The influence of flow separation mode on side-loads in a rocket nozzle

Huawei Liu1,*, Lin Zhang1, Xinhua Yu1, Huashu Liu2, Bin Wang2 and Yuanyuan Luo2

1UAV Research Institute, Northwestern Polytechnical University, Xi'an, China
2CRRC Yongji Electric CO., LTD, Yongji, China

*Corresponding author e-mail: liuhuawei19900714@163.com

Abstract. Side-loads in nozzle can cause serious structural damage. Owing to the presence of side-loads of a rocket nozzle in the actual environmental situation, the unsteady flow field of the nozzle, which is based on dynamic mesh technology, has been simulated by taking VOLVO S1 nozzle. The study calculates the flow field and side-load in the nozzle when the pressure ratio is from 4 to 16, and comprehensively studies the generation and evolution of the shock wave shape, so as to analyze the influence of the internal flow separation on the side-load under different conditions of the nozzle. The results show that the nozzle flow separation mode will significantly affect the side-load, mainly in the following: when the nozzle is in the free shock separation mode, the airflow in the nozzle passes through the shock wave, occurs separation and then no longer adheres to the wall surface, while the side-load is obvious. As the pressure ratio increases, the asymmetry of flow separation occurs inside the nozzle and the side-load gradually increases with it. The nozzle flow is close to the critical state of the conversion of the shock separation until NPR=7. The severe pressure asymmetry of the upper and lower walls occurs inside the nozzle, accompanied by serious side-load. Subsequently, the nozzle flow transforms into the restricted shock separation, which is uniform and stable, and the side-load tends to a small amount in value.

1. Introduction
With the rapid development of aerospace propulsion technology, modern rocket engines are increasingly using large-area nozzles to achieve high propulsion efficiency and large specific impulses to improve the performance of the entire rocket. The internal flow of the nozzle directly affects the performance of the entire rocket [1, 2]. However, the operation condition of the rocket engine nozzle can span a wide range of altitudes. In order to achieve acceptable performance throughout the flight, the nozzles with large area ratio are designed for intermediate environmental pressures, so in most cases, it works under off-design conditions, when the back-pressure is higher than the design value, flow separation occurs easily. Due to the instability and unsteadiness of the separation flow, the internal flow separation of the nozzle often presents complex non-axis symmetry, causing serious side-load. Severe side-loads can cause nozzle oscillation, shorten engine life, and damage the nozzle structure. The US J-2S engine, the space shuttle main engine SSME, the Fastrac engine, the Japanese LE-7A, and the European Vulcan engine have encountered side-load problems [3-5].
In this paper, based on the VOLVO S1 nozzle, the unsteady process of the nozzle under different working conditions is simulated. With the pressure ratio (the ratio of the total combustion chamber pressure to the ambient pressure) from low to high, the nozzle experienced free shock separation and restricted shock separation. This paper studies the flow field under two shock wave separation modes, explores the causes of side-loads, and analyzes the influence of flow separation on side-loads in the nozzle.

2. Research objects

2.1. Geometric Model
This paper take Volvo Aerospace’s VOLVO S1 nozzle as the research object [6]. The VOLVO S1 nozzle is a scaled model based on the Vulcain nozzle geometry and is a TOP (Thrust Optimised Parabolic) nozzle for studying the flow separation and side-loads of the Vulcain series of nozzles.

![Figure 1. Sketch for Basic geometry of nozzles.](image)

According to the basic parameters of VOLVO S1, the axisymmetric section geometry model of TOP nozzle can be established. Since the contraction section has little effect on the experimental results, the geometric model of the contraction section is established by the method of sample collection. Rao proposed that the TOP nozzle expansion section NE adopts an inclined parabola and satisfies the Rao-Shmyglevsky equation [6]. The coordinates and the tangent slope of the N and E points are known amounts, the four parameters are determined by the six parameters of \( L, D_t, D_e, r_a / r_t, \theta_N \) and \( \theta_E \). If four known quantities are substituted into the Rao-Shmyglevsky equation, it is used to determine the variables \( b, c, d, \) and \( e \), thereby determining the geometric shape of the expanded segment.

\[
\left( \frac{r + bx}{r_t} \right)^2 + \frac{cx}{r_t} + \frac{dx}{r_e} + e = 0
\]

(1)

The VOLVO S1 nozzle variable parameters are shown in Table 1.

| Table 1. VOLVO S1 basic geometry parameters. |
|-----------------------------------------------|
| Variable parameters                           | Parameter value |
| Expansion ratio (\( \sum \))                 | 20               |
| Nozzle length \( L \) / mm                    | 350              |
| Throat diameter \( D_t \) / mm                | 67.08            |
| Nozzle outlet diameter \( D_e \) /mm           | 300              |
| The Entrance Radius                           | 0.5              |
| of Dimensionless Expansion Section (\( r_{sd} / r_t \)) |                   |
| Entrance angle \( \theta_N \) ^\circ         | 35.025           |
| Dilation angle \( \theta_E \) ^\circ          | 4.0              |
| Combustion chamber total pressure \( P_0 \) /MPa | 5.0              |
| Gas total temperature \( T_0 \) /K            | 450              |
| Gas                                           | Ideal air        |
2.2. Meshing
The internal flow separation of the nozzle is complicated, and the dependence on the grid is relatively high. For the purpose of capturing the details of the nozzle flow in detail without increasing the calculation amount, the block encryption is refined in the area where the nozzle reference length is twice. In order to accurately capture the asymmetric side-load in the nozzle and reduce the influence of the grid factor on the flow asymmetry, the calculation domain is rotated by the X-axis (the axial direction of the nozzle) from the half-pipe two-dimensional grid to obtain a three-dimensional grid. The computational domain uses a hexahedral mesh with no asymmetric assumption.

![Figure 2. VOLVO S1 nozzle grid.](image)

3. Numerical Calculations
In order to accurately simulate the actual flow of the nozzle, the simulation is performed by using the ideal gas, the total temperature and pressure of the combustion chamber is set to the experimental condition. The ambient pressure is 0.1 Mpa and the static ambient temperature is 288K. The multi-state calculation is numerically simulated by changing NPR.

When the nozzle is under off-design states, the internal total pressure is less than the ambient pressure, so the nozzle is prone to flow separation. The internal flow works in an over-expanded environment, causing a shock wave formed in the nozzle. When the point is located before the flow separation, the wall pressure gradually decreases along the axial direction. The local pressure where is after the flow separation point increases rapidly till it reaches the ambient pressure, when the airflow passes through the shock.

As the total inlet pressure increases, the nozzle undergoes free shock separation and restricted shock separation in sequence. When the NPR is between 4 and 7, the airflow in the nozzle passes through the shock wave and forms "Mach disk" in the nozzle. The airflow which closes to the wall occurs separation and then no longer adheres to the wall surface, forming a free shock wave separation; As the pressure ratio increases, the internal shock gradually moves backward toward the exit. When the NPR gets larger than 7.5, a more obvious flow separation occurs inside the nozzle, and the airflow is again attached to the nozzle wall after the separation point and induce shock and expansion waves, forming a restricted shock separation.
3.1. Free shock separation

When NPR is equal to 6, the nozzle flow is free shock separation, which is considered as the research object to analyze the flow and side-load.

From the streamline diagram and the pressure cloud diagram, it can be found that as the pressure in the axial direction reduces, the flow becomes separated and the separation point on the entire nozzle wall surface is obviously asymmetrical. Meanwhile, the separated jet no longer flows against the wall surface, so as the vortex formed by the reflux of the gas can be clearly seen on the streamline diagram of the wall surface.

As the time step increases, the side-load fluctuates. The maximum normal force in the X direction can reach 888.29N, the minimum value is 52.25N, and the average value is about 450N.

From the side-load calculation results, we know:

The maximum side-load in the positive direction of Y is 157N, and the maximum side-load in the negative direction is 198N.

The maximum side-load in the positive direction of Z is 147N, and the maximum side-load in the negative direction is 199N.

The magnitude of the side-load in the Y and Z directions is substantially equivalent. Side-load’s performance is particularly pronounced in the case that the axial force of the entire nozzle is not large.
3.2. **Transient conversion from free shock separation to restricted shock separation**

The nozzle flow process is an unsteady process, and it takes a short time for the flow inside the nozzle to transition from FSS to RSS. During which FSS and RSS coexist in the nozzle, leading to asymmetrical pressure distribution and side-load in the nozzle [4].

When the NPR gets larger than 7, the shock separation gets close to the conversion status. The nozzle flow separation point moves toward the nozzle outlet, and the area ratio where the separation point is located gradually becomes larger.

The supersonic flow after the separation point gradually moves closer to the nozzle wall surface from the internal flow of the nozzle, along with the transformation of the flow separation mode.

3.3. **Restricted shock separation**

When the pressure ratio is 16, the restricted shock separation occurs in the nozzle, which is regarded as the research object to analyze the internal flow and the side-load.

It can be seen from the pressure cloud diagram that the pressure decreases in the axial direction. The airflow is again attached to the wall surface of the nozzle through the separation zone, and flows out against the wall surface. The flow line in the separation zone is sparse and the flow line in the reattachment zone is dense and uniform. The flow is basically symmetrical. The flow of the entire nozzle has a relatively small effect on the flow of the external field.

As the time step increases, the side-load also undergoes a periodic fluctuation, and the normal force in the X direction is 12000N.

The maximum side-load in the positive direction of Y reaches 3.18N, and the maximum side-load in the negative direction reaches 2.20N. The maximum side-load is less than 0.03% of the normal force in the X direction.

The maximum side-load in the positive direction of Z reaches 2.80 N, and the maximum side-load in the negative direction reaches 2.99 N. The maximum side-load is less than 0.03% of the normal force in the X direction.

Compared with the free shock separation, when the nozzle simulation under the limited shock separation reaches a stable convergence, the axial force of the entire nozzle increases continuously with the increase of the total pressure of the combustion chamber. Compared with the axial force, the side-load in the Y direction and the Z direction is a small amount in value, which almost does not damage the nozzle structure.
4. Conclusion

This paper simulates the air flow of rocket engine nozzles. The results show that the flow separation has a significant impact on the side-load of the nozzle.

The nozzle is unavoidably operated under off-design states. When the pressure ratio is small, the nozzle flow is free shock separation, and the internal flow separation is obvious, which causes a large difference in pressure distribution between the upper and lower walls, accompanying obvious side-load. As the pressure ratio increases, the shock separation undergoes the transient transition, and the flow process is unsteady, so the performance is particularly unstable. When the pressure ratio is bigger than 7.5, the internal flow of the nozzle transfers into restricted shock separation, and the axial force of the entire nozzle increases with the increase of the pressure ratio, however, the side-load is rather small compared to the axial force, which brings less damage to the nozzle.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China (11272262).

References

[1] Hadjadj A, Onofri M. Nozzle flow separation [J]. Shock Waves, 2009, 19(3): 163-169.
[2] Hagemann G, Frey M. Shock pattern in the plume of rocket nozzles: needs for design consideration [J]. Shock Waves, 2008, 17(8): 387-395.
[3] Martelli E, Nasuti F, Onofri M. Numerical calculation of FSS/RSS transition in highly overexpanded rocket nozzle flows [J]. Shock Waves, 2010, 20: 139-146.
[4] Lijo V, Kim HD, Setoguchi T, Matsuo S. Numerical simulation of transient flows in a rocket propulsion nozzle [J]. International Journal of Heat and Fluid Flow, 2010, 31: 409-17.
[5] Garelli L, Paz R R, Storti M A. Fluid–structure interaction study of the start-up of a rocket engine nozzle [J]. Computers & Fluids, 2010, 39(7): 1208-1218.
[6] Östlund J. Flow processes in rocket engine nozzles with focus on flow separation and side-loads [J]. 2002.