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Three-Dimensional FEM and Close Property Analysis of Bolted Flange Connectors

Ruifeng Cao [a], Liangmeng Zhang, Ruyuan Qiu [b]

College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao 266590，China.

[a]b15271912012@163.com, [b]240371902@qq.com

Abstract: In this paper, the bolted flange connecting parts of the tube-plate in the shell heat exchanger are studied, The standard high neck equipment flange is used as the base flange of the analysis, considering the non-linear character of gasket material and the contact relationship between the components (a non-linear relation), The static analysis of 10 kinds of components, such as bolts, flanges, gaskets and tube plates, was carried out by using ANSYS finite element analysis software. Through the finite element analysis of bolted flange connectors, the results show that: The stress distribution trend of bolted flange connectors is basically consistent with the preload and internal pressure conditions, With the increase of internal pressure, the stress intensity of each part increases, and the deformation of flange and bolt increases. The preload and the residual compressive stress of the gasket are uneven along the radial and circumferential distributions under the preload and the tube-shell process pressure difference, With the increase of the pressure difference of the tube-shell, the residual compressive stress in the inner part of the tube-gasket is reduced sharply, which leads to the infiltration of the heat transfer medium into the sealing surface of the flange and the gasket.
Keywords: bolt flange; shell-and-tube heat exchanger; gasket; nonlinearity; strength; tightness

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1. INTRODUCTION

In the petrochemical field, bolted flange connections are widely used in pressure vessels and pipelines in industries such as chemical industry and oil refining. As the structure of the connection seal, the connection is required to have reliable tight performance and sufficient strength. Due to the bolt preload and operating conditions under the medium pressure, temperature and the additional bending moment and additional axial force of the pipe system, the joint is prone to leakage, resulting in sealing failure. Not only waste energy, pollute the environment, even lead to catastrophic accidents. In 2001, according to statistical data shows that 25% of the leakage accident occurred during the installation phase, 75% occurred in the operational phase, and all the leakage accident occurred in 17% of the bolt flange connection location, it can be seen that the fastening seal of bolted flange is very important to guarantee the safe operation of pressure vessel.

2. ESTABLISHMENT OF THREE-DIMENSIONAL FINITE ELEMENT MODEL FOR BOLTED FLANGE CONNECTORS

In this paper, the high neck flange is chosen as the base flange of the analysis, which is convenient for comparison and reference, and the is shown in Fig. 1.1. Flange Joint Sealing form is concave-convex surface, withstanding internal pressure for PN =4.0MPa. The main dimensions of bolted flange connectors are as follows:

D=660mm，D_N=500mm，D_1=615mm，D_2=576mm，D_3=566mm。

Thickness of flange ring δ=46mm;Fillet radius of flange root R=12mm ;Flange ring Width δ_1=26mm ;Flange Ring Small End width δ_2=16mm ;Flange Ring Cone Neck height h=35mm ;Diameter of Bolt hole d=27mm ;Bolted flange connectors are selected as M24, number are 24;The thickness of the gasket δ_3 =3mm ;The width of the gasket N =25mm ;Diameter of tube plate D_4=563mm ;Thickness of tube plate δ_4=64mm.

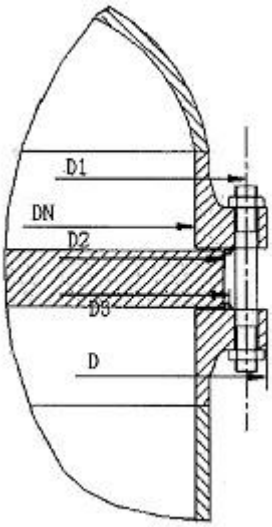

Fig. 2.1 Size diagram of Flange

Because the bolt flange joint belongs to the axisymmetric structure, if the whole mode is chosen, the computer calculation is large, in order to reduce the calculation quantity, the symmetrical flange ring structure of a bolt is chosen, which is one-twenty Fourth of the whole flange to establish the finite element model. The model includes the bolts between the two sections, the upper and lower nuts, the upper and lower method Lan, the sealing head and the flange ring connecting the cylinder and the tube plate. The length of the cylinder is based on Saint Venant's principle, which can eliminate the effect of axial stress at the edge of the cylinder on the stress distribution of the flange.

The model in this paper is more complex and needs to use three dimensional solid elements. The total number of elements is 121933, and the total number of nodes is 183411. Five kinds of element types are adopted in the bolt flange joint: SOLID95 structure entity element, PRETS179 bolt pretightening element, INTER194 pad element, CONT174 contact surface element and TARG170 target surface element.

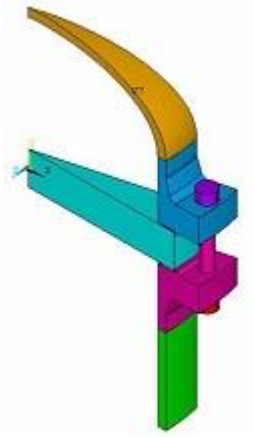

Fig. 2.2 Solid model of bolted flange joint

Fig. 2.3 Three-dimensional finite element model of bolted flange joint

3. BOUNDARY CONDITIONS OF BOLTED FLANGE CONNECTORS

The pipe plate is a non linear elastic element, the gasket is a non linear elastic element, the gasket coefficient is 2, and the rest are linear elastic materials. As shown in table 1-2.

Table 3.1 Material properties of the elastic elements of each line

Component Name	Material	Modulus of Elasticity E	Poisson Ratio μ	σ（MPa）	Sm（MPa）
Flange Ring	16Mn	2.1e11	0.3	450	150
Cylinder	16MnR	2.1e11	0.3	765	163
Head	16MnR	2.1e11	0.3	765	163
Bolt	40MnB	2.1e11	0.3	490	212
Nut	40Mn	2.1e11	0.3	490	212
Tube Sheet	Equivalent Material	5.376e10	0.355	450	150

Due to space limitations, the calculation of the modulus of elasticity and Poisson's ratio of the tube sheet material is neglected here.

The material properties of the gasket have obvious nonlinearity, and the fitted exponential curve is adopted as its material characteristic parameter.

In order to reduce the computational amount of computer, the model is one-twenty fourth flange ring structure with periodic symmetry. The two sections of the model are applied to the normal symmetry constraint, which is used to restrain the rotation angle and the normal displacement. The Lan end

faces are bound by the direction, the circumferential direction and the axial direction, the upper flange ring is unconstrained, The model length conforms to the Saint Venant's principle.Therefore, the influence of boundary conditions on the stress of tube plate is neglected. The contact elements are used to simulate the flange surface and the nut and the gasket, meanwhile, the warp and circumferential constraints of the nut are applied.

The load is divided into two stages: Bolt preload stage and internal pressure exerting stage. The preload loading stage of bolts refers to the preload force which is added from 0 to the calculated pressure, The internal pressure exerting stage refers to the nominal pressure from 0 to the flange after the preload force is applied.

The pretension force of single Bolt is taken as 5.0 e^4N.

Internal pressure load: Pre-tight to maintain the shell-process pressure 0.5MPa, the pressure from 1.0MPa to apply to the nominal pressure flange of 4.0MPa, to 0.5MPa as a loading unit, a total of 7 kinds of operating conditions.

4. THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS OF BOLTED FLANGE CONNECTORS

In this paper, the influence of the pipe pressure on the surface of the tube plate and the shell pressure of the bottom surface of the tube plate on the stress distribution of the tube plate is studied, and the influence of the temperature difference between the upper and lower surfaces on the tube plate is neglected. Apply the shell pressure 0.5MPa, The tube pressure is respectively 1.0MPa, 1.5 MPa, 2.0 MPa, 2.5 MPa, 3.0 MPa, 3.5 MPa, 4.0 MPa.

4.1 Integral stress analysis of bolted flange connectors

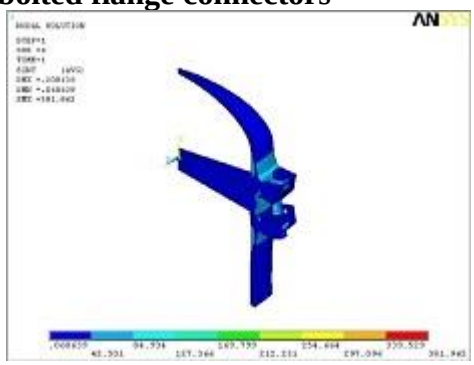

Fig. 4.1 The stress distribution of bolted flange connecting parts after pretension

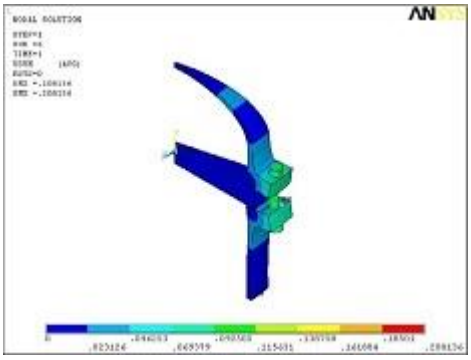

Fig. 4.2 The strain distribution diagram of bolted flange connecting parts after pretension

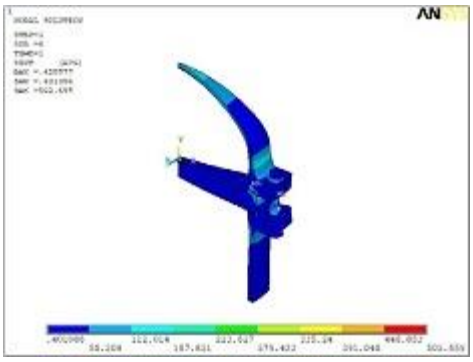

Fig. 4.3 Stress distribution of bolt flange under 3.5MPa internal pressure

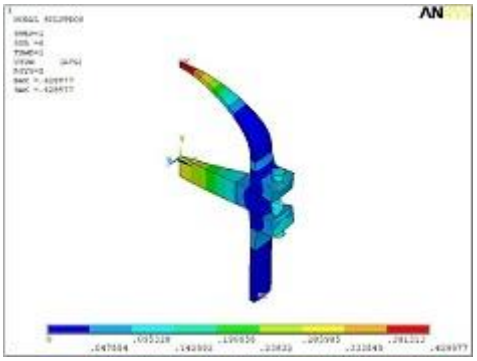

Fig. 4.4 Strain distribution under 3.5MPA bolt flange internal pressure

Fig. 4.1 and fig. 3.2 are respectively the stress and strain distributions of bolted flange connectors after the bolts are preloaded to the 5.0e4n, fig. 3.3 and Fig. 3.4 respectively are the stress and strain distributions of the bolt flange connecting parts when the 5.0e4n pressure is 3.5MPa. It can be seen from the graph that the stress distribution trend of preload and internal pressure is basically the same, but in the process of gradually exerting internal pressure, the stress intensity of each part increases, and the deformation of flange and bolt increases. The area of the connection between the head and the cylinder and the flange ring, because the geometrical discontinuity causes the edge stress, produces the stress concentration, but the influence area is small, has little influence on the bolt flange overall. When the bolt is in the preload and the internal pressure two kinds of working condition, receives the axial tensile stress, the bolt stress concentrates on the pull side, the area which the nut and the flange ring contact is under the preload Force action the stress is big. The flange ring has the tendency of opening from inside to outside when preload and internal pressure, and the deformation trend of flange and bolt becomes more and more obvious with the increase of internal pressure.

4.2 Distribution of the stress intensity components of the tube gasket

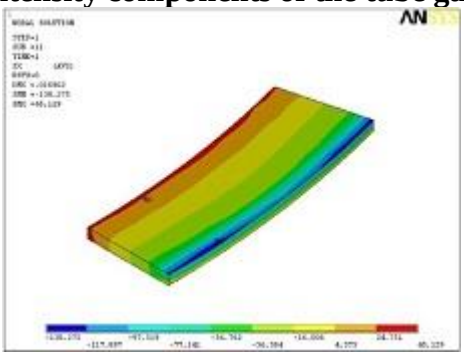

Fig. 4.5 Stress distribution in SX direction after tube gasket pretightening

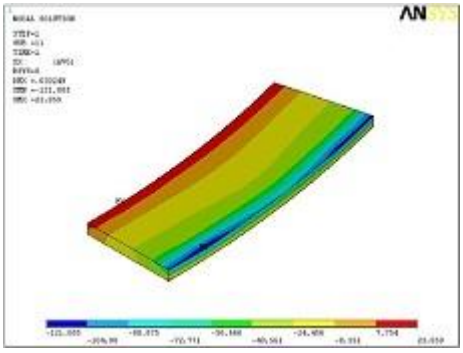

Fig. 4.6 Stress distribution in SX direction of tube gasket under internal pressure of 3.5MPa

Figures 3.5 and 3.6 are stress distribution maps of the SX direction under the preload of pipe gasket to $5.0e^4$N and the pressure difference of 3.5 MPa after pretightening.

The radial distribution of the compressive stress on the tube gasket is uneven, which can be seen from the above picture, the stress values from inside to outside are increasing along the radial direction, and are basically consistent in the circumferential direction. The stress value of the inner edge of the gasket is 48MPa, the stress value of the outer edge is 204MPa. In this paper, the selected gasket coefficient is 2. It can be seen that the stress value of the inner and outer edge of gasket is greater than 8MPa, thus, in the pipe-process gasket upward into a two-ring tight seal, and with the increase in preload, the gasket internal and external edge of the compressive stress also increases correspondingly, and the outer edge of the stress increased faster than the inner edge. The radial distribution of the compressive stress on the pipe-path gasket after applying internal pressure is uneven, the stress value increases along the radial direction from inside to outside, the radial lateral stress value is the largest, and the circumferential direction is basically consistent. The stress value of the inner edge of the gasket is 11MPa, the stress value of the outer edge is 172MPa, thus in the pipe-process gasket up into a two-ring tight seal belt. With the increase of internal pressure, the compressive stress of the inner and outer edge of the gasket decreases correspondingly, and the internal stress decreases faster than the outer edge. When the internal and external stress of the gasket is less than 8MPa, the internal pressure medium will invade the gasket and flange, gasket and tube plate, resulting in the tightness of bolted flange connectors, and even the sealing failure.

5. CONCLUSION

In this paper, the actual pipe plate with bolted flange connectors in tube and shell heat exchangers is simplified into an equivalent tube plate without holes through the flange design code of ASME boiler and pressure vessel code in the model. The results show that the axial tensile stress of bolted flange connectors is basically stable and the flange has the tendency of bending from inside to outside. When the preload and the residual compressive stress of the gasket are uneven along the radial and circumferential distributions, the stress distribution is determined by the properties of each element and the specific working conditions. With the increase of the pressure difference of the tube-shell, the residual compressive stress in the inner part of the tube-gasket is reduced sharply, which leads to the infiltration of the heat transfer medium into the sealing surface of the flange and the gasket, which causes the tightness of the connecting parts to decrease, while the residual compressive stress in the inne. The finite element analysis of bolted flange connectors can provide theoretical reference for

reasonable flange joint design, reduce the leakage of equipment during operation and ensure its safe operation.

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