Leakage Analysis on Non-axisymmetric Gasket of the Shell-tube Heat Exchanger Header

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Abstract: This paper focuses the flanged static sealing structure of shell-tube heat exchange header, builds an static sealing model based on FEM(Finite Element Method), studies the effect of bolt preload and working medium load on the gasket actual contact stress. The results indicate that: an approximately linear relationship exists among the gasket contact stress, bolt preload and working medium load. When the pressure is gradually increasing, the flat end-plate’s outward convex deformation results in the decreasing gasket stress in the center and even leakage. After locating the above leakage reason, the flange gasket structure is improved, and the bolt distribution and bolt preload is adjusted accordingly. The problem of leakage has been solved, approves that the calculating method of gasket sealing is an effective approach.

Key Words: Dry Evaporator; Non-axisymmetric Gasket; Static Sealing; Finite Element Analysis

1. Introduction
The sealing performance of gasket for shell-tube heat exchanger header is one of the critical factors affecting the efficiency of its heat exchange. Good sealing provides a great guarantee for reliability of heat exchanger. The bolt of double-system shell-tube heat exchanger has a complicated flanged sealing structure [1]. Due to changing working conditions, it is necessary to seal water and cold medium in areas, but gasket sealing is not sufficiently reliable to prevent leakage, blow-by and other failures.

In the calculation for gasket sealing design, it is therefore difficult to accurately predict the gasket leakage of shell-tube header. Traditional design methods rely on empirical design together with water pressure test, and utilize copy paper or FUJI paper to assess the sealing performance of gasket [2], which makes it difficult to satisfy the requirements for delicate design. For this reason, an analytic method should be studied to accurately predict gasket leakage.

When finite element method is employed to resolve the failure of gasket sealing in flanged structure [3-5], most studies focus on metallic axisymmetric flat gasket, which features evenly distributed load. Du et al. [6] studied how the sealing of flat gasket is affected by gasket thickness and preload, and introduced the axial displacement of gasket as a criterion in leakage evaluation. Gu et al. [7-8] studied the influence of maximum stress at the outer edge of gasket on the leakage rate of blot flanged structure. All these studies address the issue of external sealing with leakage caused by external environment, and can be simplified for solution in axisymmetric model. With regard to heat exchanger structure with non-
axisymmetric tube bundle [9], it is required to not only resolve the problem of external sealing, but also deal with the gasket sealing in some areas inside heat exchanger header. At present, there is not yet any published study on resolving the internal and external sealing problem of non-axisymmetric gasket model.

This paper addresses the non-axisymmetric gasket leakage of shell-tube heat exchanger header, creates a method for predictive analysis of gasket leakage, and studies the relationship of contact stress on non-axisymmetric gasket with bolt preload and medium load. It provides guidance for arrangement of flanged header bolts and design of bolt preload, improves the sealing performance of gasket, verifies the reliability of gasket sealing model and leakage prediction and analysis method. This proposed method provides significant guidance for design as well.

2. Finite Element Modeling

2.1. Basic Parameters of Heat Exchanger Header
A double-system dry evaporator header structure is as shown in Fig. 1. It consists of external end plate, cylinder, gasket, and internal tube plate. With internal bars, it is partitioned into three independent areas. External end plate has a large-diameter hole at top, which is cold medium outlet of system 1, and a small-diameter hole at bottom, which is cold medium inlet of system 1. The U-shaped copper tubes are arranged on tube plate to realize the inflow and outflow of cold medium on the same side. The normal operation of evaporator depends much on the integrity of load bearing in sealing structure.

![Figure 1. Structure of the Dry Evaporator Header.](image)

Among them, 27 ordinary steel bolts M16 are located to restrict at the periphery of internal tube plate and external end plate and middle bars, and hold cylinder and gasket tightly for sealing. According to the national standard GB/T 3098.1-2000, the torque of bolt preload must be 220N.m.

Tube plate, cylinder and end plate are all made of Q345 steel, while gasket is 3mm thick VALQUA V6500 asbestos free gasket [10]. The compression-rebound curve of V6500 gasket measured in tests is shown in Fig. 2. When load is applied and removed, the gasket is highly nonlinear.

![Figure 2. Compression - Rebound Curve of the V6500 Gasket.](image)
2.2. Finite Element Model for Structural Analysis
The finite element model of header is shown in Fig. 3. The solid parts use Solid185 element, and the gasket uses Inter195 low-order element. Contact pairs are formed among external end plate, cylinder, gasket and internal tube plate. Contact elements are Target170 and Target 174 in the type of Rough touch and with Normal Language Algorithm.

The working pressure of this dry evaporator is 2.30MPa. According to the requirements of regulations for test of pressure vessel, water pressure test must have the pressure 1.5 times of working pressure. When the pressure is increased to 3.45MPa, clear leakage is noticed. After disassembly and check, shell-tube and flange have no clear deformation or crack. To further ascertain the reason for leakage, the loading process of header model is simulated by first applying bolt preload F. Based on the conversion formula of bolt torque T and preload F [11], a preload F=68750N is applied onto each bolt. Thereafter, working pressure is gradually increased to 3.45MPa on the interior wall of system 1 on the basis of pre-stress.

![Figure 3](image)

**Figure 3.** Finite Element Model of Header.

2.3. Contact Surface Pressure of Gasket
Contact surface pressure of gasket is an important indicator for sealing performance of gasket. According to the principles of force balance, sealing structure can ensure sealing performance under critical condition that the contact surface pressure σ on the contact surface of gasket equals to the pressure of working medium P. Hence, sealing performance of structure can be guaranteed only if $\sigma \geq P$ is satisfied.

3. Result Analysis

3.1. Analysis on Contact Stress of Gasket
Under the effect of bolt preload, the external ring of gasket has the maximum surface pressure, up to 66.01MPa, as shown in Fig. 4(a). Meanwhile, the external ring surface pressure of gasket is greater than the surface pressure inside the ring, with the minimum contact surface pressure of 11.58MPa at the middle bar inside system 1. Based on the preload of header, a stress of 3.45MPa is applied onto the interior wall of system 1, and its results are shown in Fig. 4(b). The minimum contact surface pressure of gasket at the middle bar inside system 1 drops to 2.05MPa, down by 82.30%, which is already lower than the pressure of working medium 3.45MPa, so that header leakage occurs, which matches with the known test result. The load of working medium results in uneven distribution and decrease of contact pressure stress of gasket in system 1.
3.2. Relationship between Gasket Contact Stress Impacts

To further confirm the reason for leakage, a group of analysis data for orthogonal contrast is designed for gasket surface pressure, preload, and medium load. Eleven samples for orthogonal contrast are taken to calculate the data under the preload $T=220\text{N.m}$ when medium load is $P=\{2.40, 2.70, 3.00, 3.20, 3.45, 3.60\}\text{MPa}$, and the data under the medium load $P=3.45\text{MPa}$ when preload is $T=\{170, 180, 190, 200, 210, 220\}\text{N.m}$.

Under the preload $T=220\text{N.m}$, the analysis results of medium load are shown in Fig. 5. The minimum contact surface pressure at the middle bar inside system 1 has an approximately linear relationship with medium load, and decreases along with the increase of medium load. When medium load equals to 3.0MPa, the minimum contact surface pressure at the middle bar is 3.0MPa, which is the critical condition for gasket leakage. When medium load is greater than 3.0MPa, the minimum contact surface pressure at the middle bar is lower than medium load, so that header leakage will occur, which matches with test results.

**Figure 5.** The Relationship Curve Between Gasket surface Pressure And Medium Load.

Under medium load $P=3.45\text{MPa}$, the analysis results of bolt preload $T$ are presented in Fig. 6. The contact surface pressure of gasket has an approximately linear relationship with bolt preload. The maximum surface pressure of external ring of gasket $P_{\text{max}}$ and the minimum surface pressure inside ring $P_{\text{min}}$ increase together with bolt preload $T$.

**Figure 6.** Surface Pressure of Gasket under Bolt Preload
Based on the relationship of gasket surface pressure with bolt preload and medium load, it is judged that gasket leakage occurs for the following reasons: bolts are arranged scarcely at middle bar between systems, undermining their ability to control the outward convex deformation of external end plate. The deformation increases gradually with the increased medium load. When the contact surface stress of gasket at middle bar drops to below medium load, it causes leakage.

4. Structural Improvement and Analysis

4.1. Model Improvement
Based on the analysis of the above reasons, it is necessary to relocate middle bar to restrict the influence of outward convex deformation of external end plate. The dry evaporator must be checked in 3.45MPa water pressure test, so that bolts of larger diameter must be selected to further improve bolt preload, so as to increase the minimum contact surface pressure at middle bar of gasket.

The following design improvement is made to the original model as shown in Fig. 7. Bolts are changed from M16 to M20. According to the national standard GB/T 3098.1-2000, the bolt torque T is also adjusted to 350N.m. Using the conversion formula of torque in Reference [11], the force applied to each bolt is F=87500N. At the middle bar inside system 1, one bolt is added to increase the constraint. Hence, the total number of bolts increases from 27 to 28.

4.2. Calculation Results of Improved Model
As shown in Fig. 8(a), the minimum contact surface pressure at the middle bar of gasket after improvement is 17.79MPa, which is 6.21MPa higher than before, while the maximum contact surface pressure is 69.10MPa at the external ring of gasket.

As shown in Fig. 8(b), a pressure of 3.45MPa is applied onto the interior wall of header system 1 on the basis of preload. The surface pressure drops at both internal and external rings of gasket system 1. The minimum surface pressure of middle bar drops to 9.59MPa, down 46.09% compared to preload, and 82.30% lower than before. In other words, improvement has improved the ability to restrict the outward convex deformation of external end plate. The analysis shows that the minimum contact surface
pressure of gasket is 9.59MPa under preload 350N.m and medium load 3.45MPa, which is much higher than working pressure 3.45MPa. Hence, improved gasket sealing is favorable.

(a) Gasket Surface Pressure under Bolt Preload
(b) Gasket Surface Pressure under Medium Load

Figure 8. The Stress Result of Improved Gasket Sealing Model.

5. Conclusion
After building a non-axisymmetric sealing model of header, this paper addresses the influence of bolt preload and medium load on the contact surface pressure of gasket and comparatively analyzes the numerical analysis results after improving the sealing structure of gasket. Conclusions are drawn as follows:

1. After bolt pre-tensioning, gasket structure and bolt arrangement affect the distribution of pressure on gasket contact surface. Due to the bolt distribution at middle bar of external end plate and the deformation of external end plate under load, the contact surface pressure at gasket middle bar is lower than that at its periphery, so that its sealing performance is poorer than that at external ring;

2. The contact surface pressure of gasket has an approximately linear relationship with bolt preload and medium load. It increases when bolt preload increases, but decreases when medium load increases.

The modeling and calculation method for non-axisymmetric gasket sealing has been successfully applied in the selection and design of shell-tube heat exchanger header gasket, and has resolved the problem of shell-tube leakage and blow-by. Hence, it provides favorable reference for predictive analysis of gasket leakage.

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