Effects of thermal and pressure loads on structural deformation of liquid oxygen/methane engine combustion chamber

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Abstract
To investigate the influences of thermal and pressure loads on the structural deformation of the Liquid Oxygen/Methane rocket engine combustion chamber, a complete thermo-structural analysis scheme including fluid-thermal analysis and structural finite element analysis is developed and then verified to be reasonable. By conducting fluid-thermal analysis, the detailed distribution of the thermal and pressure loads is obtained. These results are utilized as body loads and surface loads in structural finite element analysis. Then, the stress-strain responses of the combustion chamber and the accumulation process of the deformation induced by thermal and pressure loads were studied in detail. The main conclusions are as follows: Under the action of thermal loads alone, the most pronounced residual mechanical strain is at the upstream of the nozzle divergent segment. Reducing the temperature difference between the hot run and the pre-cooling phase can be a feasible improvement measure for this issue. Under the action of the pressure loads alone, the bottom of the cooling channel bends toward the centerline of the combustion chamber. Properly increasing the thickness of the channel bottom near the coolant inlet is deemed to be an effective measure to reduce this bending trend. Under the combined action of thermal and pressure loads, the structural deformation characteristics are determined by the combination of thermal loads and pressure loads, rather than mainly by thermal loads. The accumulation rate of mechanical strain at the channel bottom corner is much rapider than the other positions. Turning the sharp bottom corner of the cooling channel into rounded corner is an alternative method of suppressing strain accumulation.

Keywords: Liquid rocket engine, Regenerative cooling, Methane, Combustion chamber, Coupled heat transfer, Thermal analysis, Structural analysis

1. Introduction

As commercial aerospace launches increasingly pursue lower cost, Reusable Launch Vehicles (RLVs) that have attracted the interests of many countries become an effective means of meeting this demand due to the meticulous design and excellent performance. The liquid oxygen (LOX)/methane rocket engine is regarded as an ideal candidate for the propulsion system of RLVs because that the propellant combination of LOX/methane has obvious advantages compared to traditional propellant combination, such as high-density specific impulse, non-toxic, cheap and easy to produce (Kobayashi et al., 2007). In the past two decades, engineers and scholars have been working on the application of methane to rocket launches (Lin et al., 2013; Rahman et al., 2012; Han et al., 2009).

As one of the critical components of the LOX/methane engine, the regenerative cooling combustion chamber...
(Xiang and Sun, 2018) consists of a nickel jacket and a copper alloy liner characterized by a high thermal conductivity. The copper alloy liner with milled cooling channels is welded together with nickel jacket, to provide adequate stiffness for the entire combustion chamber. However, the regenerative cooling combustion chamber used for RLVs is devised to operate under harsh conditions of elevated temperature and pressure for enhancing the performance (Higuchi et al., 2019; Takeuchi et al., 2018), in addition, it is also supposed to be able to start and shut down many times without any failure, to guarantee the high reliability under these severe conditions. After multiple working cycles, the cooling channel bottom of the combustion chamber will accumulate irreversible inelastic deformation, probably resulting in structural failure as shown in Fig.1 and reference (Hannum et al., 1976; Riccius and Zametaev, 2002).

Fig. 1 Structural failure of the combustion chamber observed in DLR (Riccius and Zametaev, 2002)

The failure shown in Fig. 1 will directly cause the coolant to leak into the nozzle, ultimately leading to catastrophic consequence. From 1970 to the present, numerous studies have been conducted on this issue, to analyze the deformation of the cooling channels and then estimate the damage degree as well as the service life of the combustion chamber. Based on the assumption of bilinear stress-strain relationship, Miller (1974) developed a finite element program and conducted the elastoplastic analysis for the cross section of the combustion chamber throat. According to the calculated strain range and low cycle fatigue experimental data of OFHC materials, the low-cycle fatigue life of the combustion chamber was evaluated. In Arya (1991)’s research, a viscoplastic model developed by Freed was used to predict the deformation of the combustion chamber throat cross section. The simulation results qualitatively replicated the bulging and the thinning phenomenon of the cooling channel bottom as observed from the experiment that devised to approximate the working situation of Space Shuttle Main Engine (SSME). Riccius et al. (2002; 2004) introduced a complete set of life evaluation process and structural analysis method involving the time dependent effects, to contrast the different effects of plane strain model and the generalized plane strain model on the simulation results. Ferraiuolo et al. (2016; 2017) combined the elastoplastic model with the Norton creep model to study the effect of strain hardening and the rate-dependent effects on “dog-house” phenomenon shown in Fig. 1, then, the thermo-structural response of a regeneratively cooled combustion chamber with a composite closeout was discussed in detail.

For the sake of reducing the plastic strain induced by thermo-mechanical loads and prolonging the service life of the combustion chamber, some feasible attempts have been made based on plenty of simulations and experimental researches. Pavli et al. (1992) proposed a structurally compliant design permitting the thermal expansion and contraction along the circumferential direction. The fatigue life of the combustion chamber was increased by 287% when the temperature on the gas-side wall was 1144.25K, and increased by 134% at the temperature of 1033.15K. Jankovsky et al. (1995) put forward a tubular channel construction, and then, contrasted the differences between conventional milled rectangular channel and tubular channel in the aspect of metal temperature, stress and strain range. The results suggested that total strain range of the combustion chamber with tubular cooling channels was remarkably decreased compared to the combustion chamber with rectangular channels, which contributed to extending the service life of combustion chamber. Kimura et al. (2019) made several two-dimensional simulations to investigate the effects of heat treatments to liner material, thermal barrier coating (TBC), and jacket material on lifetime of a combustion chamber. The results revealed that a suitable thickness of TBC could lead to the extension of the life time of combustion chamber by reducing the low cycle fatigue damage and creep damage.

In summary, there have been many published studies on thermo-mechanical deformation of combustion chamber under complicated working conditions, however, most of them have only focused on the impact of complex thermal
loads on the structural response. The distribution of pressure loads is often simplified to be globally uniform and sometimes even completely ignored. Recently, in our design process of a LOX/methane rocket engine, a phenomenon worthy of discussion was observed: During the simulated hydraulic pressure test, the cooling channel of the LOX/methane combustion chamber was obviously deformed. This nonnegligible mechanical strain caused only by pressure loads has not occurred in our previous design of liquid hydrogen/LOX engines. Therefore, the significant impact of pressure loads should be investigated seriously like thermal loads, not simplified or even ignored. In fact, the LOX/methane combustion chamber endures both harsh thermal loads and heavy pressure loads during operating process, the effects of thermal and pressure loads need to be analyzed in detail, respectively. But in published studies, few scholars have separated the thermal loads and pressure loads of the combustion chamber from each other, to compare and study the different results they cause.

The main objective of this paper is to investigate the influence of thermal loads and pressure loads on the thermal-structural response of the LOX/methane combustion chamber. The temperature field of the metallic solid domain and the pressure distribution of the fluid domain are obtained by fluid-thermal analysis, and these CFD (Computational Fluid Dynamics) results are loaded into the structural analysis module as thermal loads and pressure loads, respectively. The deformation distribution of the structure under the individual action of each load is acquired by conducting the FEA (Finite Element Analysis), which reveals in detail how each load affects the structural deformation phase by phase. At last, as a comparison, the thermo-mechanical response of the combustion chamber under the joint action of the thermal and pressure loads are also discussed.

2. Model and Methodology

2.1 Structure of the combustion chamber

The regenerative cooling combustion chamber of a LOX/methane rocket engine with a thrust of 20KN being developed at Beihang university is investigated in this paper. At present, the design work of the engine shown in Fig. 2 has been basically completed, and the preliminary hot run test will be carried out soon. The combustion chamber consisting of a Narloy-Z liner and a nickel jacket is picked out from the entire engine and is also shown in Fig. 2. Narloy-Z is one of the candidate materials for the combustion chamber liner of rocket engines. It is a copper base alloy containing a nominal 3% silver and 0.5% zirconium. This kind of silver-zirconium-copper alloy combines high electrical and thermal conductivity with moderate strength retention at high temperatures. This alloy is strengthened by heat treatment.

![Actual structure of the combustion chamber](image1)

![Combustion chamber mesh](image2)

Fig. 2  Combustion chamber of the LOX/methane rocket engine

Under the condition where the total mass flow rate of the propellant is 7.228 kg/s and the mixing ratio of oxidant to fuel is 3.0, throat diameter of the combustion chamber is designed to be 58.5 mm to achieve a chamber pressure of 5.1
MPa during hot run phase. The length and diameter of the cylindrical segment are 232.4mm and 117mm, respectively. The expansion ratio of the nozzle is 10.0, which enables the high-pressure gas to fully work in the combustion chamber. When the gas is discharged from nozzle, the pressure is only 0.06 MPa.

Considering the achievability of the simulation, the metal zone to be studied in the present work is simplified from actual combustion chamber shown in Fig. 2 (a), and the coolant inlet manifold is neglected. Figure 2 (b) gives the simulated structure of the combustion chamber, the layout of cooling channel and the grid distribution. Table 1 lists the total grid number of calculation domain including hot gas zone, methane coolant zone, Narloy-Z liner zone and nickel jacket zone. The hexahedral structured grid with good convergence is adopted in all zones. Since the size and quality of near-wall grid in fluid zone affect the CFD results greatly, Table 1 also gives some necessary information about the fluid zone grid. As shown in Table 1, the vertical height of near-wall mesh is set to be an appropriate value in the fluid zone, so that the y+ value on the fluid-solid surfaces can meet the requirements of the k-ε turbulence model and the standard wall function. This can make sure that the flow and heat transfer results in the turbulent boundary layer is accurate enough.

| Number of grids (Million) | Vertical height of near-wall fluid grid (m) | Averaged y+ value on coupled fluid-solid surfaces |
|---------------------------|--------------------------------------------|--------------------------------------------------|
| Hot gas zone              | Coolant zone                               | Liner zone                                       | Jacket zone                                     |
| 9.42                      | 4.27                                       | 0.81                                            | 0.33                                            | 2.0×10⁻⁵                                      | 83                                               |

2.2 Working process of the combustion chamber

Working conditions and working processes have a great influence on the thermo-mechanical deformation and service life of the combustion chamber. For the combustion chamber studied in the present work, a complete designed working process consists of four phases: pre-cooling, hot run, post-cooling, and relaxation. To understand more clearly what these four phases are, and the loads that the combustion chamber are subjected to during these four phases, Figure 3 gives the schematic of them.

During the pre-cooling phase, the coolant supplied at a low-temperature (110K) and low-pressure (3.4MPa) flows in the cooling channels of the combustion chamber, to keep the engine at a low temperature before ignition. During the hot run phase, the propellants are burned and the hot gas is generated. Hence, the combustion chamber is simultaneously heated by hot gas and cooled by coolant. It should be noted that the inlet pressure of the coolant is increased to 7.9 MPa during the hot run phase, which is significantly different from the coolant pressure of 3.4 MPa in the pre-cooling phase. During the post-cooling phase, the engine is shut down and the supply of propellant is cut off, however, the coolant is still continuously supplied at a pressure of 3.4MPa to cool the combustion chamber from high temperature to low temperature. During the relaxation phase, the coolant is no longer provided, and the entire structure exchanges heat with the surrounding environment only by natural convection.
2.3 Thermo-structural analysis scheme

During a complete working process, the combustion chamber endures the drastically changing temperature and pressure loads that play a decisive role in the elastoplastic strain of the structure. To exactly describe the thermo-mechanical response of the combustion chamber, the thermo-structural analysis work in this paper is divided into two parts: fluid-thermal analysis and structural finite element analysis. The overall computation work of the fluid-thermal analysis and structural finite element analysis is performed in FLUENT and ANSYS WORKBENCH, respectively. The fluid-thermal analysis is carried out to get temperature field as well as pressure distribution during those four phases introduced in chapter 2.2, and to provide accurate thermal and pressure loads for structural finite element analysis. The structural finite element analysis is conducted to obtain the detailed stress and strain history of the combustion chamber under the combined action of complex thermal and pressure loads, which lays a foundation for the life prediction of the combustion chamber.

In the fluid-thermal analysis, the finite volume method is employed to simulate the three-dimensional flow of coolant as well as the heat transfer between cooling channels and the coolant. The governing equations for the coupled heat transfer process are the RANS equations containing the continuity, momentum and energy equation, which can be written as:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]  
\[
\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{\tau}
\]  
\[
\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho \mathbf{u} (\rho E + p)) = \nabla \cdot \left( k_{\text{eff}} \nabla T + \left( \mathbf{\tau}_{\text{eff}} \cdot \mathbf{u} \right) \right)
\]

Where \( \rho \) is density, \( t \) is time, \( \mathbf{u} \) is velocity vector, \( p \) is static pressure, \( \mathbf{\tau} \) is stress tensor of fluid, \( E \) is total energy, \( k_{\text{eff}} \) is effective conductivity, and \( T \) is temperature. The standard k-\( \varepsilon \) model containing transport equations for turbulence kinetic energy and turbulence dissipation rate is used to simulate the turbulent flow of the coolant in the cooling channels. The heat conduction inside the metallic solid domain is govern by differential equation of heat conduction without internal heat source term:

\[
\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T)
\]

Where \( c \) is specific heat capacity of metal material that depends on type of material and varies with temperature.

For the LOX/methane combustion chamber with a pressure higher than 5.08 MPa (critical pressure of oxygen), the supercritical methane injected from the coaxial injector can be viewed as a gaseous state. Meanwhile, the cryogenic oxygen is injected at a subcritical state and eventually transports into supercritical state due to the heating from ambient hot gas. In these processes, continuous mixing of propellants controlled by turbulent diffusion instead of atomization and vaporization was observed by published experiments (Singla et al., 2005; Lux and Haidn, 2009). Therefore, in our previous published works (Song and Sun, 2016; Song and Sun, 2017), a developed real fluid flamelet model was used to calculate the turbulent mixing and combustion processed. A simplified chemical kinetic mechanism (Yang and Seshadri, 1993) verified by experimental data (Smooke, 1991) was adopted to model methane-oxygen finite-rate chemical reactions. The change in the thermophysical properties of oxygen during the transition from subcritical to supercritical state was coupled to the solver using UDF (User Defined Function). In the published article (Song and Sun, 2016), we compared the heat flux distribution on the gas-side wall calculated by this CFD method with the experimental data in the literatures (Locke et al., 2007; Ranuzzi et al., 2016), and the results agree well. For the
LOX/methane combustion chamber discussed in this article, the heat flux distribution on the gas-side wall is given in Fig. 4. The heat flux value at the throat is the largest, exceeding 20MW/m², and the heat flux near the injector head is lower due to the film cooling hole on the edge region of the injector panel.

In the structural finite element analysis involving material nonlinearity, the thermal expansion and contraction of the structure is taken into account. The total strain of the structure under thermal and mechanical loads is decomposed into the following three parts:

\[ \varepsilon = \varepsilon^e + \varepsilon^p + \varepsilon^th \]  

(5)

Where \( \varepsilon \) is total strain tensor, \( \varepsilon^e \) is elastic strain tensor that obeys the elastic stress-strain relationship known as generalized Hooke's law. \( \varepsilon^th \) is thermal strain tensor regulated by thermal expansion coefficient as well as temperature difference between reference temperature and current temperature. \( \varepsilon^p \) is plastic strain tensor associated with the load path. When the material produces plastic deformation, the evolution of plastic strain which remarkably impacted by material state and load increment obeys the flow rule described in Eq. (6) according to a general model of plasticity.

\[ d\varepsilon^p = d\lambda \frac{\partial f}{\partial \sigma} \]  

(6)

Where \( d\lambda \) is the magnitude of the plastic strain increment, \( f \) is the yield function of the constitutive model used in this article, and \( \sigma \) is the stress tensor. The Chaboche model (Chaboche, 1989) is chosen for structural elastoplastic finite element analysis. The yield function based on Von-Mises yield criterion in Chaboche model is defined as Eq. (7):

\[ f = \sqrt{(s - \alpha) : (s - \alpha)} / 2 - \sigma_y = 0 \]  

(7)

Where \( s \) is deviatoric stress tensor, \( \alpha \) is back stress tensor, \( \sigma_y \) is yield stress. The back stress tensor is given by the superposition of 3 kinematic back stress tensors. Three back stress tensors given in Eq. (8) have different functions in characterizing the deformation of material. \( \alpha_1 \) can impact the deformation behavior of medium plastic strain zone and \( \alpha_2 \) is used to depict the distortion within the transition zone between elasticity and plasticity. When the plastic deformation is large, \( \alpha_3 \) is utilized to characterize the phenomenon that the tangent stiffness is almost invariable. The evolution rule of each back stress term is presented in Eq. (9):

\[ \alpha = \sum_{i=1}^{3} \alpha_i \]  

(8)
\[ d\varepsilon = \frac{2}{3} C_i d\varepsilon^p - \gamma_i \alpha_i \sqrt{\frac{2}{3} d\varepsilon^p : \frac{2}{3} d\varepsilon^p} \]  

(9)

Where \( C_i \) and \( \gamma_i \) are material parameters that need to be determined.

2.4 Thermophysical properties of coolant

The critical pressure and critical temperature of methane are 4.6MPa and 190.56K, respectively. When entering the cooling channels, the static pressure of methane is 7.8 MPa (higher than 4.6MPa) and the temperature is 110K (lower than 190.56K). As the coolant of combustion chamber, methane continuously absorbs heat in the cooling channel and rises in temperature. When both temperature and pressure are above the critical value, methane is in supercritical state. According to our previous research (Song and Sun, 2016), the thermophysical properties of methane change sharply near the critical point, which will have a greater impact on the flow and heat transfer of coolant. Therefore, changes in thermophysical properties with temperature and pressure need to be considered in fluid-thermal analysis.

The thermophysical properties most closely related to flow and heat transfer mainly include density, specific heat,
dynamic viscosity and thermal conductivity. The density of methane is calculated using the Soave method based on the cubic state of equation (Poling et al., 2001). The specific heat of the coolant is estimated by ideal gas specific heat and specific heat deviation function (Poling et al., 2001). The thermophysical properties affecting transportation of momentum and energy such as dynamic viscosity and thermal conductivity are obtained by Chung method and TRAPP method (Poling et al., 2001), respectively. The predicted values of thermophysical properties are compared with the data from NIST (National Institute of Standards and Technology) in Fig. 5. As shown in Fig. 5, the calculated thermophysical properties match well with the data from NIST, which means that the methods used for calculation of coolant thermophysical properties are reasonable and accurate.

2.5 Material parameters and mechanical properties

The Chaboche model used in this paper is a nonlinear kinematic hardening model and has advantages in describing the Bauschinger effect and the ratcheting effect of metallic materials. Six parameters such as \( C_i (i=1,2,3) \) and \( \gamma_i (i=1,2,3) \) in Eq. (9) have no specific physical meanings and need to be obtained by curve fitting process. The parameter fitting is an optimization process and the initial values of these parameters have a certain impact on the convergence of the result.

| Temperature(K) | \( \sigma_y \) (MPa) | \( C_1 \) (MPa) | \( \gamma_1 \) | \( C_2 \) (MPa) | \( \gamma_2 \) | \( C_3 \) (MPa) | \( \gamma_3 \) |
|---------------|------------------|------------------|--------------|------------------|--------------|------------------|--------------|
| 27.6          | 184              | 31454            | 1184         | 10206            | 341          | 595              | 5            |
| 294.3         | 146              | 37715            | 2389         | 22826            | 406          | 405              | 5            |
| 533.1         | 114              | 50782            | 2861         | 23718            | 490          | 633              | 5            |
| 810.9         | 78               | 36908            | 945          | 80567            | 935          | 312              | 5            |

Since the mechanical properties of metallic materials are sensitive to temperature, uniaxial tensile experimental data at different temperatures (Esposito and Zabora, 1975) are used to fit the parameters in the Chaboche model. The estimated magnitudes of these model parameters are utilized as the initial input data by the curve fitting tool in ANSYS APDL, then, the optimized parameter values are obtained and listed in Table 2. It should be noted that the values of \( \gamma_3 \) given in Table 2 is not optimized because the exact value of \( \gamma_3 \) needs to be determined by uniaxial cyclic tension-compression experiment. However, the available data of cyclic loading test for Narloy-Z is rare in published papers. According to our previous work involving the sensitivity of the \( \gamma_3 \) (Song and Sun, 2017), it is appropriate to set \( \gamma_3 \) to 5 for Narloy-Z.

![Fig. 6 Mechanical properties of Narloy-Z](image)

To demonstrate that these applied values of Chaboche model parameters are reasonable, the simulated uniaxial
tensile results are compared with the experimental data in Fig. 6. As shown in Fig. 6, the simulated stress-mechanical
strain curve matches well with the experimental results in both the elastic and plastic intervals, which means the model
with these parameter values are accurate enough to describe the elastoplastic deformation of the material.

3. Method validation

The applied thermo-structural analysis scheme for the LOX/methane combustion chamber is validated by
comparing the simulation with the Thermo-Mechanical Fatigue (TMF) panel tests conducted at German Aerospace
Center (DLR) (Riccius, 2012; Riccius et al., 2013). The three-dimensional grid of the TMF panel is shown in Fig. 7.
The TMF test system is designed to grasp the thermo-mechanical deformation of the combustion chamber at the critical
position, especially near the throat, without performing a full-scale engine hot-run test.

As shown in Fig. 7, the TMF panel consists of two materials, copper alloy and nickel, which are the same as the
inner liner and jacket of the combustion chamber, respectively. Five cooling channels are milled inside the copper alloy
plate to approximate the actual structure of the regenerative cooling combustion chamber. A high-energy laser beam is
used as the heating source to replace high-temperature gas, moreover, the liquid nitrogen and gaseous nitrogen is
supplied as coolant of the TMF panel. The key geometric parameters of TMF panel as well as the pivotal operational
conditions (Riccius, 2012; Riccius et al., 2013) are listed in Table 3. The parameters given in Table 3 are utilized as
input conditions to carry out the fluid-thermal analysis and structural finite element analysis for TMF panel to get the
temperature field and the structural response.

| Geometric parameters       | Value | Operational conditions                           | Value |
|----------------------------|-------|-------------------------------------------------|-------|
| Hot wall thickness (mm)    | 1.0   | Heat flux on laser heated surface (MW/m²)        | 20    |
| Fin width (mm)             | 1.0   | Size of the laser heated surface (mm x mm)       | 32x12 |
| Cooling channel number     | 5     | Coolant inlet temperature (K)                    | 160   |
| Cooling channel width (mm) | 1.0   | Coolant outlet pressure (MPa)                    | 4.5   |
| Cooling channel height (mm)| 10.0  | Coolant mass flow rate (Kg/s)                    | 0.06  |

The working process of TMF panel consists of three phases: pre-cooling (cooled by liquid nitrogen), hot run
(heated by laser and cooled by nitrogen simultaneously), and post-cooling (cooled by liquid nitrogen). This is similar
with the working process of the combustion chamber. In the TMF tests conducted at DLR (Riccius, 2012; Riccius et al.,
2013), the temperature and the mechanical strain normal to the laser heated surface during the hot run phase can be
measured by special experimental facilities (Riccius, 2012; Riccius et al., 2013). In Fig. 8, the results of tests are contrasted with the simulations utilizing the thermo-structural analysis method explicated in chapter 2.3.

As exhibited in Fig. 8 (a), on the laser heated surface of the TMF panel, the difference between simulated and measured temperature distribution along the bold black monitoring line are small, which indicates that the adopted fluid-thermal analysis method to obtain the temperature field is acceptable.

The surfaces shown in Fig. 8 (b) and (c) are the same surfaces, and the physical quantity compared in Figs. 8 (b) and (c) is mechanical strain normal to the laser heated surface during the hot run phase. Figure 8 (b) is the measured result on the laser heated surface, but the color legend of the Figure 8 (b) was not given in references (Riccius, 2012;
Riccius et al., 2013). Figure 8 (c) is the simulated distribution of mechanical strain on the same surface. The red areas in Fig. 8 (b) and (c) mean that the bulging phenomenon here is more noticeable than the other areas during the hot run phase. In Fig. 8 (c), two areas with a large mechanical strain appear on the laser heated surface during the hot run phase, which indicates that the most severe bulging trend is located at the fin bottoms on both side of the middle channel. This numerical result shown in Fig. 8 (c) is consistent with the experimental result in Fig. 8 (b).

During the TMF panel tests, some irreversible deformation remains at the bottom of the middle cooling channel after each complete working cycle. As the number of working cycles increases, the remained strain accumulates more and more, eventually resulting in the structural failure shown in Fig. 8 (d). As demonstrated in Fig. 8 (d), the initial position of the structural failure is located at the bottom of middle cooling channel. To compare with the experimental result shown in Fig. 8 (d), Figure 8 (e) gives the distribution of simulated equivalent strain after a working cycle. Because the equivalent strain is a scalar without directionality, which represents the overall strain intensity and has a value that greater than 0. A large value of equivalent strain means that the current shape is very distorted compared to the original undeformed shape. It can be used to qualitatively predict where structural failure is most likely to occur. As shown in Fig. 8 (e), the large equivalent strain at the bottom of the middle channel are observed in simulation, which is consistent with the experimental result in Fig. 8 (d).

In summary, the quantitative comparison in Fig. 8 (a) proves that the fluid-thermal analysis method in this paper is convincing enough. The qualitative comparisons in Fig. 8 (b), (c), (d) and (e) indicate that the finite element analysis method is reasonable in predicting the structural deformation trend and the distorted location. In addition, before the TMF panel test system was invented at DLR, the quantitative verification in the field of thermal-structural analysis for combustion chamber was mainly comparing the simulated mechanical properties of materials with experimental data from NASA Lewis Research Center (Esposito and Zabora, 1975). If the simulated mechanical properties agree well with the data from NASA, the numerical models were deemed to be convincing. These comparisons have already been done in Section 2.5. All the available published experimental data has been used for validation and the comparison results shows the finite element analysis method in this paper is also credible like the fluid-thermal analysis method.

4. Results and discussion
4.1 Thermal loads distribution

As discussed in chapter 2.2, thermal and pressure loads experienced by combustion chamber vary widely during the transition from one working phase to another, which directly affects the elastoplastic deformation of the structure. Figure 9 gives the temperature fields of the combustion chamber in four working phases.
As shown in Fig. 9 (a), the liner and the jacket are cooled completely by the methane with a temperature of 110K during the pre-cooling phase, the temperature distribution of the entire structure is uniform.

As shown in Fig. 9 (b), the temperature of the combustion chamber exhibits a complicated three-dimensional distribution due to the simultaneous heating of the hot gas and the cooling of the methane during the hot run phase. In the radial direction, the temperature of the liner is significantly higher than nickel jacket. Along the axial direction, the position with the highest temperature is located near the throat region because of the heat flux distribution on the gas-side wall demonstrated in Fig. 4. In addition, affected by the arrangement of cooling channels, film cooling holes and injector elements, there are some small fluctuations in the circumferential temperature distribution on the gas-side wall.

As shown in Fig. 9 (c), the temperature distribution of the combustion chamber returns to the uniform state in the post-cooling phase. Because the combustion chamber is only cooled by methane, just like in pre-cooling phase. As shown in Fig. 9 (d), the entire structure gradually recovers from 110K to the room temperature (295.15K) without any active cooling measures.

Since the gas-side wall of the liner is in direct contact with the hot gas, it is one of the areas that should be pay more attention when analyzing thermal loads. According to the contours of temperature given in Fig. 9, Figure 10 plots the circumferential average temperature distribution of the gas-side wall along the axial direction. As shown in Fig. 10, in the pre-cooling, post-cooling and relaxation stages, the temperature distributions of the gas-side wall are uniform, and the values are 110K, 110K, and 295.15K, respectively. However, during the hot-run phase, the temperature changes greatly along the axial direction. In addition to the maximum temperature of 688K near the throat, there is also a noteworthy extreme value point in the divergent section of the nozzle, which is approximately 515K. Most of the divergent section has a higher temperature than the contraction section and the cylindrical section.

4.2 Effect of thermal loads

The LOX/methane rocket engine discussed in this article is designed to be reusable, not to be used only once like a normal rocket engine. Whether the next working cycle of the combustion chamber can be safely performed after the end of one working cycle is a question that needs to be concerned. The residual mechanical strain after the end of working cycle is valuable to judge the current safety of the structure and accurately locate which position is worthy of further quantitative analysis. Thus, it is a physical quantity that will be involved many times in this article. To reveal the influences of the thermal loads on the deformation behavior of the combustion chamber, those thermal loads expounded in chapter 4.1 are utilized as the body loads and are imported to the structural finite element analysis. The temperature fields in pre-cooling, hot run, post-cooling and relaxation phases are loaded in sequential order to observe the response of stress and mechanical strain. Figure 11 gives the residual stress and mechanical strain distribution caused by thermal loads at the end of the relaxation phase.
As shown in Fig. 11(a), the residual circumferential stress is large on the gas-side wall of the combustion chamber throat. In addition, the shape of the residual stress distribution is stripe at the divergent section of the combustion chamber. The residual stress on the gas-side wall of the channel bottom is significantly larger than that on the gas-side wall of the rib bottom. As shown in Fig. 11(b), the distribution of residual mechanical strain on the coolant-side surface is relatively uniform, and there is no noticeable position of large mechanical strain. As shown in Fig. 11(c), the mechanical strain distribution on the gas-side surface is similar to the stripe shape, just like the stress distribution shown in Fig. 11(a). And there is a region where the compressive mechanical strain is most pronounced at the divergent section of the combustion chamber.

In the field of thermo-structural analysis for combustion chamber, the conventional research scheme can be divided into two steps. First, accurately identify the most severely deformed location according to the mechanical strain distribution. Second, extract stress and strain responses at critical locations. Plot recorded data as curves and analysis the stress-strain histories. These quantitative results need to be studied in detail to reveal the reasons of strain accumulation. Based on the results shown in Fig. 11, Node 1 is the most obviously deformed location determined by mechanical strain distribution, which requires special attention. Node 2 is located at throat region and is a potential failure location that identified in previous designs of liquid hydrogen/LOX engines, which is used for quantitative comparison with Node 1. Because the most obvious residual mechanical strain appears at the divergent section of the combustion chamber rather than at the throat, which is a phenomenon worthy of further study. In order to quantitatively study the causes of this phenomenon, stress, elastic strain, plastic strain, and mechanical strain histories of Node 1 and Node 2 are compared in Fig. 12.
During the pre-cooling phase, as shown in Fig. 12 (a) and (b), both Node 1 and Node 2 are subjected to tensile stress, and no plastic strain is generated, so the mechanical strain is entirely composed of elastic strain. In Fig. 12 (c), the stress-mechanical strain curves of Node 1 and Node 2 during pre-cooling are straight completely, which means that the material is in elastic state. This state is easy to understand. Because during the pre-cooling phase, the jacket and the inner liner have a tendency to shrink due to the temperature reducing from 295.15K to 110K. However, the structure is circumferentially symmetrical and the thermal expansion coefficient of the jacket is smaller than the inner liner, so the thermal shrinkage of the liner induced by temperature drop is limited by the symmetry plane and the jacket. Moreover, since the yield stress of the Narloy-Z is large at the low temperature, the tensile stress during the pre-cooling phase is insufficient to bring the material into the yield state, so the mechanical strain is completely elastic strain.

During the hot run phase, the temperature of the inner liner increases to a high level due to the heating of the hot gas, however, the temperature rise of the jacket is not as evident as that of the inner liner, so the thermal expansion of the inner liner is limited by the jacket and the symmetry plane. As shown in Fig. 12 (a) and (b), in hot run phase, the stress of Nodes 1 and 2 change from tensile stress to compressive stress, tensile elastic strain becomes compressive elastic strain, and the material also produces compressive plastic strain. This phenomenon can be explained easily in Fig. 12 (c). As shown in Figure 12 (c), during the hot run phase, the stress-mechanical strain curves of Node 1 and Node 2 are straight at first, and then begin to bend. This phenomenon indicates that the material enters to the yield state from the elastic state. This also means the stress-strain relationship is not linear and plastic strain starts to be generated quickly. The temperature of Node 1 (located at divergent section) is lower than Node 2 (located at throat) during the hot run phase, which makes the compressive yield stress of Node 1 can be larger than Node 2. Thus, as shown in Figure 12...
Node 1 reaches a larger compressive stress level in the yield state than Node 2 during the hot run phase, which results in Node 1 producing more plastic strain than Node 2 during the hot run phase. This process also can be clearly seen in Figure 12 (a) and (b). So, the compressive mechanical strain (elastic strain plus plastic strain) of Node 1 is more obvious than Node 2 during the hot run phase.

During the post-cooling phase, as shown in Fig. 12 (a) and (b), as a result of the decreasing temperature, the restricted shrinking of the inner liner causes the compressive stress of Node 1 and Node 2 to become tensile stress again. Compressive elastic strain also translates into tensile elastic strain, and the compressive plastic strain also advances toward the positive direction. As shown in Fig. 12 (c), in post-cooling phase, the stress-mechanical strain curves of Node 1 and Node 2 are also straight and then bent. The material transits to yield state from elastic state like in hot run phase. Although the mechanical strain of Node 1 and Node 2 increase toward the positive direction during the post-cooling phase, the strain recovery of Node 1 during the post-cooling phase cannot completely offset the compressive strain generated during the hot run phase. So, the Node 1 still has obvious compressive strain than Node 2 after the end of post-cooling phase. Moreover, although Node 1 recovers much plastic strain under the action of tensile stress in post-cooling phase, Node 1 generates too much plastic compressive strain during the hot run phase, so the mechanical strain of the Node 1 is still negative at the end of the post-cooling phase, while the Node 2 is positive.

During the relaxation phase, as shown in Fig. 12 (a) and (b), the tensile stress of Node 1 and Node 2 is partially removed due to the temperature recovery from 110K to 295.15K. As a consequence of the stress unloading process, the elastic strain is also partially removed. However, the stress unloading process does not cause the material of inner liner to reach the yield state, so plastic strain does not change during the relaxation phase, and the change of mechanical strain is consistent with the change of elastic strain. The stress unloading processes of Node 1 and Node 2 Finally, the residual plastic compressive strain of Node 1 is more obvious than that of Node 2 at the end of the relaxation phase.

In summary, it can be seen from Fig. 12 (c) that the large compressive mechanical strain of the Node 1 generated during the hot run phase is the main reason of the residual mechanical strain being negative, and appreciable strain recovery during the post-cooling phase cannot completely offset the negative strain. Besides, since the strain of Node 2 recovered during the post-cooling phase is greater than the negative strain generated during the hot-test phase, the final residual mechanical strain is positive.

### 4.3 Pressure loads distribution

According to the explication in chapter 2.2, pressure loads generated by hot gas and cryogenic coolant mainly act on the gas-side wall and the surfaces of the coolant flow zone. Figure 13 gives the pressure distributions on the surfaces directly subjected to the pressure loads.
As shown in Fig. 13 (a), in the pre-cooling phase, the static pressure drops from 3.36 MPa to 3.16 MPa when the coolant flows through the cooling channels. The pressure loss along the path is about 0.2 MPa. As shown in Fig. 13 (b), in the hot run phase, the pressure loss reaches 0.5 MPa, which is obviously higher than that in pre-cooling phase. Because according to Fig. 5 (a) and Fig. 9 (b), the coolant absorbs heat from the Narloy-Z liner during the hot run phase, the increased temperature causes the coolant density to decrease. Then, the coolant expands and accelerates, the average velocity of the methane becomes faster, which ultimately leads to a greater overall pressure loss. As shown in Fig. 13 (c), hot gas pressure is the lowest in the divergent section and the highest in the cylinder section. Moreover, the chamber pressure induced by combustion process of the propellant is highly closed to the designed value of 5.1MPa, which indicates that the designs of combustion chamber shape and the injector head are reasonable. Figure 13 (d) gives the pressure distribution of the coolant in post-cooling phase, which is the same as that in pre-cooling phase because the two phases have the same working conditions.

In fact, the pressure difference between bottom surface of cooling channel and the gas-side wall is the direct reflection of the pressure loads on the Narloy-Z liner. In order to quantitatively analyze the pressure loads, Figure 14 shows the axial distribution of the pressure difference between the channel bottom surface and the gas-side wall.

As shown in Fig. 14, the pressure difference of the divergent section is higher than the other sections during pre-cooling phase. During hot run phase, since the divergent section is subjected to the minimum gas pressure and the maximum coolant pressure, the pressure difference here, which is nearly 7MPa, is the largest in the entire working process. During post-cooling phase, the distribution of pressure difference is the same as that in post-cooling phase, which is caused by the same working condition discussed in previous chapters. During relaxation phase, no pressure load is applied to the combustion chamber so the pressure difference between channel bottom surface and gas-side wall is zero.

### 4.4 Effect of pressure loads

The pressure loads demonstrated in chapter 4.3, which are caused by the cryogenic coolant and the hot gas, are applied as surface loads in structural finite element analysis. Just like analyzing the effect of thermal loads on deformation, the pressure loads at each phase are also loaded in the corresponding order. It should be pointed out that no pressure load acts on the combustion chamber during the relaxation phase, therefore, the pressure load in post-cooling phase is removed during this phase.

Since the mechanical properties of the metallic materials need to be determined before the analyzing process, and these properties are directly affected by temperature. Therefore, the initial temperature of the materials is defined to be globally uniform and remains constant during conducting each case study. The four globally uniform temperature of 150 K, 350 K, 550 K, and 750 K, which basically cover the temperature range of the materials, are chosen to reveal the effect of pressure loads under diverse temperature conditions. Figure 15 gives the circumferential mechanical strain...
results caused by the pressure loads under different temperature conditions after a whole working process. In order to directly and clearly observe the deformation trend of the structure, the scale factor of the deformation is set to 300.

As can be seen in Fig. 15, the residual mechanical strain of the structure is mainly concentrated at the tail of nozzle divergent segment. When the material temperature is defined as 750K, the residual mechanical strain at the tail of the nozzle divergent segment is more pronounced compared to the other cases. As the material temperature is defined lower and lower, the residual mechanical strain becomes less and less noticeable, and the area of the region where residual mechanical strain exists is smaller and smaller. When the material temperature is set to be 150K, the residual mechanical strain is barely visible and the bending of the channel bottom is almost negligible although the deformation scale factor as high as 300. This phenomenon can be explained by the stress-mechanical strain curves at different temperatures given in Fig. 6. The lower the temperature of the material, the greater the yield stress. If the temperature is lower than 200K, the plastic strain of the combustion chamber can be generated only at a relatively high stress level.

In order to explicate quantitatively how the pressure loads given in Chapter 2.2 causes the structure to produce residual mechanical strain step by step, a node named Node 3 at the tail of the nozzle divergent segment is selected to record the process of stress and strain changes. The exact location of the monitored node is marked in Fig. 15 (a). Figure 16 shows the stress and strain response history of Node 3 under the influence of pressure loads alone.
As shown in Fig. 16, during the pre-cooling phase, Node 3 is subjected to tensile stress. This is because the coolant pressure is applied to the surfaces of the cooling channel in the pre-cooling phase, and the bottom of the cooling channel has the tendency to bend. Regardless of the material temperature is defined as 750K or 150K, the mechanical strain in pre-cooling phase is completely composed of elastic strain. Because the coolant pressure loads in the pre-cooling phase are not sufficient to cause plastic bending deformation at the bottom of the channel.

As shown in Fig. 16, the tensile stress of the Node 3 in the hot run phase is larger than that in pre-cooling phase. Because according to the differential pressure curves given in Fig. 14, the pressure difference at the position where the Node 3 is located exceeds 7.4 MPa during the hot run phase. This results in a more pronounced bending tendency at the channel bottom, which in turn leads to greater tensile stress at Node 3. Moreover, when the material temperature is set at 750K, the plastic strain of the Node 3 is obvious during the hot run phase, and the proportion of plastic strain in the mechanical strain is close to the elastic strain. As the material temperature is defined lower and lower, the plastic strain of the Node 3 becomes less and less visible, and the proportion of plastic strain in the mechanical strain gradually decreases. When the material temperature is set to be 150K, no plastic strain is generated in the hot run phase, and the mechanical strain of the Node 3 is completely elastic strain.

As shown in Fig. 16, during the post-cooling phase, the tensile stress falls back to a relatively low level. Because the pressure difference between channel bottom surface and gas-side wall during post-cooling phase is restored to the same value as in the pre-cooling phase, which has been exhibited in Fig. 14. Although no more plastic strain is produced in this phase, the plastic strain generated before is not recovered at all.

As shown in Fig. 16, during the relaxation phase, all the pressure loads are removed and the elastic strain of the
Node 3 is also unloaded. However, the compressive stress due to the unloading process does not bring Node 3 into the yield state, and therefore, the plastic strain remains unchanged.

4.5 Thermo-mechanical response

In chapter 4.2 and 4.4, the individual influence of thermal and pressure loads on the structural deformation is studied respectively. On the basis of the analysis results in chapter 4.2 and 4.4, only under the action of thermal loads, the residual mechanical strain of the structure is mainly concentrated on the upstream gas-side wall of the nozzle divergent segment, and under the action of pressure loads alone, the residual mechanical strain at the tail of the nozzle divergent segment is the most obvious. However, the LOX/Methane engine combustion chamber is subjected to both thermal and pressure loads in actual working conditions, rather than only one of the loads. In order to compare with the analysis results exhibited in chapter 4.2 and 4.4, Figure 17 (a) gives the residual mechanical strain distribution of the structure after a complete working process under the combined action of the thermal and pressure loads.

![Fig. 17 Residual mechanical strain distributions induced by thermal and pressure loads](image-url)
As demonstrated in Fig. 17 (a), after four phases of pre-cooling, hot run, post-cooling and relaxation, the area with more residual mechanical strain of the structure is downstream of the nozzle divergent segment. This position is neither upstream of the nozzle divergent segment nor at the tail of the nozzle, but between the two positions. This result indicates that under actual working conditions, the most severely deformed position of the combustion chamber is determined by the combination of thermal loads and pressure loads, rather than mainly by thermal loads.

The LOX/methane combustion chamber studied in this paper is designed to be reusable, which means it will go through many working cycles. Therefore, Figure 17 (b), (c), and (d) show the variation of the residual mechanical strain distribution of the combustion chamber with the increase of the working cycle number. With the increase of the working cycle number, the residual mechanical strain distribution of the combustion chamber does not change substantially, but the absolute values of the maximum and minimum mechanical strain enlarge unceasingly, and the bottom of the cooling channel bends gradually toward the center line of the combustion chamber.

Figure 17 also gives the mechanical strain distribution on the cross section of the copper alloy liner, from which it can be seen that the most serious structural deformation point is located at the bottom corner of the cooling channel. From the structural deformation trend of the cross section given in Fig. 17, the following prediction can be made: after many working cycles, a large amount of residual mechanical strain is accumulated at the bottom corner of the cooling channel, and eventually, the structural destruction occurs at this location. This prediction is consistent with the results of the TMF experiment conducted at DLR (Riccius, 2012; Riccius et al., 2013).

(a) Evolution history induced by thermal and pressure loads   (b) Evolution history induced by thermal loads alone

(c) Evolution history induced by pressure loads alone

Fig. 18  Stress-mechanical strain evolution history of the channel bottom corner

To clearly reveal the process of the mechanical strain accumulation, the stress-mechanical strain history of the cooling channel bottom corner with the most residual mechanical strain is recorded in Fig. 18 (a) during 10 working cycles. As a comparison, the stress-mechanical strain histories of the bottom corner caused by thermal loads and pressure loads are also exhibited in Fig. 18 (b) and (c), respectively. As shown in Fig. 18 (a), at the end of each working cycle, some positive mechanical strain remains on the bottom corner of the cooling channel. As the number of working cycle increase, the stress-mechanical strain curve rolls forward and the residual mechanical strain accumulates quickly under the combined influence of thermal loads and pressure loads. However, as can be seen from Fig. 18 (b), if the combustion chamber is only affected by the thermal loads, the rate of residual mechanical strain accumulation is
relatively slow compared to the stress-mechanical strain curve given in Fig. 18 (a). At last, when the structure is only subjected to pressure loads, the stress-mechanical strain curve of the bottom corner is demonstrated in Fig. 18 (c). In accordance with Fig. 18 (c), after the first working cycle, the material at the bottom corner enters in the elastic interval, which means that the relationship between stress and strain becomes linear, the and the stress-mechanical strain curve does not roll forward or backward as the working cycle goes on.

5. Conclusions

The influences of thermal loads and pressure loads on the structural deformation of LOX/Methane engine combustion chamber are investigated in detail in this article. The conclusions were based on the designing process of a LOX/methane rocket engine. Some trends differ from the phenomenon observed in the liquid hydrogen/LOX combustion chamber. Therefore, some conclusions in the manuscript may not be applicable to all kinds of rocket engines, but they can provide some valuable information for the design of LOX/methane engines. The conclusions summarized in present work are as follows:

(1) Thermal loads are uniform in the pre-cooling, post-cooling and relaxation phase but not in the hot run phase. The temperature distribution in hot run phase is uneven significantly along the axial, circumferential and radial direction. The nonuniform distribution of thermal loads during the hot run phase, which is caused by the layout of the cooling channel and the arrangement of the injector element, is a noteworthy issue in the design process of the combustion chamber.

(2) Under the separate action of the thermal loads, the region where the residual compressive mechanical strain is most pronounced is located at the upstream of the nozzle divergent segment, not at the throat. The main reason is that the strain recovery during the post-cooling phase cannot completely offset the negative strain generated at the upstream of nozzle divergent segment during the hot run phase. Reducing the temperature difference between the hot run and the pre-cooling phase within the allowable range of working conditions can be a feasible improvement measure.

(3) The position with the heaviest pressure load is located at the tail of the nozzle divergent segment because it’s the location of the coolant inlet. The pressure loss of coolant in the hot run phase is greater than in the other three phases, which is caused by increase of the flow velocity after heat absorption and the density decrease. When checking the strength of the combustion chamber, the distribution of pressure loads should not be simplified to be globally uniform, and the pressure loss in the cooling channel is nonnegligible.

(4) Under the action of the pressure loads alone, the bottom of the cooling channel tends to bend and deform toward the centerline of the combustion chamber, and the most conspicuous region of the bending is at the tail of the nozzle divergent segment. The higher the material temperature is defined, the more obvious the influences of the pressure loads on the structural deformation. Properly increasing the thickness of the channel bottom near the coolant inlet can be used as an effective measure to reduce the bending of the cooling channel.

(5) Under the actual working conditions of the combustion chamber, the characteristics of structural deformation are determined by the combination of thermal loads and pressure loads, rather than mainly by thermal loads. Multi-cycle analyses reveal that the channel bottom corner is the potential location of the structural failure, and the strain accumulation mode is different from that under the separate action of thermal or pressure loads. Turning the sharp bottom corners of the cooling channels into rounded corners is an alternative method of suppressing strain accumulation.

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