

Numerical investigation of low cycle fatigue life for channel wall nozzles

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Abstract: The thermal-structural response and low cycle fatigue life of a three-dimensional (3D) channel wall nozzle with regenerative cooling were numerically investigated by coupling the finite volume fluid-thermal method, nonlinear finite element thermal-structural analysis and local strain methods. The nozzle had a high area ratio (nozzle exit area divided by throat area) under cyclic working loads. Parametric studies were carried out to evaluate the effects of channel structural parameters such as channel width, channel height, liner thickness and rib width. Results showed that the integrated effects of three-dimensional channel structure and load distribution caused serious strain, which mainly occurred at the intersectant regions of liner wall on the gas side and the symmetric planes of channel and rib. The cooling effect and channel structural strength were significantly improved as the channel width and height decreased, leading to substantial extension of the nozzle service life. On the other hand, the successive decrease in liner thickness and rib width apparently increased the strain amplitude and residual strain of channel wall nozzle during cyclic work, significantly shortening the service life. The present work is of value for design of the channel wall nozzle to prolong its cyclic service life.

Key words: liquid propellant rocket engine; low cycle fatigue; channel wall nozzle; regenerative cooling; nonlinear structural analysis; finite element method

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Increasing requirements for high performance, reliability and service life of cryogenic liquid rocket engines and low production and operational cost have led to the concept of reusable space transportation systems^[1-2]. As indispensable part of high performance, reusable liquid rocket engine such as the space shuttle main engine (SSME)^[3-4] and RD-0120^[5], the regeneratively cooled nozzle with large area ratio (nozzle exit area divided by throat area) has been recognised as a significant contribution to the successful development and application of launch vehicles. Jeffry, et al.^[6] introduced a brazed, milled channel wall nozzle construction that is different

from the current SSME tube wall nozzle. They indicated that nozzles with slotted liners provide an alternative with more robust and lower cost to the tube wall nozzles. Moreover, the simple configurations of a typical channel wall nozzle than a tube wall nozzle enhance the reliability and service life. During a full cyclic operation including pre-cooling, start up, hot run, shut down, post-cooling and relaxation, the elastic-plastic deformation of the channel wall nozzle, induced by the synergy of high-speed combustion gas and high-pressure cryogenic coolant, results in residual strain, and subsequently accumulates the initiation and growth of the cracks (i. e. fail-

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ure occurs) in the cooling channels after a number of cycles. Hence, the low-cycle fatigue (LCF)^[7-8] is the main factor that limits the cycle life of regeneratively cooled nozzle with slotted liner.

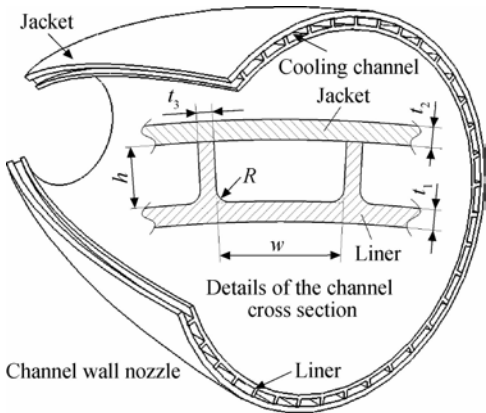
Recently, investigations of prediction methods on fatigue life for combustion chambers with cooling channels have been carried out. Most of the investigations, however, were focused on the typical regeneratively cooled combustion chambers and the analytical models were restricted to two-dimensional (2D) cross section of the nozzle throat^[9-13]. For the combustion chamber at high temperature condition, the cycle service life is determined by many factors, such as creep deformation, low cycle fatigue, high cycle fatigue, thermal corrosion, hydrogen embrittlement, oxidation, degradation. The load-bearing condition of the nozzle extension is quite different from that of the combustion chamber during a full working cycle. Few investigations have been done on the fatigue damage mechanisms and working life predictions of channel wall nozzles with large area ratio. Specifically, the pressure load and heat flux are determined by the flow of coolant and combustion gas, the coolant pressure being the dominant factor. In addition, the flow and heat transfer of the coolant as well as the deformation of the channel wall are three-dimensional with a sharp variation of channel aspect ratio along the nozzle. The nonlinear deformation and life time estimation of the combustion chamber wall are not applicable for the channel wall nozzles.

In the present paper, the channel wall nozzles with regeneratively cooling have been designed. The finite volume fluid-thermal coupling method, nonlinear finite element thermal-structural coupling analysis and local strain model are used to simulate the flow field and structure stress distribution. Based on analyses of the nonlinear deformation of the channel wall under cyclic thermal and mechanical loading, a post-processing method is applied in order to estimate the service life. A number of 3D cases are per-

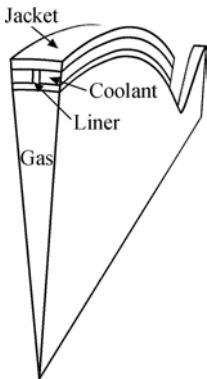
formed to investigate the thermal-structural deformation and low cycle fatigue life of channel wall nozzles. Parametric studies are carried out to evaluate the effects of structural parameters such as channel width, channel height, liner thickness and rib width on fatigue life.

1 Computational domain and mesh

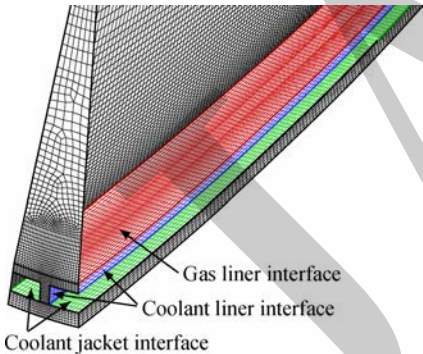
Figure shows calculation model and mesh of channel wall nozzle. The layout of the channel wall nozzle and details of the channel cross-section are shown in Fig. 1(a). t_1 is the liner thickness, t_2 is the rib width, w is the channel width and h is the channel height. The channel number of basic contrasted nozzle are chosen to be 60, h is 4 mm, t_1 and t_2 are 2 mm. The liner is made of NARloy-Z, a copper-based alloy with high thermal conductivity. The jacket is made of Inconel 718, a nickel-based alloy with high strength. The combustion propellant (LO_2 (liquid oxygen)) and LH_2 (liquid hydrogen) and coolant used in the design process are given in Table 1. To obtain the maximum thrust, Rao's method^[14] was applied to design and optimize the contour of regeneratively cooled nozzle extension. Referring to the sub-scale hot-firing test nozzle in the experimental work of Volvo Aero Corporation^[15-16], a simplified design approach was employed to configure the cooling channels. Considering the accuracy of numerical results and computer capacity available, one uniform block, as shown in Fig. 1(b), is chosen as the computation domain. The block is divided from the 3D channel wall nozzle corresponding to each circularly symmetric rib. The domain includes the zones of the gas flow, coolant flow, liner and jacket. The mesh (finite volume) is used for the gas and coolant flows and 3D eight-node element mesh (finite element) is used for structural analysis shown in Fig. 1(c) and Fig. 1(d), respectively. To improve the accuracy of the simulation, the mesh in the vicinity of the coupling surfaces, where the gradients of velocity and temperature are larger, is further refined using the hexahedral structured grid processing.



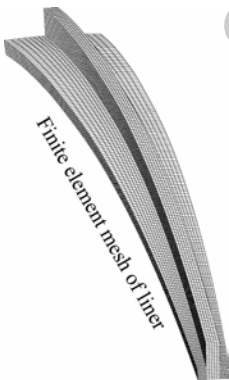
(a) Channel wall nozzle layout



(b) Calculation model



(c) Finite volume mesh



(d) Finite element mesh

Fig. 1 Calculation model and mesh of channel wall nozzle

Solid 70 and Solid 45 in the ANSYS WorkBench software were used for fluid flow and structural

analyses, respectively.

Table 1 Primary propellant and structural parameters of channel wall nozzle

Parameter	Value and detail
Chamber pressure/MPa	11
Propellant	LO ₂ ,LH ₂
Mixture ratio	6.0
Throat diameter/mm	24.8
Coolant operating pressure/MPa	20
Coolant mass flow/(kg/s)	0.8
Coolant initial temperature/K	40
Nozzle extension area ratio	5 : 1~50 : 1

2 Computational scheme

Because low cycle fatigue damage is closely related to the history of the structural load, the simulation is divided into four typical load steps. Table 2 gives the pressure and thermal loads of the four steps^[13,17]. First, the conjugated heat transfer between gas, solid wall and coolant is performed; Second, the temperature and heat flux distributions at the gas and coolant sides of the wall are set as the thermal boundary conditions for structure analysis; Third, the structural analysis is conducted to obtain the strain history of slotted liner under cyclic thermal and mechanical loads. The above three steps are iterated until convergent results are obtained. Four assumptions below are made:

- 1) During the pre-cooling and post-cooling process, the thermal field varies linearly between the uniform environmental temperature field and pre/post cooling temperature field.
- 2) Neglecting the pressure drop along cooling channel, the coolant pressure varies linearly during cyclic operation. The gas side wall pressure of nozzle extension is neglected.
- 3) The elastic-plastic structural deformation of the channel wall of the nozzle is not influenced by the progressing low cycle fatigue damage of the wall.
- 4) The creep deformation of channel wall

material is negligible.

The signed von Mises equivalent method is employed to acquire the cyclic strain amplitude for each finite element according to the “stretch” or “compress” status during cyclic work process. Combined with the low cycle fatigue characteristics of channel wall materials, the local strain approach is adopted to solve the nozzle fatigue life. Following Jorg, et al^[12], we assumed that the stress-strain response of the channel wall for the second and all subsequent cycles are in principle the same as that in the first cycle.

Table 2 Calculation load steps of channel wall nozzle

Loadstep	Operation stage	Coolant pressure /MPa	Assumed time /s
I	pre-cooling	0~15.6	22.5
II	start up, hot run	15.6~20	190
III	shut down, post-cooling	20~0	287.5
IV	relaxation	0	100

2.1 Fluid flow regions

Since the flow in the regeneratively cooled nozzle is complicated including supersonic, compressible flow of the gas and low speed incompressible flow of the cryogenic coolant, Navier-Stokes equations are with noticeable stiffness in numerical calculation. Hence, the time-derivative preconditioning method^[18] has been applied to add time derivative of pressure to the continuity equations. The induced coupled pressure-velocity relation enhances the computational stability and convergence rate for incompressible flow, and yet has negligible influence on the simulation convergence for supersonic flow. The preconditioned governing equations^[19] can be written in vector notation as follow:

$$\mathbf{F} \frac{\partial}{\partial t} \int_V \mathbf{X} dV + \oint (\mathbf{F} - \mathbf{F}_v) dA = \int_V \mathbf{H} dV \quad (1)$$

where $\mathbf{F}$ is the preconditioning matrix, $\mathbf{X}$, $\mathbf{F}$, $\mathbf{F}_v$ and $\mathbf{H}$ are the vectors of primitive, convective, viscous and source variables, respectively. $\mathbf{X} = \{\rho, u, v, w, E\}^T$. The standard $k-\epsilon$ models are

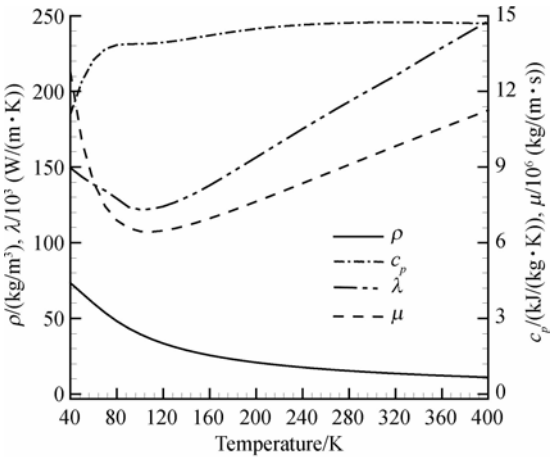
applied for turbulence flows. Eq. (1) can be used to calculate the flow and heat transfer of gas and coolant simultaneously. Temperatures and heat fluxes at surfaces between gas, solid wall and coolant are considered as the coupling interface conditions. The thermal field of the channel wall is described as the function of temperature inside solid zone.

The fully implicit finite volume method is used. The convective terms are discretized by a second-order upwind scheme, and the viscous terms are discretized by a central difference scheme.

The gas is assumed to be an ideal gas. Its properties are assumed to be constant; the average molar mass $\bar{M}$ is 13.505 kg/kmol, specific heat capacity c_p is 8 267.6 J/(kg · K), thermal conductivity λ is 0.606 W/(m · K), and dynamic viscosity μ is 9.74×10^{-5} kg/(m · s). As shown in Fig. 2(a), the thermodynamic and transport properties of the coolant vary as functions of temperature for pressure is 20 MPa. As shown in Fig. 2(b), thermal conductivities of the liner and jacket vary as functions of temperature. The variations of these parameters are applied during the calculation process.

2.2 Heat conduction in channel wall

Since the specific heat capacity and thermal conductivity of the channel wall are dependent on temperature and the boundary conditions at both gas and coolant sides vary with time, the transient heat conduction in the channel wall of



(a) Coolant LH₂ for pressure of 20 MPa

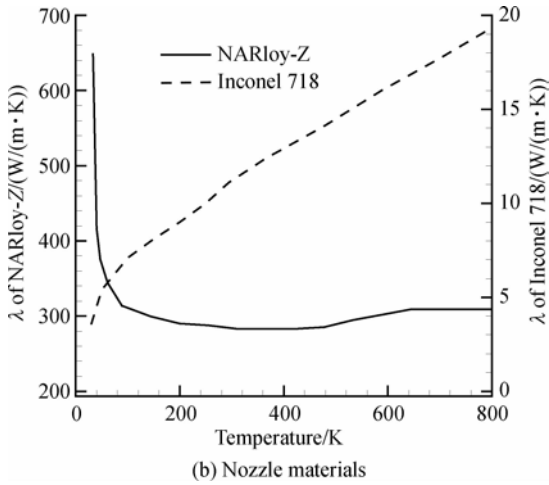


Fig. 2 Properties of coolant and nozzle materials

the nozzle is written as follow:

$$\mathbf{C}(T) \frac{\partial \mathbf{T}}{\partial t} + \mathbf{K}(T) \mathbf{T} = \mathbf{Q} \quad (2)$$

where $\mathbf{C}(T)$ and $\mathbf{K}(T)$ are the matrixes of specific heat capacity and thermal conductivity of the wall, respectively; $\mathbf{T}$ and $\mathbf{Q}$ are the vectors of node temperature and node heat flux, respectively. The Newton-Raphson method is adopted to obtain the iterative solution of Eq. (2) corresponding to gradually applied thermal boundary load by automatic time steps. The Galerkin weighted residual method is used to solve the energy equation^[20].

2.3 Structural analysis in channel wall

Taking account of the nonlinear constitutive relation of channel wall material due to the elastic-plastic deformation induced by the cyclic thermal and mechanical loads, the static equilibrium equation is given as follow:

$$\mathbf{K}_T(\boldsymbol{\delta}) \boldsymbol{\delta} = \mathbf{R} + \mathbf{R}^{\text{th}} \quad (3)$$

where $\mathbf{K}_T(\boldsymbol{\delta})$ is the global tangent stiffness matrix; $\boldsymbol{\delta}$, $\mathbf{R}$ and $\mathbf{R}^{\text{th}}$ are the vectors of node displacement, node mechanical load and node thermal load, respectively. Eq. (3) is solved by finite element method. Because the stress is closely related to the loading history during elastic-plastic deformation stage, the Euler-Newton method was used for solving the nonlinear Eq. (3). The global tangent stiffness matrix $\mathbf{K}_T(\boldsymbol{\delta})$ is determined by the material constitutive relation. Based on the incremental theory, the e-

lastic-plastic constitutive equation, applying von Mises yield criterion and isotropic hardening hypothesis^[13] during loading process, is given as follow:

$$\begin{cases} d\boldsymbol{\varepsilon} = d\boldsymbol{\varepsilon}^e + d\boldsymbol{\varepsilon}^p + d\boldsymbol{\varepsilon}^{\text{th}} \\ d\boldsymbol{\varepsilon}^e + d\boldsymbol{\varepsilon}^p = \mathbf{D}^{-1} d\boldsymbol{\sigma} + \frac{1}{A} \cdot \frac{\partial f}{\partial \boldsymbol{\sigma}} \left(\frac{\partial f}{\partial \boldsymbol{\sigma}} \right)^T d\boldsymbol{\sigma} \\ A = - \left[\mathbf{B} + \left(\frac{\partial f}{\partial \boldsymbol{\sigma}^p} \right)^T \mathbf{D} \frac{\partial f}{\partial \boldsymbol{\sigma}} \right] \\ \mathbf{B} = \frac{\partial f}{\partial \boldsymbol{\kappa}} \boldsymbol{\sigma}^T \frac{\partial f}{\partial \boldsymbol{\sigma}} (\boldsymbol{\kappa} = w^p) \end{cases} \quad (4)$$

where $\boldsymbol{\varepsilon}$, $\boldsymbol{\varepsilon}^e$, $\boldsymbol{\varepsilon}^p$, $\boldsymbol{\varepsilon}^{\text{th}}$, $\boldsymbol{\sigma}$ and $\boldsymbol{\sigma}^p$ are the vectors of node total strain, node elastic strain, node plastic strain, node thermal strain, node total stress and node plastic stress, respectively; $\mathbf{D}$ is the elastic matrix; $f = f(\boldsymbol{\sigma}, \boldsymbol{\kappa})$ is the loading function with $\boldsymbol{\kappa}$ being the strengthen parameter reflecting the load history and w^p being the plastic work. The stress-strain behaviour at different operational temperatures (T) of liner material NARloy-Z^[21] is shown in Fig. 3. It is seen that the thermal load affects the structural response by directly causing the deformation of the channel wall and also influencing material constitutive relation.

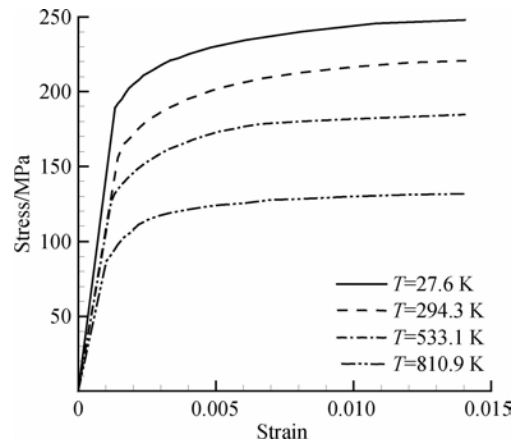


Fig. 3 Stress-strain curves of liner material at different operation temperatures

2.4 Prediction method for low cycle fatigue life

The local strain method is primarily used to assess the initiation and growth of the crack for low cycle fatigue failure induced by cyclic elastic-plastic deformation during higher load level. Combining with the Morrow mean stress correc-

tion method^[22], the fatigue life calculation according to Basquin equation and Coffin-Manson equation^[23] is provided as follow:

$$\epsilon_a = \frac{\sigma'_f - \sigma_m}{E} (2N_f)^b + \epsilon'_f (2N_f)^c \quad (5)$$

where ϵ_a , N_f , σ'_f , ϵ'_f , σ_m and E are cyclic strain amplitude, fatigue life, fatigue strength coefficient, fatigue ductility coefficient, mean stress and Young modulus, respectively. b and c are fatigue strength exponent and fatigue ductility exponent. The low-cycle fatigue characteristics of materials of the channel wall are shown in Fig. 4, which is provided by the Manson universal slope method^[24].

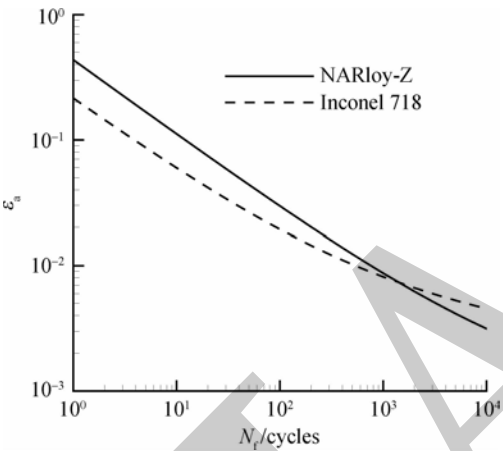


Fig. 4 Low cycle fatigue behaviour of nozzle materials

3 Results and discussion

3.1 Thermal-structural response of channel wall

The temperature distribution during stationaryload and von Mises strain distributions in representative stages of the basic contrasted nozzle are presented in Fig. 5(a) and Fig. 5(b), respectively. The maximum temperature occurs at the gas side of nozzle extension inlet and its value is lower than 850 K. The temperature of the liner at nozzle outlet is approximately 460 K, while the temperature of the jacket is lower than 300 K. The more serious von Mises equivalent strain is mainly located at the intersectant regions of liner gas side wall and the symmetric planes of the channel and rib. The equivalent strain distribution during stationary work has

somewhat similarity to the temperature distribution owing to the considerable thermal strain and reduction of material strength induced by thermal load. The equivalent strain distribution after the first work cycle reveals that the largest residual strain occurs in the middle region of milled channel liner, which is caused by the integrated effect of three-dimensional channel structure and load distribution. For more detailed comparison, the time histories of y component (i. e. radial direction) of node strain (ϵ_y) for typical nodes 20256 and 21848 are illustrated in Fig. 6(a) and Fig. 6(b), respectively. The nodes locations are given in Fig. 5(b). The time history of the total node strain is dominated by the

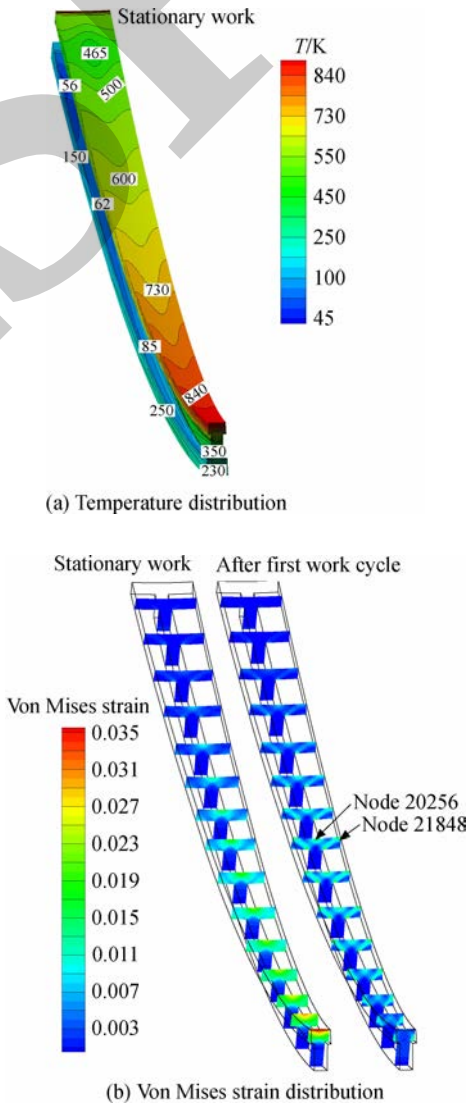


Fig. 5 Temperature and von Mises strain distribution of basic contrasted nozzle

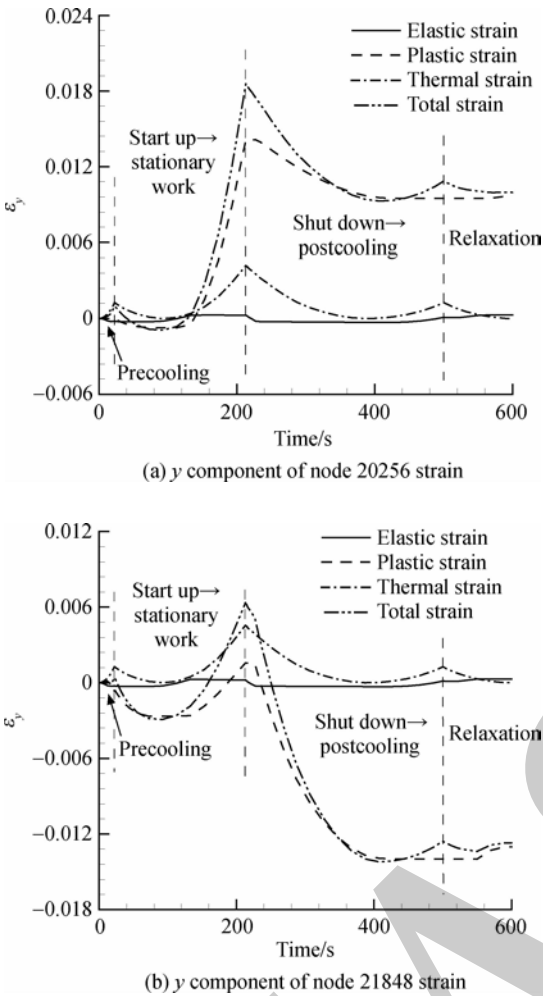


Fig. 6 Node strain history of basic contrasted nozzle

variation of plastic strain and is also significantly affected by the thermal strain whereas the effect of elastic strain can be neglected. Moreover, due to the disparate forced state and deformation mode, conspicuous difference is seen between the node strain histories of nodes 20 256 and 21848.

3.2 Effect of channel width

Since channel width is mainly determined by channel number of the nozzle, fluid-thermal-structural analyses have been implemented for nozzles with different channel numbers. The temperature distributions for the nozzles during stationary work are depicted in Fig. 7(a). The cooling effect of the nozzle improves noticeably with increase in channel number (i. e. decrease in channel width) by virtue of accelerating coolant flow and enhancing fin efficiency. Subsequently, the reduced channel width results in

the obvious diminution of residual equivalent strain for cyclic work exhibited in Fig. 7 (b) through enhancing material strength and reinforcing the structure robustness. To further describe the structural response caused by changed channel width, distinct comparisons of node shear stress (τ_{xy})-shear strain (γ_{xy}) curves for nozzles with different channel numbers are given in Fig. 8. The nodes of 20256, 23380 and 28881 lie in the identical location on liner gas side wall and the same for the nodes of 21848, 25736 and 26939. For both considered node groups, the strain amplitude (i. e. maximal strain difference per cycle) and residual strain (i. e. remaining strain after the full cycle) decrease effectively as a result of the growth of channel number, while the loading-deformation responses tend in ap-

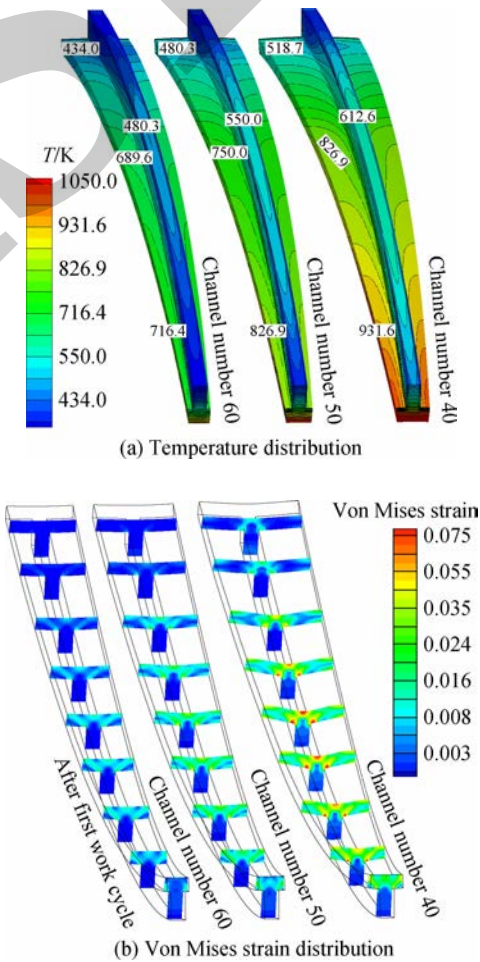


Fig. 7 Comparison of temperature and von Mises strain distribution for nozzles with different channel numbers

proximately opposite direction. The variation of estimated numbers of cycles for nozzles with different channel numbers are comparison in Fig. 9. It makes clear that the minimum channel width possesses the longest low cycle fatigue life, which is consistent with the results of structural response. Besides, Fig. 9(b) also exposes that node 21 848 abnormally behaves less cycles for

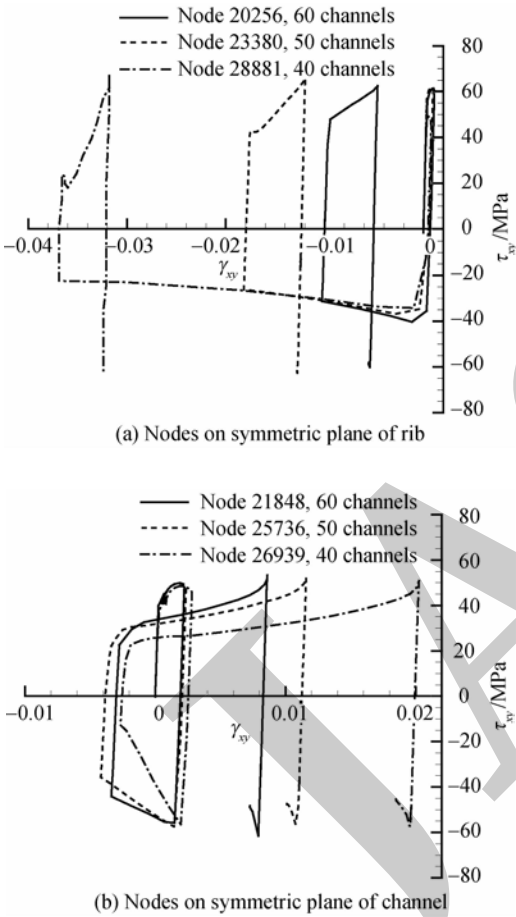


Fig. 8 Comparison of node shear stress-strain response for nozzles with different channel numbers

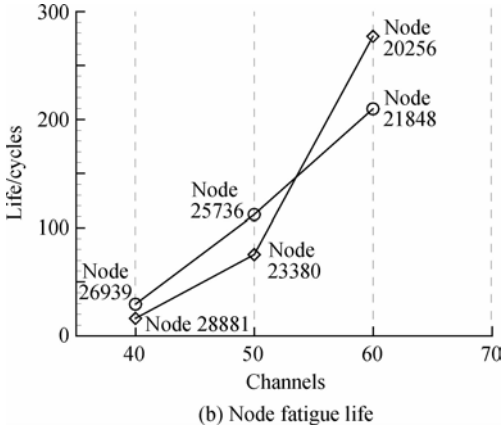
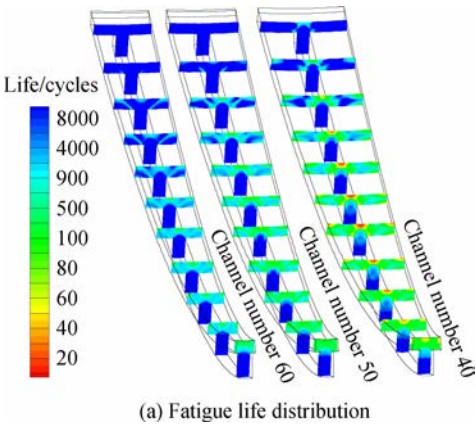
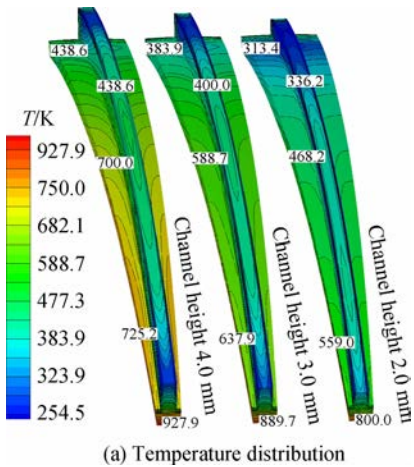


Fig. 9 Comparison of low-cycle fatigue life for nozzles with different channel numbers

the 60 channels nozzle, while the minimum number of cycles ordinarily appears at symmetric plane of rib for the nozzles with large channel width (e. g. , node 23 380 for the 50 channels nozzle and node 28 881 for the 40 channels nozzle).

3.3 Effect of channel height

The comparisons of thermo-mechanical behaviour for nozzles with different channel heights are diagrammed in Fig. 10 and Fig. 11. While the channel height decreases, the entire temperature distribution of liner decrease about 130 K due to the continuously accelerated coolant flow. With the interaction of enhanced strength of channel structure, it leads to the persistent reduction of residual strain after one full work cycle. The nodes of 20 256, 24 475 and 23 920 lie in the identical location in the symmetric plane of rib and the same for the nodes of 21 848, 23 174



(a) Temperature distribution

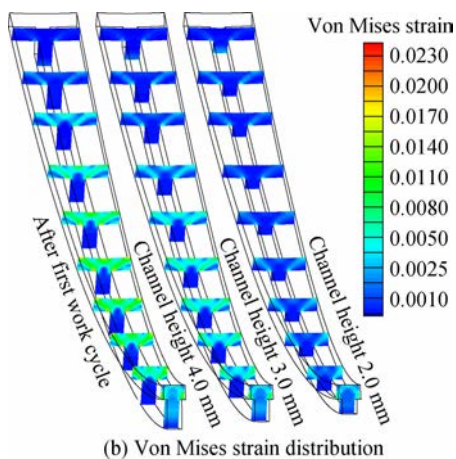
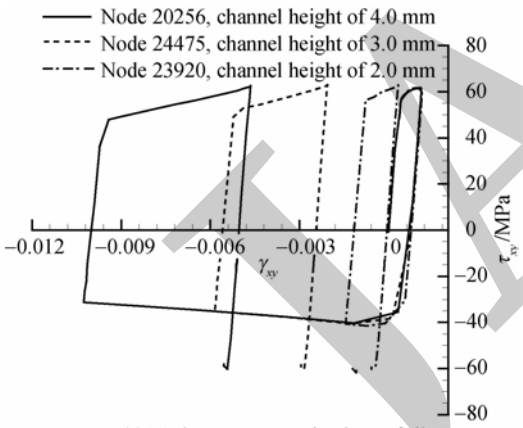
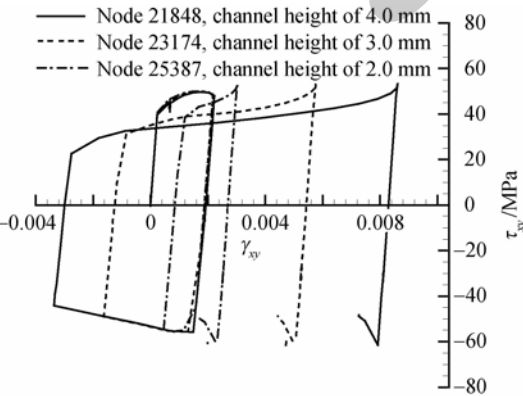


Fig. 10 Comparison of temperature and von Mises strain distribution for nozzles with different channel heights

and 25387 in the symmetric plane of channel. The shear stress-strain curves of the two representative node groups reveals in a more apparent manner that the strain amplitude and residual strain of cyclic work decline substantially with



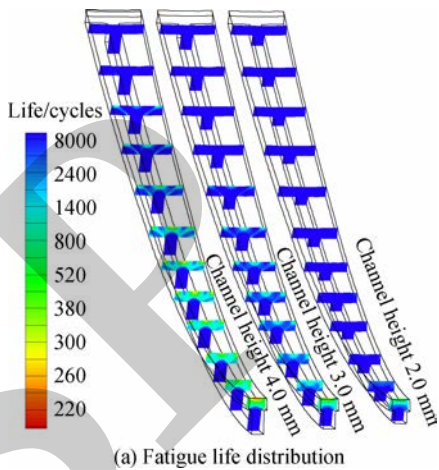
(a) Nodes on symmetric plane of rib



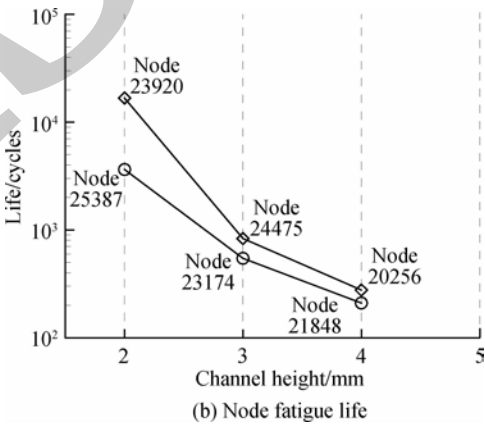
(b) Nodes on symmetric plane of channel

Fig. 11 Comparison of node shear stress-strain response for nozzles with different channel heights

the decrease of channel height. The low cycle fatigue life distributions of milled channel liners and the life time of typical nodes are reflected in Fig. 12. It presents a similar variation with the preceding structural response caused by changed channel height. That is to say, the diminution of channel height brings about significant service life extension of milled channel nozzle.



(a) Fatigue life distribution



(b) Node fatigue life

Fig. 12 Comparison of low-cycle fatigue life for nozzles with different channel heights

3.4 Effect of liner thickness

The temperature distributions for nozzles with different liner thickness during stationary work are compared in Fig. 13(a). The thinning down liner results in the nozzle temperature rising slightly. However, because of the enhanced heat transfer, the temperature in the liner gas side region of nozzle extension inlet decreases contrary. Mainly due to the on-going weakening of channel structure induced by the reduced liner thickness, the residual equivalent strain after the

first work cycle shown in Fig. 13(b) unceasingly increases. This can be acquired in more detail in Fig. 14, where the nodes of 20 256, 19 394 and 26 253 lie in the identical location on liner gas side wall and the same for the nodes of 21 848, 21 048 and 27 701. In general, the strain amplitude and residual strain enlarge with the decrease in liner thickness. But yet, the structural responses between nodes 19 394 and 26 253 as well as those between nodes 21 848 and 21 048 appear somewhat abnormal variations. As a consequence, the life cycles for the typical nodes reveal a similar variation with the structural behaviours. The general trend of low cycle fatigue life of channel wall nozzle in Fig. 15 is going down with dwindling liner thickness.

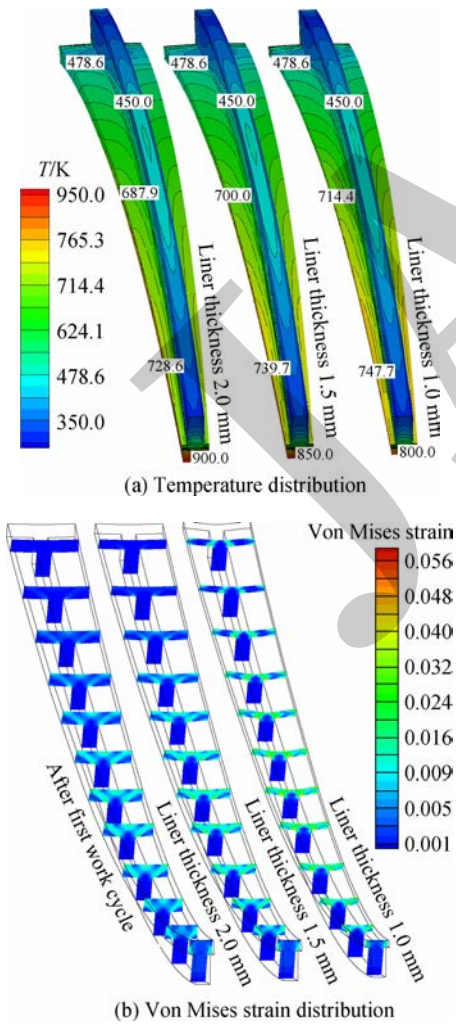


Fig. 13 Comparison of temperature and von Mises strain distribution for nozzles with different liner thicknesses

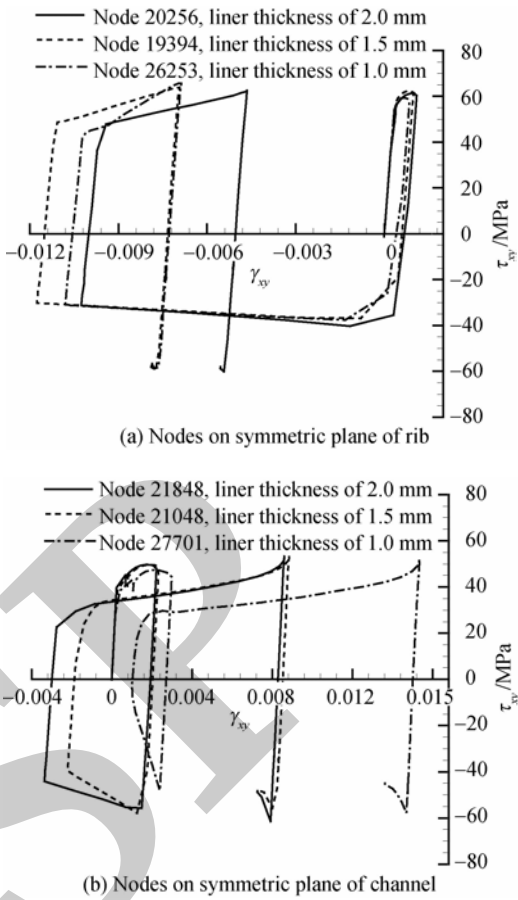
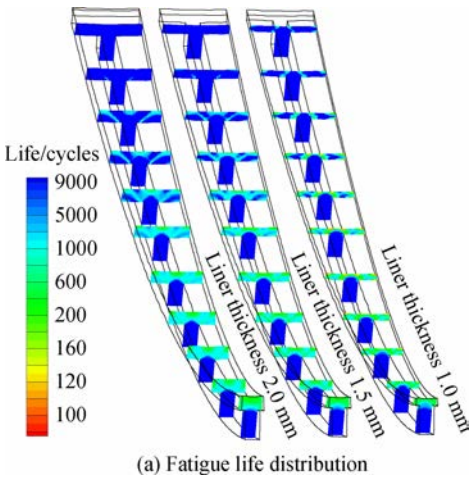


Fig. 14 Comparison of node shear stress-strain response for nozzles with different liner thicknesses

3.5 Effect of rib width

The distributions of temperature during stationary work and residual equivalent strain after first work cycle for nozzles with different rib width are presented in Fig. 16. Because of the weakened fin efficiency, the successively decreased rib width results in the liner thermal



(a) Fatigue life distribution

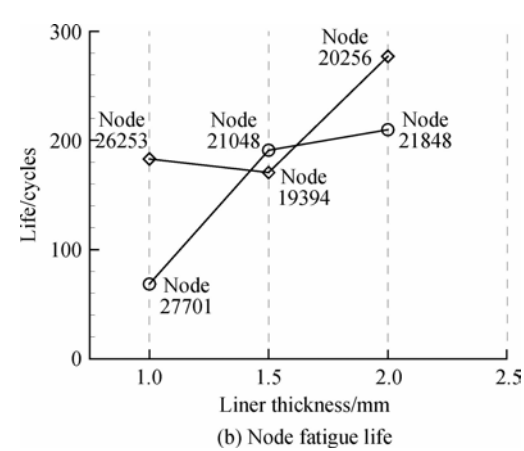


Fig. 15 Comparison of low-cycle fatigue life for nozzles with different liner thickness

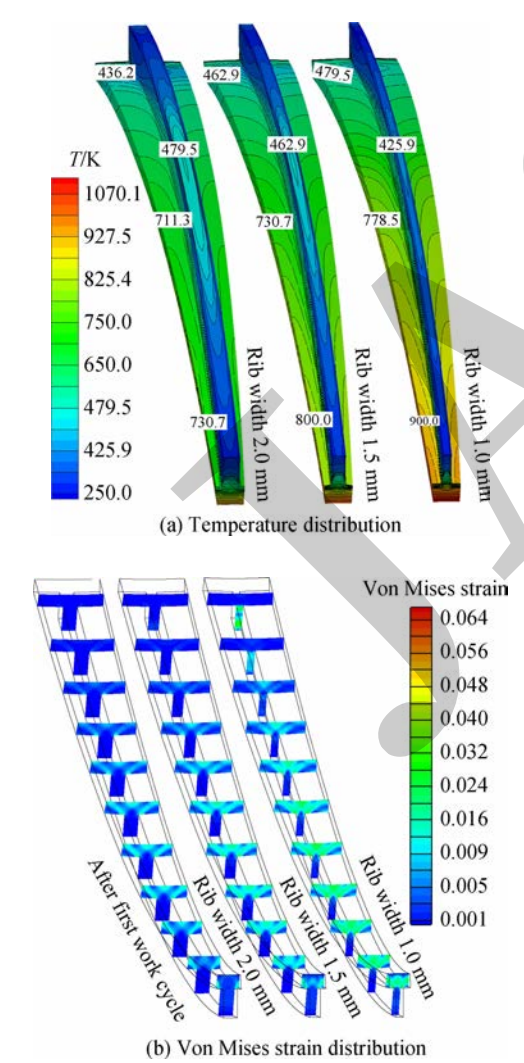


Fig. 16 Comparison of temperature and von Mises strain distribution for nozzles with different rib widths

remaining strain after a full load cycle. The more obvious variations of strain amplitude and residual strain can be obtained from the shear stress-strain curves in Fig. 17. The nodes of 20256, 26908 and 28035 lie in the identical location on liner gas side wall and the same for the nodes of 21 848, 27 947 and 29 074. It further confirms the thermal-structural responses incurred by the reductive rib width. The comparative numbers of cycles of low cycle fatigue are described in Fig. 18. It reveals that the decreased rib width results in the service life of channel wall nozzle shortening seriously. Besides, nodes located at the intersectant region of liner gas side wall and symmetric plane of rib for thin rib nozzle (e. g. nodes 28035 and 26908) give the minimum fatigue life cycle.

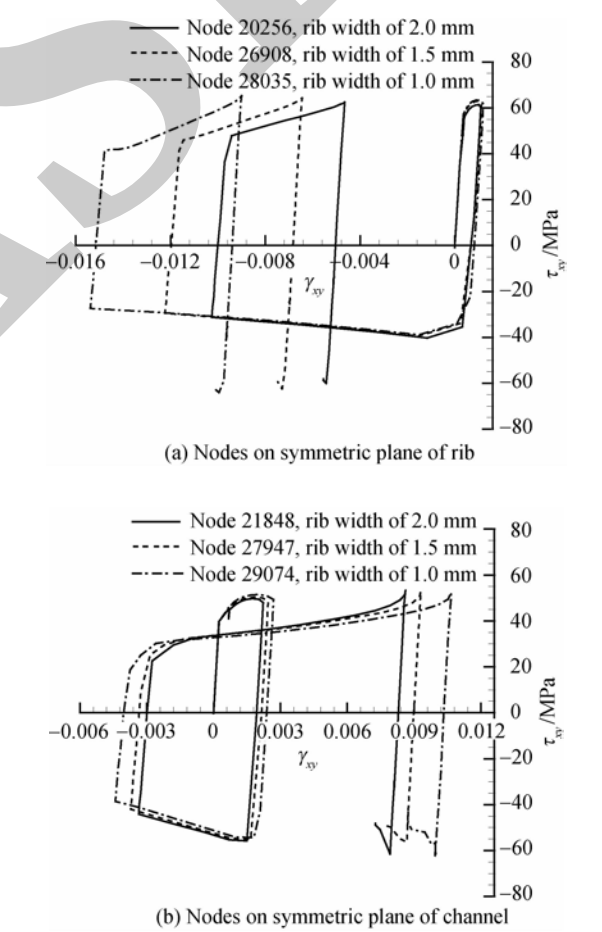


Fig. 17 Comparison of node shear stress-strain response for nozzles with different rib widths

load ascending. Subsequently, it leads to higher

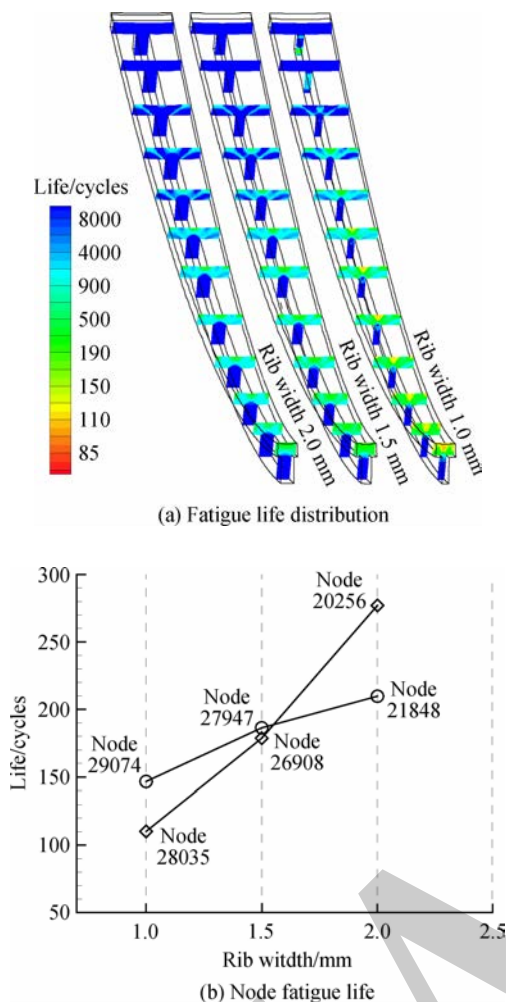


Fig. 18 Comparison of low-cycle fatigue life for nozzles with different rib widths

4 Conclusions

In the paper, we have investigated the thermal-structural response of regeneratively cooled channel wall nozzle under cyclic working loads. The provided nonlinear finite element analysis method and low cycle fatigue life estimation approach were adopted. The effects of channel structural parameters on the nozzle fatigue service life have been systematically studied. The following conclusions may be drawn:

1) The integrated effects of 3D channel structure and load distribution under cyclic work result in serious strain, which is mainly occurring at the intersectant regions of liner gas side wall and symmetric planes of channel and rib. The time history of total node strain is primarily dominated by the plastic strain variation.

2) The increased channel number (i. e. decreased channel width) has significantly improved the cooling effect of channel wall nozzle. Also more channels effectively reduced the strain amplitude and residual strain for cyclic work, which leads to the longer low cycle fatigue life.

3) The temperature of the liner drops as channel height decreases. This enhances the strength of the nozzle and extends the service life of the nozzle substantially.

4) The decreased liner thickness results in the strain amplitude and residual strain of channel wall nozzle enlarging, mainly due to the successively weakened channel structure. Hence, the general trend of low cycle fatigue life time goes down.

5) With decreasing rib width, the thermal load of the liner increases considerably and the amplitude and residual of the strain consequently increase for cycle work. This shorts the serving life of the nozzle.

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