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To cite this article: Peng Du *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **569** 032027

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Research on the Optimization Design of Metallic Gasket Based on DOE Methodology

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Abstract: In the present study, the method of simulation and Statistical Design of Experiment (DoE) combined approach has been applied to investigating the influence of metallic gasket, flange and bolt on sealing performance. In order to analyze the influence of wavy shape, bolt distribution, wavy height, gasket thickness, top flange thickness, top flange material, gasket materials and bottom flange material, the contribution degree of each factor to the bolt axial force and pressure distribution was taken as the evaluation index. Research results show that the corrugated shape and bolt distribution have the greatest influence on the pressure distribution of gasket and the range of the bolt axial force.

1. Introduction

Metallic gasket seal are widely used, because of its excellent performance, in the working environment including low temperature, high temperature, high pressure and other harsh working conditions, high sealing requirements and other requirements which non-metallic gasket form is difficult to meet [1]. In the fields of aviation, aerospace, automobile, nuclear power, petroleum, chemical industry and construction machinery, pressure vessels, pipelines and valves, Metallic Gaskets are usually taken as the first choice[2].

The design method of sealing system in which metallic gasket is selected as a gasket has been using the design standard of non-metallic gasket[3-8]. Different gasket coefficients are proposed in different standards, which leads to the need to evaluate and analyse gasket measured data in the actual design process of the sealing system. This makes the design and failure analysis difficult.

If the sealing system is composed of metallic gaskets and flanges, there are many factors affecting the sealing performance such as wavy shape, bolt distribution, wavy height, gasket thickness, top flange thickness, top flange material, gasket materials, bottom flange material. Previous studies on metal gaskets have established that the contact width, contact stress, and surface roughness are important design parameters for optimizing gasket performance[9-14].



This paper aims to study the influence of gasket parameters include wavy shape, bolt distribution, wavy height, gasket thickness, top flange thickness, top flange material, gasket materials, bottom flange material on the distribution of gasket contact pressure.

2. Analysis and validation

2.1. Distribution test of seal pressure

The Fujifilm was selected to test the pressure distribution of the sealing system of a certain type of engine. The shape of the test gasket and the corrugated shape of the cross section are shown in figure 1.

The axial force of bolts was indirectly controlled by torque control in the test. The preset value of axial force of bolts was 18kN. Due to the error, the actual range of axial force was between 13.5kN~22.5kN. The display range of medium pressure film pressure is 0MPa~50MPa, and the display range of high pressure film pressure is 50MPa~130MPa. The test results of medium pressure film and high pressure film are shown in figure 2 and figure 3 respectively. It shows that the pressure distribution of the gasket is very uneven. The pressure distribution on the front of the gasket is relatively weak, and the pressure in the lower left corner is the lowest. Discontinuity of the sealing belt appears on the opposite side of the gasket.

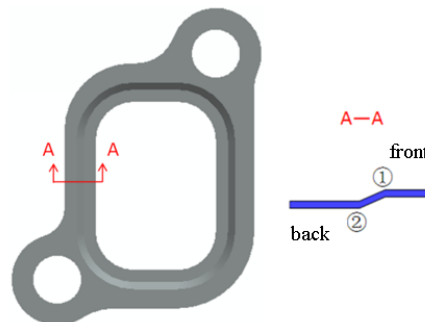


Figure 1. Structure of metallic gasket

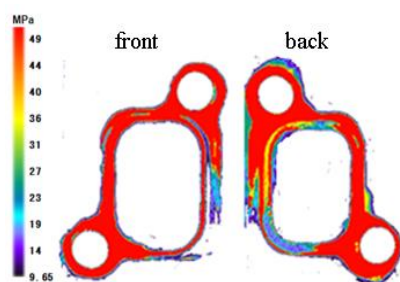


Figure 2. Distribution of sealing pressure under medium pressure film

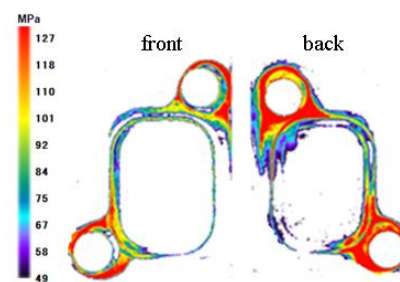


Figure 3. Distribution of sealing pressure under high pressure film

2.2 The simulation calculation

The Fujifilm used in the test is a static pressure film, which has the characteristics of instantaneous color development under load, so the test results cannot accurately reflect the pressure distribution under the final mounting state of the gasket. It is affected by the whole loading process and the color effect of gasket. In order to make the calculation method reasonably verified by pressure distribution test, the calculation is set as process calculation.

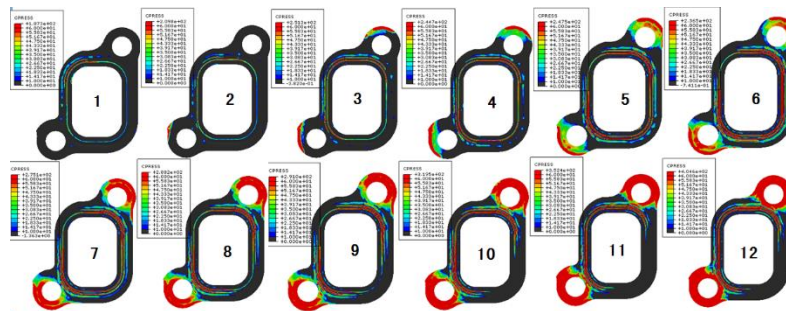


Figure 4. Variation of pressure distribution on the front of gasket with the change of the bolt axial force

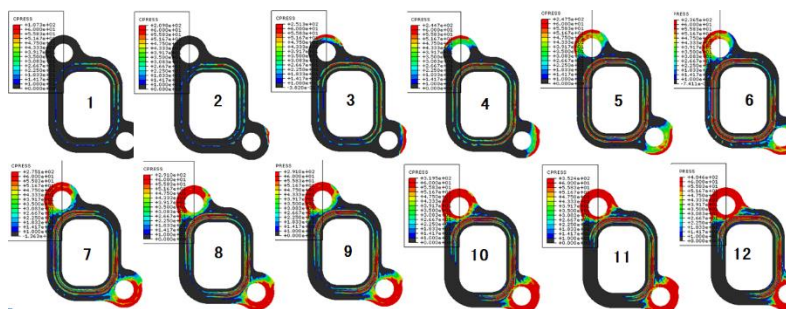


Figure 5. Variation of pressure distribution on the back of gasket with the change of the bolt axial force

The axial force of the bolt is gradually increased from 0kN to 25kN according to the physical modeling. It makes the result accurately which reflect the change of the contact pressure of the gasket during its being compressed by bolts. The calculation results are shown in Fig.4 and Fig.5 respectively.

Table 1. bolt axial force

No	1	2	3	4	5	6
bolt axial force (N)	1105.9	2283.4	6670.0	9958.1	11763.7	13961.8
No	7	8	9	10	11	12
bolt axial force (N)	15731.3	17590.1	19294.2	21237.1	23513.2	24918.0

2.3 Validation of calculated results

With the increase of the bolt axial force, Fig.4 and Fig.5 respectively show the changes of the pressure distribution on the front and back of the gasket. The values of the bolt axial force corresponding to the 12 working conditions are shown in table 1. The color rendering range of the cloud image is set as 10MPa~60MPa, and the pressure area higher than 60MPa is shown in red.

It can be seen from the calculation results that in the process of the bolt axial force from small to large, the pressure on the front and back of the gasket changes constantly, and the sealing belt at the metal corrugated of gasket changes from the initial non-closure to closure, and then from closure to non-closure. The pressure distribution on both sides of the gasket in working conditions 8 and 9 is consistent with the test results. At this point, the axial force range of the bolt is 17.5kN~20kN.

Table 2. The factors and levels (low and high)

factor	Test parameters							
	wavy shape	wavy height (mm)	Bolt distribution	gasket thickness (mm)	top flange thickness (mm)	Top flange material	Gasket materials	Bottom flange material

-1	half wavy cross section	0.4	diagonal distribution	0.25	20	HT250	10	HT250
1	Arc cross section	0.3	Center distribution	0.35	15	YL112	12Cr17Ni7	YL112

According to the statistical theory, it can be concluded that the probability of the bolt axial force is within this range after the gasket is installed during the pressure distribution test. Due to sufficient time for color development in the final state of gasket installation in the test, the pressure distribution of gasket is shown to be the most sufficient. In addition, the influence of gasket installation process on the film makes the difference between the test results and the calculated results. In summary, the calculated results are consistent with the pressure distribution test results, and the calculation method adopted is reasonable.

3. Optimization module

3.1 Establishment of simulation model

The original calculation model was simplified and five factors including wavy shape, bolt distribution, wavy height, gasket thickness and top flange thickness. In addition, the influence of three factors such as top flange material, bottom flange material and gasket material on sealing effect is considered. All the above eight factors were set as -1 and 1, and the specific values were shown in table 2. The DOE test method was adopted to design 16 sets of calculation schemes. The specific calculation schemes are shown in table 3.

3.2 Effect of bolt axial force

The applicable range of bolt axial force is that the sealing pressure belt at the gasket ripple is closed within a certain range of bolt axial force and the minimum pressure is not less than 5MPa. The actual axial force of the bolt is about 18kN, and there is 25% deviation due to controlling the axial force by torque.

For the convenience of grading, the axial force of the bolt is considered to be in line with the normal distribution of $X \sim N(18,1)$. The upper limit of the bolt axial force is set as 25kN because only the bolt axial force within the range of 0~25kN is calculated. The actual score is 10 times the area occupied by the axial force in the normal distribution.

Table 3. The program of computer simulation

No	wavy shape	wavy height (mm)	Bolt distribution	gasket thickness (mm)	top flange thickness (mm)	Top flange material	Gasket materials	Bottom flange material
1	half wavy cross section	0.4	diagonal distribution	0.35	15	HT250	10	YL112
2	Arc cross section	0.4	diagonal distribution	0.25	20	HT250	12Cr17Ni7	YL112
3	half wavy cross section	0.35	diagonal distribution	0.25	15	HT250	12Cr17Ni7	YL112
4	Arc cross section	0.35	diagonal distribution	0.35	20	HT250	10	YL112
5	half wavy cross section	0.4	Center distribution	0.35	20	HT250	12Cr17Ni7	YL112
6	Arc cross section	0.4	Center distribution	0.25	15	HT250	10	YL112
7	half wavy cross section	0.35	Center distribution	0.25	20	YL112	10	YL112
8	Arc cross section	0.35	Center distribution	0.35	15	YL112	12Cr17Ni7	YL112
9	half wavy cross section	0.4	diagonal distribution	0.25	20	HT250	10	HT250
10	Arc cross section	0.4	diagonal distribution	0.35	15	HT250	12Cr17Ni7	HT250

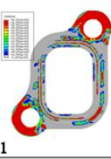
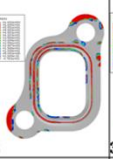
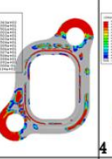
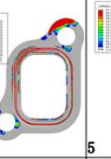
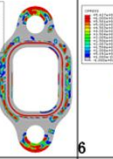
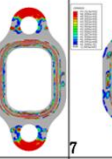
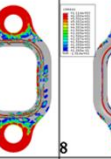
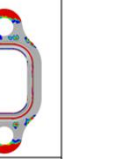
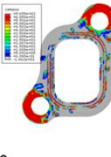
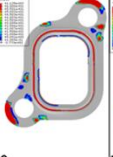
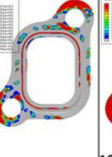
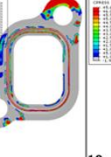
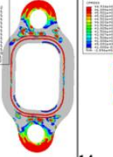
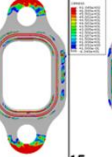
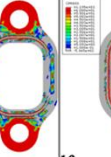
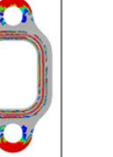
11	half wavy cross section	0.35	diagonal distribution	0.35	20	YL112	12Cr17Ni7	HT250
12	Arc cross section	0.35	diagonal distribution	0.25	15	YL112	10	HT250
13	half wavy cross section	0.4	Center distribution	0.25	15	YL112	12Cr17Ni7	HT250
14	Arc cross section	0.4	Center distribution	0.35	20	YL112	10	HT250
15	half wavy cross section	0.35	Center distribution	0.35	15	HT250	10	HT250
16	Arc cross section	0.35	Center distribution	0.25	20	HT250	12Cr17Ni7	HT250

For the convenience of grading, the axial force of the bolt is considered to be in line with the normal distribution of $X \sim N(18,1)$. The upper limit of the bolt axial force is set as 25kN because only the bolt axial force within the range of 0~25kN is calculated. The actual score is 10 times the area occupied by the axial force in the normal distribution.

3.3 Effect of design scheme on pressure distribution

The calculation results when the bolt axial force is 18kN are analyzed and the effect of different schemes is graded according to the distribution of gasket contact pressure. The distribution results of different schemes and scores are listed in table 4.

Table 4. Contact pressure distribution and scoring of different schemes

Sealing pressure								
score	3	10	2	10	10	10	6	10
Sealing pressure								
score	4	10	4	10	8	10	6	10

3.4 Analysis of the contribution values of each factor

The contribution values of each factor to the applicable range of bolt axial force and the pressure distribution under the axial force of 18kN are shown in table 5.

Table 5. contribution value analysis

	wavy shape	wavy height (mm)	Bolt distribution	gasket thickness (mm)	top flange thickness (mm)	Top flange material	Gasket materials	Bottom flange material	Score of axial force	Score of pressure distribution
1	-1	-1	-1	1	1	1	-1	1	0	3
2	1	-1	-1	-1	-1	1	1	1	10	10
3	-1	1	-1	-1	1	-1	1	1	0	2
4	1	1	-1	1	-1	-1	-1	1	10	10
5	-1	-1	1	1	-1	-1	1	1	10	10
6	1	-1	1	-1	1	-1	-1	1	10	10
7	-1	1	1	-1	-1	1	-1	1	0	6
8	1	1	1	1	1	1	1	1	10	10

9	-1	-1	-1	-1	-1	-1	-1	-1	0	4
10	1	-1	-1	1	1	-1	1	-1	1.7	10
11	-1	1	-1	1	-1	1	1	-1	0	4
12	1	1	-1	-1	1	1	-1	-1	10	10
13	-1	-1	1	-1	1	1	1	-1	9.8	8
14	1	-1	1	1	-1	1	-1	-1	10	10
15	-1	1	1	1	1	-1	-1	-1	0	6
16	1	1	1	-1	-1	-1	1	-1	10	10
51.90 -11.50 28.10 -8.10 -8.50 8.10 11.50 8.50									The contribution of different factors to the applicable range of bolt axial force	
37.00 -7.00 17.00 3.00 -5.00 -1.00 5.00 -1.00									The contribution of different factors to the pressure distribution	

The most prominent factors influencing the applicable range of bolt axial force and the pressure distribution are the wavy shape and the bolt distribution. The sealing effect can be improved obviously by using Arc cross section and bolt centered distribution. The decrease of the wavy height and top flange thickness will have an adverse effect on gasket seal. The increase of gasket thickness has an adverse effect on the axial force of the bolt, but it can improve the pressure distribution. When the top flange and bottom flange are made of soft materials, it has a slight adverse effect on the pressure distribution, but it has obvious improvement effect on the applicable range of bolt axial force. If the gasket is made of materials with good elasticity and high yield strength, ideal results will be obtained.

4. Conclusions

The main conclusions of the study are listed below:

(1)The results of FEM of the sealing system which selected metallic gasket are verified by FUjifilm test. The calculated results are consistent with the pressure distribution test and the calculation method adopted is reasonable.

(2)With the pressure distribution and the applicable range of bolt axial force as evaluation indexes, eight factors including wavy shape, bolt distribution, wavy height, gasket thickness, top flange thickness, top flange material, gasket materials, bottom flange material were studied with DOE.

(3)The contribution degree of each factor in different schemes is analyzed comprehensively. The research results show that adopting the form of arc cross section and bolt centered distribution can greatly improve the sealing performance. The decrease of wavy height and the top flange thickness will have an adverse effect on gasket seal. The increase of gasket thickness will have a negative impact on the range of the bolt axial force, but it will improve the pressure distribution. If the soft material is used as the material of the top flange and the bottom flange, it will have a slight adverse effect on pressure distribution of gasket, but it will improve the applicable range of bolt axial force. If the material with good elasticity and high yield strength is used as the gasket material, it will have a favorable influence on the range of the bolt axial force and the distribution of the gasket pressure.

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