Study of coupling thermal and mechanical effect on submerged nozzle in solid rocket motor

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Abstract. The thermo-structural response of submerged nozzles is widely investigated in the design of modern rockets upon thermal loading and aerodynamic pressure. In this paper, by means of commercial finite element software with the subroutine of non-uniform pressure and non-uniform heat transfer coefficients, the simulation was performed to study the thermo-structural response of a submerged nozzle at the pressure 6MPa and stagnation temperature 3200K. By means of fluid software, the steady flow field with hot gas was determined. The aerodynamic parameters and heat coefficients were obtained. It was found that the thermal loading has an important influence on stress of throat insert for the solid rocket motor (SRM). Secondly, the hoop stress increases at first and then decreases with the increase of time for the throat insert. Finally, the ground hot firing test of SRM with submerged nozzle was carried out. The structural integrity of the submerged nozzle is very perfect during SRM operation. The present method is reasonable, which can be applied to study the thermo-structural response of submerged nozzle for SRM.

1. Introduction

The SRM nozzle always acts as the energy transformation equipment where the chemical energy of propellant turns into the kinetic energy of gas. It is classified as a submerged nozzle, as its entrance extends to within the combustion chamber of the SRM. In generally, the submerged nozzle is always working under extremely harsh circumstances [1-3]. Hence, the structure integrity is of great importance for the normal operation of the nozzle [4].

A variety of recent works account for the growth in knowledge and techniques in the assessment of the structural behavior of SRM nozzles. Kumar et al. [5] undertook an extensive thermo-structural analysis of composite structures, incorporating temperature dependent properties, and thermal, thermo-chemical and mechanical loads, and subsequently performed a coupled thermo-structural stress analysis of an SRM nozzle comprised of various orthotropic and isotropic materials. Morozov et al. [6] investigated the dynamic thermo-structural response of a composite rocket nozzle throat using the commercial finite element code ADINA. It is found that the dynamic response oscillates about the quasi-static response in all cases, and that, in generally, the variance in stress magnitudes between the two solution techniques is significant. Tian et al. [7] studied the problems with gap design and contact stress about the SRM nozzle under thermal loading and pressure using finite element method. Li et al.
[8] had focus on the thermal structural analysis of the nozzle throat insert, the influences of the thermo elastic stress are discussed by the computational software ABAQUS. Zheng [9] studied the thermo structural analysis and failure behaviors of carbon-carbon composite throat insert. Hu et al. [10] determined the temperature and stress field of conical trapped joint carbon-carbon nozzle divergent section. Sun et al. [11] studied the thermo-structural response of a typical nozzle with consideration of the structure gap based on the finite element method. YU et al. [12] considered the influence of the fit clearance of the throat insert on the deformation and stress distribution of the nozzle based on the three-dimensional finite element model. The research shows that the fit clearance of throat insert does not change the overall distribution of stress, but can affect the stress on the matching surface. Cozart et al. [13] performed a finite element axisymmetric stress analysis of a 3-D braided preform ablative composite rocket nozzle, incorporating a material ablation model. In the work of Yoo et al. [14], a kick motor nozzle utilizing spatially reinforced composites was subjected to finite element thermoelastic analyses following the development of a material model used to homogenize various spatial reinforcement architectures.

To sum up, a large amount of work has been done for investigating the thermo-structural response. However, literature on the thermo-structural response of the submerged nozzle at the initial stages of operation is scarce. This study focuses on the numerical simulation of submerged nozzle under the condition of internal pressure and thermal loading. It addresses a method for analyzing the thermal-structural response of nozzle using finite element analysis program and discusses the development of a user subroutine which allows us to model the non-uniform pressure and non-uniform heat transfer coefficients on the wall. Furthermore, the ground hot firing test of SRM is carried out. Finally, some conclusions are drawn in the end.

2. Submerged model

2.1. Geometry

The three dimensional cyclic symmetry finite element analysis is performed for the submerged nozzle made of different composites. This nozzle consists of five substructures, namely throat insert made from the punctured carbon-carbon composite, the tape wound 2D silica-phenolic entrance insulator - which isolates the hot gas and metal case, the silica-phenolic liner – which isolates the hot and cooler substructures, divergent insulator made from the silica-phenolic, and metal case made from the titanium alloy, as shown in figure 1. In figure 1, the coordinates are dimensionless by the nozzle length. Furthermore, in order to reduce the thermal stress of throat insert, the clearance was set up in the internal interface of throat insert. The values of interface AB, BC, DE, EF are all 0.05 millimeter.

![Figure 1. Model of submerged nozzle.](image)

2.2. Assumptions

Some reasonable assumptions are considered as follows to simplify the geometry model:

1. The outer surface of nozzle has no heat exchange.
2. The pure gas steady gas is considered, the flow field is steady.
(3) The contact thermal resistance is totally ignored for the simulation.
(4) The complicated phenomena of erosion and pyrolysis behavior of the erosion and heat insulation materials are neglected;
(5) The radiation heat transfer are not considered.

2.3. Mesh
A properly sized mesh can generate more accurate results and reduce the computing resources for the thermo-structural simulation. The computational model is established on the 1/12th of the submerged nozzle in the circumferential direction. The cylindrical coordinate system is adopted to impose symmetric constraints on symmetric surface. Figure 2 shows the mesh generation result of the thermo-structural simulation. This model is also used to simulate the nonlinear and orthotropic material properties. The finite element model is generated by structured grid. The number of grid is 9453. The figure 2 shows the mesh generation result.

![Figure 2. Mesh generation.](image1)

2.4. Boundary conditions
There exist two kinds of thermal boundary conditions for this simulation, i.e., the adiabatic condition between the outermost structural steel and the air, and the forced convection from the inner flow. For thermal-structural simulation, the heat transfer coefficient along the wall should be provided by means of fluid software. The result is shown in figure 3, figure 4, figure 5, respectively. figure 3 shows the temperature distribution, gradually decreasing along the wall. figure 4 shows the force convective coefficient between hot gas and wall. As can be seen, the maximum value of forced convection coefficient is about 8266 W/(m²·K) and the minimum is about 324 W/(m²·K). It is noticed that the variation curve of heat transfer coefficient presents a peak at the upstream of throat insert. Figure 5 shows the pressure distribution, gradually decreasing along the wall, because of the gas exhaust flow.

![Figure 3. Temperature distribution about the steady field of SRM.](image2)
3. Results and discussion

3.1. Thermal loading

For the submerged nozzle, the distribution of temperature was obtained at times 28s based on finite element method on the conditions of thermal loading, as shown in figure 6. The stagnation temperature is 3200K. The transient thermal analysis is run to get the temperature profile of the nozzle at the end of 28 seconds. It indicates that the convection heat transfer between the gas and the throat insert is very obvious, and the temperature of this material increases greatly. Because the conductivity of the carbon-carbon composite is high, and the heat transfer coefficient is large as shown in figure 4. Secondly, the outer surface of the case is low, which is 300K environmental temperature, because the conductivity of the liner is much lower than that the throat insert. This plays an important role in the insulation of the case. Finally, the heat transfer depth of entrance insulator and the divergent insulator are both shallow, because these convective coefficients are low as shown in figure 4.

3.2. Pressure loading

For the submerged nozzle, the distribution of Mises stress was obtained at 28s based on the same method on the condition of pressure, as shown in figure 7. The chamber pressure is 6MPa. It can be seen that the position of the maximum Mises stress is the outer surface of case, and the value is...
106MPa. Secondly, the stress of the protective materials for the nozzle is small under the press, and the maximum of Mises stress for the throat insert is only 12MPa.

![Figure 7](image_url)  
Figure 7. Mises stress distribution under the press at time 28s.

### 3.3 Combined thermal loading and pressure

On the condition of the thermal loading and press, the distribution of Mises stress was obtained at time 28s for the submerged nozzle, as shown in figure 8. The stagnation of temperature and press is 3200K and 6Mpa, respectively. It is interesting to note that the position of the maximum Mises stress is the front end of the cylindrical section of the case, and the maximum value is 176MPa. Compared with the figure 7, the maximum Mises stress increased obviously, the thermal expansion of the thermal protective materials is caused by the rise of the internal temperature. The contact interfaces of these materials is compressed from each other due to the inconsistency of the expansion deformation. It is shown that the stress of the case is mainly caused by the thermal expansion of the protective materials.

![Figure 8](image_url)  
Figure 8. Mises stress distribution of submerged nozzle at 28s under thermal loading and pressure.

Figure 9 shows the hoop stress of the throat insert at different times. It is clear that the position of the maximum hoop compressive stress is upstream at the convergent section of the throat insert, because of the maximum heat transfer coefficient in the upstream of the throat insert, the temperature difference is large and the thermal expansion deformation of throat insert is obvious. Secondly, the position of the maximum hoop tensile stress is at the inner fillet of the throat insert. In order to avoid the damage of throat insert during the test, the radius of the inner fillet can be increased. Finally, the hoop stress increases at first and then decreases with time for the throat insert.

![Figure 9](image_url)  
Figure 9. Hoop stress of throat insert at different times: (a) at 1.3s, (b) at 4.1s, (c) at 6.1s, (d) at 10.1s, (e) at 15.1s, (f) at 20.1s, (g) at 24.1, (h) at 28.0s.
Figure 10 shows the distribution of contact stress for the throat insert. It indicates that the value of contact stress is larger at the front face AB, and the value of contact stress is smaller at the back face EF, and because the gas temperature of the front face of the throat insert is obviously higher than that of the back face. In order to ensure the reliability of the throat insert, the interface gap of the front face of the throat insert can be properly increased, and the interface gap of the back face can be reduced.

![Figure 10. Distribution of contact stress for the throat insert.](image)

3.4. Experimental verification of structural integrity for the throat insert

On the condition of combustion chamber pressure 6MPa, the ground hot firing test of SRM with the submerged nozzle was carried out, and the working time was 28s. The structural integrity of submerged nozzle is excellent. Figure 11 shows the structure of throat insert after the test of submerged nozzle. During the SRM operation, the submerged nozzle is excellent. It can be shown that the method of thermo-structure response of submerged nozzle developed in this paper is reasonable. The structure design and interface clearance of throat insert is valid. The distribution of stress field and temperature field for the throat insert are sound, which yields meet the material strength.

![Figure 11. Throat insert after the ground hot firing test.](image)

4. Conclusion

In summary, an attempt is made in this paper to determine the thermal stress of three-dimensional submerged nozzle under the condition of thermal loading and pressure. The ground firing test of SRM has been completed. This article establishes a numerical method for verifying submerged nozzle design. Some conclusions can be drawn as follows:

(1) Thermal loading is found to have the most dominating influence on the thermal stress of nozzle.

(2) The hoop stress of throat insert increase at first and then decreases with the increase of time.

(3) In order to ensure the reliability of submerged nozzle, the design of throat insert clearance and structure are extremely important.

References

[1] Y W Guan, J Li and Y Liu 2017 *Acta Astronautica* 80-9

[2] J Li, M F Guo and X Lv 2018 *Acta Astronautica* 293-330
[3] Y Liu, Y W Guan and J Li 2018 *Acta Astronautica* 138-45
[4] Q Li, P J Liu and G Q He 2015 *Acta Astronautica* 180-90
[5] R R Kumar, G Vinod and S Renjith 2005 *Materials Science and Engineering A* 66-70
[6] E V Morozov and J Beaujardiere 2009 *Composite Structures* 412-20
[7] S P Tian, G J Tang and D K Li 2005 *Journal of Propulsion Technology* 448-51
[8] S L Li, F Zhang and B Xiong 2013 *Structure and Environment Engineering* 56-63
[9] Q Zheng 2011 *Thermo-structural analysis and failure behavior of C/C composite throat* (Harbin: Harbin Institute of Technology)
[10] J H Hu, S H Meng and X L Chang 2012 *Journal of Solid Rocket Technology* 64-8
[11] L Sun, F T Bao and N Zhang 2016 *Energies* 1-21
[12] X J Yu, S Yu and Y Wang 2018 *Thermo-structure coupled computation for the influence of fit clearance on the stress distribution of composite nozzle* (AIAA Propulsion and Energy Forum, Cincinnati, Ohio)
[13] A B Cozart and K N Shivakumar 1999 *Stress analysis of a 3-D braided composite ablative nozzle* (USA: St. Louis)
[14] J S Yoo, I H Cho and C G Kim 2003 *Journal Spacecraft Rocket* 83–91