

Analysis of fatigue reliability for high temperature and high pressure multi-stage decompression control valve

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Abstract. Based on stress-strength interference theory to establish the reliability mathematical model for high temperature and high pressure multi-stage decompression control valve (HMDCV), and introduced to the temperature correction coefficient for revising material fatigue limit at high temperature. Reliability of key dangerous components and fatigue sensitivity curve of each component are calculated and analyzed by the means, which are analyzed the fatigue life of control valve and combined with reliability theory of control valve model. The impact proportion of each component on the control valve system fatigue failure was obtained. The results is shown that temperature correction factor makes the theoretical calculations of reliability more accurate, prediction life expectancy of main pressure parts accords with the technical requirements, and valve body and the sleeve have obvious influence on control system reliability, the stress concentration in key part of control valve can be reduced in the design process by improving structure.

1. Introduction

High temperature and high pressure multi-stage decompression control valve (HMDCV) is gradually developing for the lightweight and high performance objective in the backgrounds that low-carbon economy is an important part in social development. The strength reliability problem of HMDCV which works at high temperature and high pressure for a long period has become more prominent. There are many valve products abandoned and many production accidents happened for structural fatigue failure every year. So it is absolutely necessary to fatigue analysis for HMDCV. The prediction and evaluation methods of HMDCV's small sample test are deficient so far, the accuracy of the results provided by analysis and prediction of product reliability couldn't be guaranteed.

The HMDCV hasn't the conditions of large sample test to at present, and lack of information system reliability evaluation. Even if fatigue performance test of small sample is still faced with many difficulties for many reliability researchers, such as insufficient fund, the test conditions are difficult to control, the experiment in design optimization stage results in waste of resources and so on. Theoretical calculation and finite element analysis are adopted in this paper for fatigue reliability calculation and structural optimum of HMDCV. The influence of high temperature to fatigue strength is considered in studying. It can reduce or avoid to produce the probability of failure in the test [1], and improve the reliability of products.



2. Structure and mathematical model

2.1 Structure and operation parameter

Take the high temperature and high pressure multi-stage decompression control valve (HMDCV) for instance to study the fatigue reliability. The HMDCV is mainly used to regulate water system, its material trademark of main body is WC6, the basic technological parameters are as follows:

Nominal diameter is DN100, nominal pressure is PN150, design temperature is 425°C, design pressure is 12.53MPa and service life is more than 10000 times.

2.2 Fatigue reliability calculation model of HMDCV

Fatigue Probability of thermal stress on the HMDCV is analyzed according to the FMECA method [2]. The pressure parts of HMDCV are main research objects (valve body, valve cover and sleeve) for fatigue reliability analysis.

As known probability density function $f(S)$ and $f(\delta)$ of stress and strength, numerical integration can be conducted associate with probability density function, and the reliability $R(t)$ can be reached. Because fatigue strength of valve basically consistent with the normal distribution, the distribution of stress and strength also should be normal distribution. According to normal distribution probability density function and cumulative distribution function are calculated as follows:

As $\zeta = \delta - S$, then the probability of reliability with $\zeta > 0$ can be represented as $R(t) = P(\zeta > 0)$.

As $h(\zeta)$ is distribution function of the difference between $f(\delta)$ and $f(S)$, $h(\zeta)$ is the normal distribution function because $f(\delta)$, $f(S)$ and all are normal distribution function according to the theory of probability and statistics, and it can be expressed as:

$$h(\zeta) = \frac{1}{\sigma_{\zeta} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{\zeta - \bar{\zeta}}{\sigma_{\zeta}} \right)^2} \quad (1)$$

where,

$$\bar{\zeta} = \bar{\delta} - \bar{S} \quad (2)$$

$$\sigma_{\zeta} = (\sigma_S^2 + \sigma_{\delta}^2)^{1/2} \quad (3)$$

The probability of positive ζ is the reliability, it can be shown as:

$$R(t) = \Gamma(\zeta > 0) = \int_0^{\infty} h(\zeta) d\zeta = \frac{1}{\sigma_{\zeta} \sqrt{2\pi}} \int e^{-\frac{1}{2} \left(\frac{\zeta - \bar{\zeta}}{\sigma_{\zeta}} \right)^2} d\zeta \quad (4)$$

If $h(\zeta)$ is transformed into a standard normal distribution, then

$$R(t) = \int_0^{\infty} h(\zeta) d\zeta = \int_0^{\infty} \phi(Z) dz \quad (5)$$

In eq. (5),

$$\phi(Z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} \quad (6)$$

$$Z = \frac{\zeta - \bar{\zeta}}{\sigma_{\zeta}} \quad (7)$$

From eq.(7) can be obtained these,

$$\text{When } \zeta = \infty, \quad Z = \frac{\infty - \bar{\zeta}}{\sigma_{\zeta}} = \infty \quad (8)$$

$$\text{When } \zeta = 0, \quad Z = \frac{0 - \bar{\zeta}}{\sigma_{\zeta}} = -\frac{\bar{\delta} - \bar{S}}{(\sigma_{\delta}^2 + \sigma_S^2)^{1/2}} \quad (9)$$

Where Z is the connection coefficient that can be referred to as the reliability coefficient. So when the mean and standard deviation of the stress and strength on the parts in valve are known, the reliability can be calculated by eq. (6) and eq. (9) [3].

2.3 Correct on ultimate fatigue strength of structures of HMDCV

Because material properties, structure size, manufacturing process are uncertainty, the fatigue limit strength of HMDCV has appropriate certain dispersity. The temperature is usually ignored at researching on initial fatigue limit strength of valve parts, there are three influencing factors being considered such as structure size, surface processing and stress concentration. But the temperature has certain influence for fatigue limit in the state that the creep temperature of materials has not been reached. This paper is in view of the above-mentioned four influencing factors, introducing the size coefficient(ε), surface factor(β), effective stress concentration factor(K_f), temperature correction coefficient(γ), and for more accurate calculation of valve part fatigue limit. Because existing literatures have many methods solve the problems for dimension coefficient, surface processing coefficient and effective stress concentration factor, temperature correction coefficient γ is theoretically calculated in this paper as follows:

$$\gamma = \delta'_T / \delta_T \quad (10)$$

Where δ'_T is the fatigue limit of standard sample in working temperature, δ_T is the fatigue limit of standard sample in normal temperature.

Test shows that temperature has little influence on fatigue limit at working temperature of steel below 300~400°C, and fatigue limit decreases with the increasing temperature exceeds 400 °C. There is a critical temperature T_1 for the material, and fatigue limit decreases while working temperature exceeds T_1 . The fatigue limit δ'_T of standard sample in working temperature can be shown as:

$$\delta'_T = \delta_T - \Delta\delta_T(T - T_1) \quad (11)$$

Where $\Delta\delta_T$ is fatigue limit reduction in unit temperature.

Combining eq. (10) and eq. (11) lead to

$$\gamma = \frac{\delta_T - \Delta\delta_T(T - T_1)}{\delta_T} = 1 - \frac{\Delta\delta_T}{\delta_T}(T - T_1) \quad (12)$$

While $C = \Delta\delta_T / \delta_T$ (C according with normal distribution), then

$$\gamma = 1 - C(T - T_1) \quad (13)$$

It can be seen that the temperature correction coefficient also satisfies the normal distribution, and γ is shown as $(\bar{\gamma}, S_\gamma)$.

Supposing the fatigue limit of standard sample material is $(\bar{\delta}_r, S_{\delta_r})$ measured by the tests, then the fatigue limit of valve parts is $(\bar{\delta}_{re}, S_{\delta_{re}})$. The fatigue limit of s material combined with all the above factors can lead to

$$(\bar{\delta}_{re}, S_{\delta_{re}}) = \gamma(\beta \cdot \varepsilon / K_f)(\bar{\delta}_r, S_{\delta_r}) \quad (14)$$

Where $(\bar{\delta}_{re}, S_{\delta_{re}})$ is the fatigue limit of valve parts.

3. Finite element analysis of HMDCV

3.1 Basic properties of materials

Finite element software was used to analyze the fatigue life of the object, mechanical properties and physical properties of materials for each parts should be confirmed, it ca be showed by Tab.1.

Table 1. Mechanical properties and physical parameters of parts material

Parts	Material	σ_b /MPa	σ_s /MPa	E/GPa	Poisson ratio
Pressure parts	WC6	485	275	207	0.30
Valve stem	13Cr	485	275	197	0.29

3.2 Numerical simulation analysis of thermal - structure coupling

3.2.1 Model establishment and mesh generation. The overall structure of HMDCV is so symmetry and regular that it can be taken half model to analyze by finite element method. Because complex structure of HMDCV and large number of grid number can obvious influence on calculation speed, it should uses unstructured tetrahedral mesh which has the advantages of fast, automatic generation and refinement to mesh.

3.2.2 Setting and solving of boundary conditions. The objective of thermal analyze to HMDCV is to get basic data for fatigue reliability. Inner wall temperature of HMDCV is 425°C in actual work situation and it can be set to medium temperature in calculation condition, the reference temperature of environment can be set to 27°C, adiabatic condition is applied on symmetry plane. Middle flange and outer surface of the HMDCV are wrapped by insulation layer and applied on adiabatic boundary condition. The boundary condition of parts above valve cover is natural convection heat transfer with normal environment [4]. The temperature distribution on HMDCV should be the first solved.

The boundary condition of thermal - structure coupling for HMDCV can be set as follows

(1) Thermal analysis results are imported to the analysis of structural statics and as to one of set boundary condition,

(2) Constraint condition is set on the symmetry plane,

(3) Displacement constraint is set on the HMDCV end faces of inlet and outlet,

(4) Constraint condition is set on the bottom of HMDCV,

(5) The medium pressure 12.53MPa is imposed on inner surface of valve body,

(6) Bolt force is imposed on flange connection in HMDCV.

3.2.3 Analysis of simulation results. Nephogram of thermal stress distribution on valve body, valve core and sleeve can be gotten by numerical simulation. The stress value of the dangerous parts are selected to calculating stress response value through analyzing above parts on the nephogram according to 3 times the standard deviation principle. The calculation results are shown in Tab.2.

Table 2. Stress cycle parameters of parts key nodes

Parts	$\bar{\sigma}_{\max}$ /MPa	$\bar{\sigma}_{\min}$ /MPa	$\bar{\sigma}_m = \bar{\sigma}_a$ /MPa	$S_{\sigma_m} = S_{\sigma_a}$ /MPa	$\bar{\sigma}_r$ /MPa	S_{σ_r} /MPa
Valve body	124.07	0	62.04	1.034	87.74	1.034
Valve core	65.15	0	32.58	0.543	46.08	0.543
Sleeve	85.19	0	42.60	0.710	60.25	0.710

3.2.4 Fatigue reliability calculation. According to related literatures and theoretical calculation mode in Section 1.3, correction factors in formula are determined as be shown in Tab.3. Fatigue limit of materials is known, the fatigue limit of parts can be calculated if temperature correction coefficient be considered according to the datum in Tab.3. It can calculate the part reliability combining with the stress limit in Tab.2. The calculated results are shown in Tab.4.

Table 3. Fatigue limit calculations of parts

Parts	Effective stress concentration factor	Dimension coefficient	Surface processing coefficient	Temperature correction coefficient
Valve body	(1.215,0.020)	(0.768,0.026)	(0.841,0.028)	(0.948,0.031)
Valve core	(1.768,0.030)	(0.619,0.021)	(0.772,0.026)	(0.948, 0.031)
Sleeve	(1.647,0.028)	(0.657,0.022)	(0.879,0.029)	(0.948, 0.031)

There are the results of fatigue reliability contrast to if temperature influence which is considered in Tab.4 can be seen, fatigue reliability is obviously reduced introducing temperature correction coefficient. It proves that the reliability calculation results can be more accurate considering the temperature influence.

Table 4. Data and results of parts fatigue limit

Parts	Unconsidered temperature correction factor		Considered temperature correction factor	
	Fatigue limit /MPa	Reliability	Fatigue limit /MPa	Reliability
Valve body	(147.47,14.18)	0.948665	(139.80,12.69)	0.947748
Valve core	(80.79,7.66)	0.956908	(76.58,6.95)	0.948665
Sleeve	(103.55,9.84)	0.954332	(98.16,8.91)	0.948263

3.3 Numerical simulation analysis of fatigue life

3.3.1 Boundary condition setting. The boundary condition of the fatigue life analysis can be set base on the numerical simulation result of thermal - structure coupling [5], it be listed as follows

- (1) To define the maximum number of boundary conditions and load,
- (2) To define fatigue properties of the material parameters consisted of elastoplastic parameters, temperature stress curve, stress life curve (S-N curve),
- (3) To make sure stress position and define stress concentration coefficient,
- (4) To make sure the stress in different loads and working conditions at potential fault location, and set up repetitions and proportionality coefficient of events.

3.3.2 Fatigue life analysis. The fatigue life distribution nephogram of valve body is shown in Fig.1, it can be seen that the shorter life spans of valve body are located the transition place of inlet between upper cavity, bottom cavity between outlet. The result agrees with the actual situation. The shortest life is 58836 times exceeding 10000 times regulated by technical requirement. So the valve body's life in fatigue load meets the requirements.

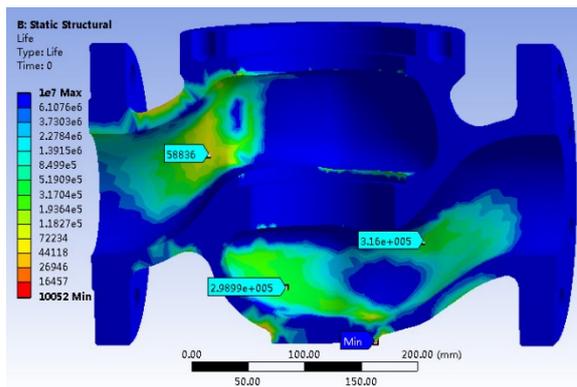


Figure 1. Valve body fatigue life distribution

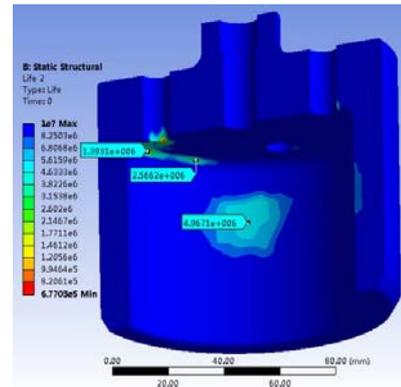


Figure 2. Valve core fatigue life distribution

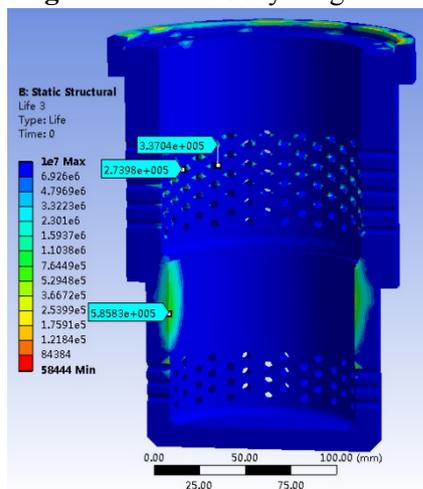


Figure 3. Sleeve fatigue life distribution

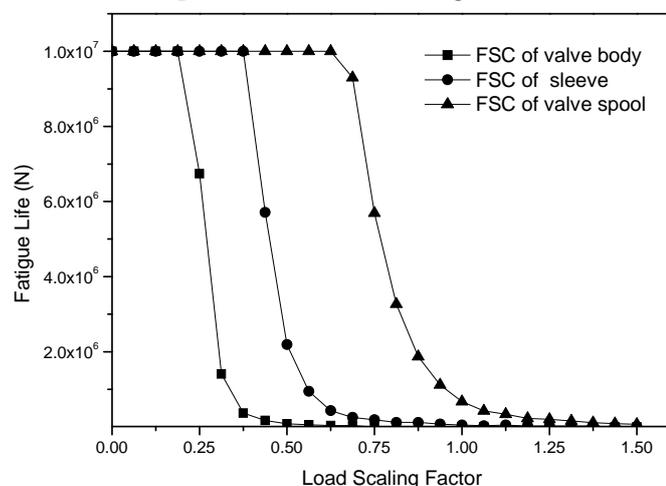


Figure 4. Fatigue life sensitivity curves

The fatigue life distribution nephogram of valve core is shown in Fig.2, it can be seen that the shorter life spans of valve body are located the transition place of the bottom and the structure with abrupt change. The shortest life is $6.77e5$ times more than 10000 times regulated by technical requirement. So the valve core's life in fatigue load meets the requirements.

The fatigue life distribution nephogram of the sleeve is shown in Fig.3, it can be seen that the shorter life spans of valve body are located the transition place of the boss edge and the upper end of the sleeve. The shortest life is 58444 times exceeding 10000 times regulated by technical requirement. So the sleeve's life in fatigue load meets the requirements.

Contrast to the fatigue life of valve body, valve core and sleeve can be seen that the life of valve core is the longest more than valve body and sleeve. The life of sleeve is 58444 less than 58836 times of valve body's life. So the sleeve is more easily fatigue failure than valve body.

3.4 Reliability sensitivity analysis of HMDCV

The curve of fatigue sensitivity can show the change that life, damage and safety factor of parts follow with load changing in critical region. The sensitivity curve of fatigue life for three components can fitting with fatigue life analyzed in the Section 2.3. It is shown in Fig.4.

From Fig.4, it can be seen that the life curve of valve boy, valve core and sleeve have a horizontal line while load scaling factor is less, and the fatigue life hasn't changing follows with the increasing of load scaling factor. There has a critical value in the increasing process of load scaling factor, the fatigue life begin to reduce at the critical value and it will reduce in logarithmic trend along with rising of load scaling factor^[11,12].

Influence specific gravity of parts for system reliability ca be calculated by contrasting fatigue sensitivity in Fig.4, it be shown in Tab.5.

Table 5 Parts fatigue life sensitivity parameter list

Parts	Decay point of life	Lift on 150% load	Influence specific gravity
Valve body	Load value 18.5%	2.90e3	0.489
Valve core	Load value 62.5%	1.09e5	0.072
Sleeve	Load value 37.5%	1.54e4	0.440

From Tab.5, it can be seen that minimal ineffective influence in system of HMDCV is valve core, ineffective influence relatively large are valve body and sleeve.

4. Conclusions

The research aims at fatigue strength reliability of the HMDCV. The following conclusions can be drawn from the present study.

(1) By considering the influence for fatigue limit of materials about size, surface processing and stress concentration, it makes theoretical calculation value of reliability introducing temperature correction coefficient.

(2) According to analysis result of fatigue life, predicted life of main pressure parts meets the requirements. It can be seen that valve body and sleeve have more influence to the system of the HMDCV through analyzing fatigue life sensitivity curve, so it should be optimized for structure and serviced regularly.

(3) There are complex structure in the HMDCV and main pressure parts exist the obvious phenomenon of stress concentration, it should reduce structural sudden change and ensure strength assurance to reduce stress concentration in the design phase.

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