundary results in better thrust vectoring. Also, sonic secondary jets resulted in a decrement of vehicle acceleration, and the supersonic secondary jets proved to be more efficient in thrust vectoring with the same mass flow rates. It can be observed that the supersonic secondary jet will be more powerful than the sonic secondary jet having the same mass flow rate and jet pressure for an efficient and lucrative thrust vectoring [1]. Prince Raj L et.al mentioned about various performance parameters like thrust augmentation and secondary jet amplification are calculated. The static pressure increased by more than three times than the undisturbed nozzle flow. Study shows that by injecting from two ports simultaneously control force along a given direction can be achieved by placing these ports appropriately [2]. M Deepu et.al examines the effect over the secondary fuel injection system for expanding as well as non-expanding supersonic flow and also analyses the effect of thrust augmentation on a rocket engine. A rise in static pressure by the wall of the nozzle because of secondary fuel injection, showing compatibility with fuel injection pressure. It can be seen for sufficient chamber pressure, secondary injection system causes thrust augmentation [3]. Ankit et.al reviewed about pintle injector mentioning about spray patterns and the effect of thrust based on total momentum ratio as well as length to duct ratio. It also shows the discussion fact on nozzle discharge coefficients and flux ratios [4]. Elham Mohammadi et.al performed a study on dual SITVC to normal secondary injection system using CFD, the effect caused by two injector port varying in distances is analyzed and results shows that injection system provides more side force at 8.5 times of diameter as of usual injector port having same mass flow rate. Dual SITVC produces more thrust force for a particular distance between the ports with less mass flow rate and there is less probability of getting shock impingement than single injection system [5].

2. Methodology

The nozzle flow field has been numerically simulated with the secondary fuel injector system. A conical nozzle having two circular port openings in the divergent portion is used for this and is made with the help of rocket propulsion analysis (RPA) software and the design was drawn on fusion 360 CAD software with varying distances for two secondary injector ports. Simulation analysis was carried out on Ansys Fluent having initial conditions of primary flow chamber pressure 5MPa, inlet temperature 3500k, and secondary flow inlet pressure of 3MPa, inlet temperature 300k.

2.1. Numerical Methodology

The realizable k-ε model is defined by the following equations:

The turbulence kinetic energy equation is given by:

\[
\frac{D}{Dt}(\rho k) = \nabla \cdot (\rho D k \nabla k) + \rho G - \frac{2}{3} \rho (\nabla \cdot \mathbf{u}) k - \rho \varepsilon + S_k
\]  

(1)

And the dissipation rate by:

\[
\frac{D}{Dt}(\rho \varepsilon) = \nabla \cdot (\rho D \varepsilon \nabla \varepsilon) + C_1 \rho |S| \varepsilon - C_2 \rho \frac{e^2}{k + (\varepsilon \nu_s)} + S_\varepsilon
\]

(2)

The turbulence viscosity is calculated using:

\[
\nu_t = C_{\mu} \frac{k^2}{\varepsilon}
\]

(3)
Where the $C_\mu$ is given by:

$$C_\mu = \frac{1}{A_0 + A_s \mu \frac{\nu}{c}}$$

(4)

To calculate the thrust produced by the rocket nozzle, the below-mentioned equation is used:-

$$F = m_i \nu_e + (p_e - p_0) * A_e$$

(5)

The mass flow rate of the nozzle can be found from the basic geometry and the fluid properties that can be given as

$$m_i = \rho_l v_t A_t = \frac{p_0 A_t \nu^2}{RT_0^2} \frac{1}{\gamma \gamma} \left( \frac{2}{\gamma + 1} \right)^{\gamma + 1}$$

(6)

2.2. Meshing and boundary condition

In engineering processes meshing plays a very important role. Creating high-quality mesh is one of the critical factors that should be ensured for simulation accuracy. Here, we have different geometries to be tested where the secondary injection ports are placed at various distances from the throat of the nozzle. The following cases are mentioned along with the meshing and boundary conditions.

Initially, there is only one secondary injector placed 10 cm from the throat of the nozzle. Splitting the surfaces and face meshing them separately results in more accurate values during the simulation. In addition to that edge-sizing gives finer meshing at the edges. Edge sizing of 100 divisions is entered on average for accurate meshing. Named selections are given to the edges concerning their inlet and outlet conditions. The edge on the left most is named as pressure inlet and the secondary injector ports are also named as pressure inlets 1, 2 respectively. The rightmost edge of the nozzle is named as pressure exit and all the remaining edges are named as walls of the nozzle. Here are the images of meshing for different geometric cases.

Figure 1. The meshing of single port

Figure 2. Meshing of port with distance 1cm

Figure 3. Meshing of port with distance 2cm

Figure 4. Meshing of port with distance 3cm
Boundary conditions – for all the cases the energy equation was turned on and used k – epsilon realizable model and a density-based solver is used for solving the problem. The primary inlet pressure is given as 5, 7 MPa depending on the cases studied and the secondary inlet pressure is given as 3, 5 MPa. The pressure outlet has a vacuum condition i.e. 0 MPa for making the problem simpler. All the walls are stationary in the problem. Initially, for the single secondary injector, it is investigated under two primary pressure conditions 5 MPa and 7 MPa and the secondary inlet pressure will be the same for both cases. Later there are two secondary injectors are introduced at a distance of 1cm. the distance between the ports is varied as 1cm, 2cm, 3cm, 4cm respectively. All the inlet conditions are the same for are the cases mentioned. The second-order upwind method is used for Flow, Turbulent Kinetic Energy, and Turbulent Dissipation Rate for the accurate solving process. The setup was initialized using standard initialization from pressure inlet values.

3. Results and discussions
A parametric study on varying distances between the dual injectors of secondary fuel injection systems as well as the advantage of dual SITVC over single SITVC is analyzed.
After the analyses, results show that using dual secondary fuel injection system over usual secondary fuel injection system makes the flow of fluid stable as well as decreases the probability of getting shock impingement when compared with single secondary injection system. Single SITVC faces problem of shock impingement over the walls of nozzle which increasing the use of mass flow rate of fluid and lead to decrement in side force required for thrust vectoring and this problem seems to be solved using dual injection system.

| Test number | Distance from the fixed port (cm) |
|-------------|----------------------------------|
| A           | 0 (single injection)             |
| B           | 1.0                              |
| C           | 2.0                              |
| D           | 3.0                              |
| E           | 4.0                              |
| F           | No injection                     |

From the above table, it is observed that for tests A-E thrust was directed towards only a particular direction which shows the proper working of the thrust vectoring control system. For test D which is having 3cm distance from the fixed port, supplies greatest amount of thrust as compared to test A which is having only a single injection port for same inlet conditions, the amount of thrust produced by test D which is having 3cm port distance is 299.574KN, whereas, the amount of thrust produced by test A which is having only single injection is 250.235 KN. While performing analysis for test F where no injection is considered, symmetrical flow inside the nozzle is observed. It is also observed that the flow of fluid inside the nozzle is much more stable for a dual thrust vectoring control system as compared to the single secondary fuel control system.

| Distance from the fixed port | Thrust produced |
|-----------------------------|-----------------|
| 0(singel injection)         | 250.235 KN      |
| 1cm                         | 133.941KN       |
| 2cm                         | 212.987KN       |
| 3cm                         | 299.574KN       |
| 4cm                         | 100.45KN        |
After analyses it is also observed that as we increase the distance between the two injection ports to 3cm the value of the Mach number increases rapidly and drastically decreases as distance is increased to 4cm. As well as the velocity increases with the increase in distance between the ports till 3cm and decreased as the distance between the two ports get large.

Table 3. Mach number variation with a distance of the port

| Distance between ports (cm) | Velocity (m/s) | Mach number |
|-----------------------------|----------------|-------------|
| 0 (single injection)        | 1519.25        | 4.416       |
| 1                           | 1070.79        | 3.11        |
| 2                           | 1367.2498      | 3.974       |
| 3                           | 1687.527       | 4.9         |
| 4                           | 962.216        | 2.79        |

4. Conclusion

The efficiency of a dual secondary injector system for TVC is weighed up to that of a usual secondary injector for thrust vector control system in this research. Fluent is used as a CFD code to utilized to analyze the nozzle cases. The impact of injector port distance on flow field shape and SITVC performance was also examined. For a test where distance between the fixed port and second port is taken to be 3 cm, a dual secondary fuel injection thrust vectoring control (SITVC) system shows superior results as compared to single secondary fuel injection thrust vectoring control system, according to observations and thrust calculations. Also, it is found that the second injector for a distance of 3cm between the fixed and secondary port works better than other distances having same initial conditions as well as dual secondary injection system for 3cm works better than single injection system. Dual secondary fuel injection gives stable flow compared to a single fuel injection system. It is also observed that chances of getting shock impingement during the flow gets lesser as we use dual injection system for thrust vectoring.

5. References

[1] Subanesh Shyam Rajendran Aravind Kumar T R Nareshkumar K S Ragothaman S Riyana Raveendran and Sanal Kumar V R 2013 Studies on Thrust Vector Control using Secondary Injection Sonic and Supersonic Jets 2nd International Conference on Mechanical, Electronics and Mechatronics Engineering
(ICMEME’2013) June 17-18 2013 London (UK).

[2] Prince Raj L Rejith P and Balu R 2012 Numerical simulation of a hot gas injection thrust vector control system performance Procedia Engineering 38 (2012) 1745 – 1749.

[3] G Anugrah P Raja M Deepu and R Sadanandan 2019 Experimental and Numerical Studies of Secondary Injection in Nozzle Divergence for Thrust Augmentation Journal of Applied Fluid Mechanics Vol 12 No 5 pp 1719-1728 2019.

[4] Ankit Kumar Mishra, Janani Kavipriya VS A Technical Review on effect of spray angles and characteristics for a pintle injector Journal of Advanced Engineering Research (JAER) vol7 no2 2020.

[5] Elham Mohammadi, Alireza Toloei Analysis of dual secondary fuel injection system for thrust vectoring Aircraft Engineering and Aerospace technology vol 83 iss 4 pp 213-220.

[6] H R Noaman Tang Hai Bin and Elsayed Khalil 2018 Numerical Simulation of Nozzle Flow Field with Secondary Injection Thrust Vector Control MATEC Web of Conferences 179 01003.

[7] H R Noaman Hai Bin Tang and Elsayed Khalil 2019 Numerical Simulation on the Influence of Injection Location Injection Angle and Divergence Half Angle on SITVC Nozzle Flow Field International Journal of Aerospace Engineering Volume 2019.

[8] S Vignesh N Vishnu S Vigneshwaran M Vishnu Anand D K Babu and V R Sanal Kumar 2015 Numerical studies on thrust vectoring using shock-induced self-impinging secondary jets International Journal of Mechanical, Aerospace Industrial Mechatronic and Manufacturing Engineering vol 9 no 6 pp 1118–1124 2015.

[9] N Vishnu S Vigneshwaran S Vignesh C Nichith S Sharan and V R Sanal Kumar 2016 3D numerical studies on thrust vectoring using shock induced self-impinging secondary jets in 52nd AIAA/SAE/ASEE Joint Propulsion Conference Salt Lake City UT USA 2016.

[10] M. Salehifar M. Tahani M. Hojaji and A. Dartoomian 2016 CFD modeling for flow field characterization and performance analysis of HGITVC Applied Thermal Engineering vol. 103 pp. 291–304 2016.

[11] G P Sutton and O Biblarz Rocket Propulsion Elements John Wiley & Sons 7 edition 2001.

[12] Chuan Tian and Yijia Lu Turbulence models of separated flow in shock wave thrust vector nozzles Engineering applications of fluid mechanics vol7 no 2 2013.

[13] M salehifar M Hojaji A Dartoomian 2016 CFD modeling for flow field characterization and performance analysis of HGITVC applied thermal engineering 103 291-304 2016.

[14] Thirumalai R and Sadhasivam, C Experimental Measurement and Computational Investigation on the Effect of Inlet Winglet Turbulators on the Heat Exchange Behaviour of Radiator of Tubes Journal of Applied Fluid Mechanics Vol. 11 pp. 135-139 2018.

[15] Kuppusamy, M., & Ramanathan Thirumalai, K Udayakumar, M Seenivasan Experimental Analysis Of the combustion chamber coated with Mo and Al2O3 – TiO2 in a Diesel Engine Materials and Technology vol 55 no 4 pp 509-515 2021.