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Thermo-mechanical stress and fatigue damage analysis on multi-stage high pressure reducing valve

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ABSTRACT

A multi-stage high pressure reducing valve (MSHPRV) is proposed. It can achieve a multi-stage pressure reducing way. Valve failure mainly occurs under high pressure and high temperature conditions, thus it is necessary to investigate the strength of MSHPRV under those complex conditions. In this paper, the mathematical model of MSHPRV is established and Computational Fluid Dynamics (CFD) method is employed to simulate its flow fields and thermo-mechanical stress. Next, the stress of MSHPRV under different opening time and the fatigue damage of MSHPRV under different valve openings are studied. Finally, two changes are provided on geometry of MSHPRV and the geometrical factors are optimized. The results show that, the radial direction from inner wall to outer wall is the main heat transfer direction for valve body. At opening time 50 s, the working condition of MSHPRV is dangerous condition. Meanwhile, the maximum value of thermal stress is 487 MPa, which is located at the upper end face of valve chamber region B3. There is a lag effect of stress distribution with respect to temperature distribution. The combined stress of valve body is composed of thermal stress and mechanical stress, in which thermal stress holds the dominant position. Moreover, with the increasing of valve opening, the fatigue damage of valve body increases correspondingly. It can be concluded that MSHPRV can cope with complex conditions like high pressure and high temperature. In the optimization design of MSHPRV, it can be found that the best strength of MSHPRV is achieved with such geometrical factors as angle 15, diameter 4 mm and 2 stage plates. Besides, radian design as the improved structure is recommended. This work can benefit the further research work on the regulation performance and safe operation of high pressure reducing valve.

1. Introduction

Nowadays, pressure reducing valves are widely used in nuclear power system to regulate fluid pressure. However, for traditional pressure reducing valves, there exist a series of problems such as high energy consumption, large transmission loss and low efficiency. In order to deal with these problems, a new multi-stage high pressure reducing valve (MSHPRV) was proposed (Jin et al., 2016), and its internal flow fields had been investigated to reveal the mechanisms of energy conversion and pressure reduction. Valve failure mainly occurs in high pressure and high temperature conditions. However, there is no work on investigating the strength of MSHPRV under those complex conditions. Therefore, in this paper, the analysis of thermo-mechanical stress and fatigue damage on MSHPRV is conducted.

Up to now, there have been lots of literatures dealing with the thermo-mechanical stress and fatigue damage of different types of valves or other devices. Li et al. (2015) conducted the heat transfer and thermal stress analyses in fluid–structure coupled field. In the work, the temperature distribution, thermal deformation and thermal stress were calculated. Witek, 2016 investigated thermo-mechanical stress and failure of the exhaust valve in diesel engine, and the results showed that a high bending stresses were occurred in the valve stem. Li et al. (2016) conducted analysis of thermo-mechanical stress on valve plate friction pair of axial piston pump in electro hydrostatic actuator of aircraft. Sun et al. (2016) calculated the thermal stress of heat transfer tubes with tube support plate gaps in a steam generator through the one-way flow-heat-solid coupling method by software Workbench. Zhang et al. (2016) conducted analysis of transient thermal–hydraulic charac-

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Nomenclature

α	thermal diffusivity (m^2/s)	φ	stress function
q_v	strength of internal heat source (W/m^3)	E	elastic modulus (MPa)
c_p	heat capacity at constant pressure (J/(K·mol))	β	thermal expansion coefficient (m/)
ρ	fluid density (kg/m^3)	T	temperature (°C)
t	time (s)	σ	stress (MPa)
h	heat transfer coefficient (W/(m^2·K))	σ_{eq}	equivalent stress (MPa)
λ	thermal conductivity (W/(m·K))	$\sigma_z \sigma_r \sigma_\theta$	axial force, radial stress and circumferential stress respectively (MPa)
T_f, T_w	fluid temperature and inner wall temperature respectively (°C)	τ_{rz}	shear stress (MPa)
d	characteristic length (m)	$\sigma_{\max}$	the maximum stress (MPa)
N_u	Nusselt number		
R_e	Reynolds number		
P_r	Prandtl number		

teristic on a space thermionic reactor. Maher et al. (2016) investigated mechanical and thermal stresses that arise in the exhaust valve due to its operating with and without thermal coating layer on face exhaust valve. Liu et al. (2015) proposed a conceptual structure design of helium-cooled solid breeder blanket as one of the candidates for the Chinese Fusion Engineering Test Reactor and calculated its thermo-mechanical stress. Şentürk et al. (2016) analyzed the 3-D transient heat transfer and thermo-mechanical stress by using the thermo-mechanically coupled theory. Yazdanipour and Mohammad (2016) investigated the stochastic fatigue crack growth of metallic structures under multiple thermal–mechanical stress levels. Subhasish et al. (2016) conducted thermal–mechanical stress analysis on pressurized water reactor pressure vessel with/without a preexisting crack under grid load following conditions. Jan et al. (2016) presented a semi numerical method for solving inverse heat conduction problems encountered in the monitoring of thermal stresses in pressurized thick-walled elements of steam boilers. Cai et al. (2017) conducted a numerical investigation on the thermal stratification in a pressurizer surge line. Lu et al. (2017) studied the thermal temperature fields and thermal stress under steady temperature field of diesel engine piston. Bahman et al. (2017) evaluated the thermal damages and residual stresses in dry grinding by structured wheels. Tevatia and Srivastava (2017) investigated the influence of residual thermal stresses on fatigue crack growth life of discontinuous reinforcements in metal matrix composites. Reza et al. (2015) focused attention on the fretting fatigue failure mechanism of automotive shock absorber valve. Yan and Jian (2016) conducted theoretical and experimental investigations of vibration waveforms excited by an electro-hydraulic type exciter for fatigue with a two-dimensional rotary valve. Sharifi et al. (2016) presented a three dimensional analysis on low cycle fatigue failure in engine part subjected to multi-axial variable amplitude thermo-mechanical load. Eftekhari and Fatemi (2016) investigated the creep-fatigue interaction and thermo-mechanical fatigue behaviors of thermoplastics and the composites.

In the previous work, MSHPRV was proposed, and attention was paid to its structural and flow characteristics (Chen et al., 2017). However, when facing with such complex working conditions as high flow velocities, high parameters and large pressure ratios, the strength of MSHPRV will be challenged. Therefore, in this paper, the mathematical model of MSHPRV is established and thermo-fluid-solid coupling method is employed to numerically calculate its flow fields and thermo-mechanical stress. The object of this study is to obtain the dangerous working condition and dangerous point of valve body in the entire process and to provide guidance for the regulation performance and safe operation of high pressure reducing valve.

2. Numerical method

2.1. Mathematical model

Due to that flow field is the basis for calculating the thermo-mechanical stress, thus flow characteristic of fluid in MSHPRV is studied first. For steam with high pressure and high temperature in MSHPRV, compressible gas model and RNG k-ε turbulence model are adopted. Moreover, steam flow in MSHPRV should satisfy the following equations (Jin et al., 2016).

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

In the formula, ρ refers to density, u_i refers to velocity.

Momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} - \rho u_i' u_j') + \rho F_i \tag{2}$$

In the formula, p refers to pressure, τ_{ij} refers to stress tensor, ρ refers to density, $-\rho u_i' u_j'$ refers to Reynolds stress, F_i refers to the force of gravity in I direction.

Energy equation:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}[u_i(\rho E + p)] = \frac{\partial}{\partial x_i}\left(k_{\text{eff}}\frac{\partial T}{\partial x_i} - \sum_{j'} h_{j'} J_{j'} + u_j \tau_{ij}\right) + S_h \tag{3}$$

In the formula, k_{eff} refers to effective conductivity, J_j refers to diffusion flow component.

Turbulent kinetic energy equation:

$$\frac{\partial}{\partial t}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{ef} f \frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon - Y_M \tag{4}$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon \mu_j) + \frac{\partial}{\partial x_i}\left(\alpha_k \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon \tag{5}$$

In the formula, u_i refers to velocity, G_k refers to turbulent kinetic energy from average velocity gradient, G_b refers to turbulent kinetic energy from buoyant force, Y_M refers to turbulent kinetic energy from fluctuation dissipation.

Heat transfer equation:

$$\alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{q_v}{c_p \rho} = \frac{\partial T}{\partial t} \tag{6}$$