NUCL SCI TECH (2018) 29:120
https://doi.org/10.1007/s41365-018-0457-2

Stress and thickness calculation of a bolted flat cover with double metal sealing rings

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Received: 11 October 2017 / Revised: 26 February 2018 / Accepted: 19 March 2018 / Published online: 7 July 2018

Abstract The design of a bolted flat cover is extremely important for the structural integrity of pressure vessels. The present design codes provide the thickness calculation equations for a bolted flat cover with single metal gasket. However, the rules for a bolted flat cover with double metal sealing rings are not developed to date. In the study, a new thickness calculation equation for the bolted flat cover with double metal sealing rings is proposed. First, the theoretical stress solution for bolted flat cover with the double metal sealing rings is obtained, based on the theory of simply supported circular plate and then verified using the results from finite element analyses. The results indicate that the influence of double metal sealing ring on the stress of the flat cover is more serious compared to single metal gasket. Second, a more accurate and reasonable equation is proposed to calculate the thickness of bolted flat cover with double metal sealing rings based on the derived theoretical equations of maximum stress. Finally, the influence of linear load and the spacing between rings on the thickness are discussed. Subsequently, a few suggestions are provided to design low-pressure or atmosphere pressure vessels. The study provides a theoretical foundation to develop design codes of pressure vessels in nuclear reactors.

The study was supported by the "Strategic Priority Research Program" of the Chinese Academy of Sciences (No. XDA02010000).

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Keywords Thickness calculation equation · Pressure vessel · Bolted flat cover · Double metal sealing rings · Design codes

List of symbols

C_{11}, C_{13}, C_{21}, C_{22}, C_{23}	Constants in Eqs. (2)–(5)
D	Bending stiffness of the plate
D_c	Calculation diameter of the flat cover
D_m	Average diameter of the single metal gasket
D_b	Diameter of the circle center for bolt holes
D_i	Inner diameter of the pressure vessel
D_1	Average diameter of the inner metal sealing ring
D_2	Average diameter of the outer metal sealing ring
E	Elastic modulus
K	Structural characteristic coefficient
K^*	Modified structural characteristic coefficient
L_G	Distance from the bolt circle to the gasket center line, $L_G = (D_b - D_m)/2$
m	Uniform moment, $m = W(D_b-D_2)/(2\pi D_2)$
M_{r1}, M_{r2}	Radial bending moment
$M_{\theta 1}$, $M_{\theta 2}$	Circumferential bending moment
P	Pressure

Q_i	Reacting force of the inner metal sealing ring
Q_o	Reacting force of the outer metal sealing ring
Q_r	Shear force along the radius of the plate
R_1	Radius of the inner ring
R_2	Radius of the outer ring
S	Allowable stress at the design temperature
W	Bolt pretension
Y_0	Linear load of the inner metal sealing ring under the preloading condition
Y_1	Linear load of the inner metal sealing ring under the operation condition

Greek symbols

α	$\alpha = R_1/R_2$
β	$\beta = R_2 - R_1$
δ	Thickness of the plate
μ	Poisson's ratio
ϕ	Welding coefficient
r, θ, z	Radial, circumferential, and axial direction in cylindrical coordinate system
σ_r, σ_θ	Radial stress, circumferential stress
ω_1, ω_2	Deflection of the plate
η	Constant in Eq. (10)

Abbreviations

TMSR	Thorium molten salt reactor
FEA	Finite element analyses
SSCP	Simply supported circular plate

1 Introduction

A bolted flat cover is a candidate head structure for a pressure vessel in nuclear reactors. Accurate calculation of stress and thickness during the design of the bolted flat covers ensures the strength of the pressure vessel and also plays an extremely important role in the safety of the reactor [1].

The thickness calculation equations of the bolted flat cover with a single metal gasket including a flat gasket and an octagonal gasket among others are provided in the design standards of pressure vessels, such as GB150 [2] and ASME code [3, 4]. However, the rules for a bolted flat cover with double metal sealing rings are not included in these codes. Flat cover structures are rarely adopted for most reactor pressure vessels and especially high-pressure vessels. They prefer to design a formed head that is directly connected with the bolted flanges, and the flanges are subsequently sealed with double metal O-rings or C-rings [5–7]. In view of the simple manufacturing process of flat covers, bolted flat covers constitute a candidate design for low-pressure vessels or atmospheric vessels such as a thorium molten salt reactor (TMSR) pressure vessel [8]. Based on the design experience of existing reactors, double metal sealing rings are proven as a safer and more reliable alternative. Therefore, double metal sealing rings are used in a bolted flat cover for TMSR pressure vessel to prevent radioactive leakage and ensure a certain safety margin of sealing performance [9].

Extant studies on bolted flanges demonstrate that the mechanical performance of the metal sealing rings, such as linear load, significantly affects the stiffness of the flanges and therefore is closely related to the thickness of the flanges [10–13]. Similarly, the property and arrangement of double metal sealing rings can directly affect the thickness of bolted flat covers. Consequently, it is extremely important to examine and analyze stress and thickness calculations of a bolted flat cover with double metal sealing rings. However, there is a paucity of research in this field [14, 15].

In the study, the theoretical equations of maximum stress for a bolted flat cover with double metal sealing rings are derived based on the theory of simply supported circular plate (SSCP) to obtain the thickness calculation equation applicable to double metal sealing rings [16–20]. Subsequently, the thickness calculation equation of the flat cover is developed and verified. Finally, the influence of the linear load and the spacing between rings on the thickness is investigated. The study is of specific guiding significance for flat cover design in nuclear reactors that provide the theoretical foundation to develop design codes of a pressure vessel.

2 Stress analysis of the bolted flat cover with double metal sealing rings

Based on the stress analysis method of the bolted flat cover with single metal gasket [1, 16], the theory of SSCP is adopted to obtain the maximum stress of the bolted flat covers with double metal sealing rings.

2.1 Forces analysis

With respect to the operation conditions, a bolted flat cover with double metal sealing rings is subjected to pressure (P), bolt pretension (W), and also the reacting force of inner and outer metal sealing rings (Q_i and Q_o) as shown in Fig. 1. In order to further simplify the forces analysis, the force conditions of a bolted flat cover with

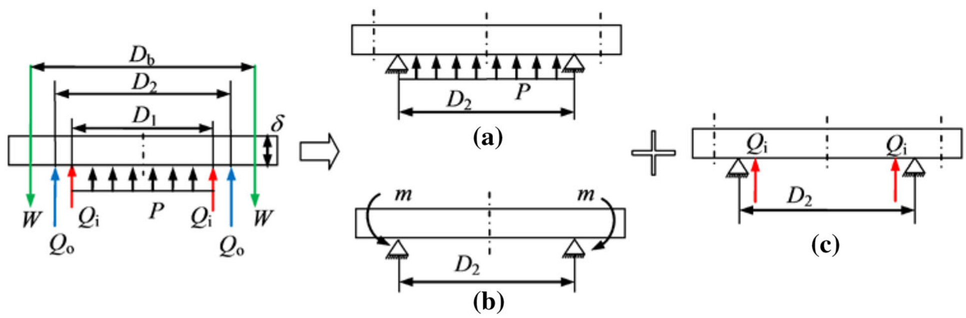

Fig. 1 (Color online) Forces analysis diagram of the bolted flat cover with double metal sealing rings. SSCP subjected to a **a** uniform transverse load, **b** uniform moment, **c** uniform shear force

double metal sealing rings are divided into the following three typical cases: (a) an SSCP subjected to uniform transverse load (namely, the pressure P); and (b) an SSCP subjected to uniform moment. When bolts and the sealing ring are relatively close and the bolts are densely distributed along the periphery, the bolt loads are simplified to a uniform moment m and $m = W\ (D_b\text{-}D_2)/(2\pi D_2)$; (c) an SSCP subjected to uniform shear force (i.e., the reacting force Q_i of inner metal sealing ring). The reacting force Q_o of the outer metal sealing ring is provided by the support of the SSCP (see Fig. 1).

2.2 Theoretical equation derivations

The maximum stress equation of an SSCP subjected to pressure and uniform moment (which is also the theoretical stress solution of the bolted flat cover with a single metal gasket) is as follows [1]:

$$(\sigma_r)_{max} = (\sigma_\theta)_{max} = \frac{3(3+\mu)}{32}\frac{PD_m^2}{\delta^2} + \frac{6WL_G}{\pi D_m \delta^2}, \tag{1}$$

where μ denotes the Poisson's ratio; D_m denotes the average diameter of the single metal gasket; L_G denotes the distance from bolt circle to the gasket center line, $L_G = (D_b - D_m)/2$, and δ denotes the thickness of the plate.

Based on the basic equation of axis-symmetric bending of a circular plate, the maximum stress of a SSCP under uniform shear force is derived as follows. First, the radius R_2 of the outer ring is assumed ($R_2 = D_2/2$). Given the uniform shear force Q_i loading at the radius $R_1 = D_1/2$, the shear force Q_r of the plate along the radius direction r is discontinuous. When $0 \le r < R_1$, $Q_r = 0$; and when $R_1 \le r < R_2$, $Q_r = -R_1Q_i/r$.

Based on the deflection differential equation and equilibrium equation of the circular plate, the deflections and bending moments are derived at $0 \le r < R_1$ and $R_1 \le r < R_2$, respectively.

When $0 \le r < R_1$, the following expression holds:

$$\omega_1 = \frac{C_{11}}{4}r^2 + C_{13}, \tag{2}$$

$$\left.\begin{aligned} M_{r1} &= -D\left(\frac{d^2\omega_1}{d^2r} + \mu\frac{1}{r}\frac{d\omega_1}{dr}\right) = -\frac{C_{11}}{2}D(1+\mu) \\ M_{\theta 1} &= -D\left(\frac{1}{r}\frac{d\omega_1}{dr} + \mu\frac{d^2\omega_1}{d^2r}\right) = -\frac{C_{11}}{2}D(1+\mu) \end{aligned}\right\}. \tag{3}$$

When $R_1 \le r \le R_2$, the following expression holds:

$$\omega_2 = \frac{Q_iR_1}{4D}r^2\left(\ln\frac{r}{R_2} - 1\right) + \frac{C_{21}}{4}r^2 + C_{22}\ln\frac{r}{R_2} + C_{23}, \tag{4}$$

$$\left.\begin{aligned} M_{r2} &= -D\left[\frac{1}{2D}(1+\mu)R_1Q_i\ln(r/R_2) + \frac{1}{4D}(1-\mu)R_1Q_i + \frac{1+\mu}{2}C_{21} - \frac{1-\mu}{r^2}C_{22}\right] \\ M_{\theta 2} &= -D\left[\frac{1}{2D}(1+\mu)R_1Q_i\ln(r/R_2) - \frac{1}{4D}(1-\mu)R_1Q_i + \frac{1+\mu}{2}C_{21} + \frac{1-\mu}{r^2}C_{22}\right] \end{aligned}\right\}, \tag{5}$$

where ω_1 and ω_2 denote the deflections of the plate; M_{r1} and M_{r2} denote the radial bending moments; $M_{\theta 1}$ and $M_{\theta 2}$ denote the circumferential bending moments; D denotes the bending stiffness of the plate, $D = \frac{E\delta^3}{12(1-\mu^2)}$; E denotes the elastic modulus; and C_{11}, C_{13}, C_{21}, C_{22}, and C_{23} are constants.

The boundary conditions of the SSCP are defined as $(\omega_2)_{r=R2} = 0$ and $(M_{r2})_{r=R2} = 0$. The angle of rotation, deflection, and bending moment of the plate are equal when $r = R_1$. Thus, $(\omega_1)_{r=R1} = (\omega_2)_{r=R1}$, $(d\omega_1/dr)_{r=R1} = (d\omega_2/dr)_{r=R1}$, and $(M_{r1})_{r=R1} = (M_{r2})_{r=R1}$. Therefore, five linear equations are obtained, and thus the constants are solved.

$$\begin{aligned} C_{11} &= \frac{Q_iR_1\left[(R_2^2 - R_1^2)(-1+\mu) + 2R_2^2(1+\mu)\ln(R_1/R_2)\right]}{2DR_2^2(1+\mu)} \\ C_{13} &= \frac{Q_iR_1\left[(R_2^2 - R_1^2)(3+\mu) + 2R_1^2(1+\mu)\ln(R_1/R_2)\right]}{8D(1+\mu)} \\ C_{21} &= \frac{Q_iR_1(R_2^2 - R_1^2)(-1+\mu)}{2DR_2^2(1+\mu)}. \\ C_{22} &= \frac{Q_iR_1^3}{4D} \\ C_{23} &= \frac{Q_iR_1\left[R_1^2(-1+\mu) + R_2^2(3+\mu)\right]}{8D(1+\mu)} \end{aligned} \tag{6}$$

The bending moments of the circular plate are obtained by substituting the constants into Eqs. (3) and (5). Based on the relationship between stresses and bending moments, the stress expressions of the SSCP under uniform shear force are derived by assuming $\alpha = R_1/R_2$.

When $0 \le r < R_1$, the following expression holds:

$$\begin{aligned}\sigma_{r1}^{q} = \sigma_{\theta 1}^{q} &= \frac{12M_{r1}}{\delta^3} z \\ &= \frac{3Q_i R_1 z}{\delta^3}\left[\left(1-\alpha^2\right)(1-\mu) - 2(1+\mu)\ln\alpha\right].\end{aligned} \tag{7}$$

When $R_1 \le r \le R_2$, the following expression holds:

$$\left.\begin{aligned}\sigma_{r2}^{q} &= \frac{12M_{r2}}{\delta^3} z = \frac{3Q_i R_1 z}{\delta^3}\left\{\left[(R_2/r)^2 - 1\right]\alpha^2(1-\mu) - 2(1+\mu)\ln(r/R_2)\right\} \\ \sigma_{\theta 2}^{q} &= \frac{12M_{\theta 2}}{\delta^3} z = \frac{3Q_i R_1 z}{\delta^3}\left\{-\left[\left((R_2/r)^2 + 1\right)\alpha^2 - 2\right](1-\mu) - 2(1+\mu)\ln(r/R_2)\right\}\end{aligned}\right\} \tag{8}$$

Based on Eqs. (7) and (8), the maximum stresses of the SSCP subjected to uniform shear force are obtained, and they occur at the center point ($r = 0$) of the upper or lower surfaces ($z = \pm\delta/2$).

$$\begin{aligned}\left(\sigma_{r}^{q}\right)_{\max} &= \left(\sigma_{\theta}^{q}\right)_{\max} \\ &= \frac{3Q_i R_1}{2\delta^2}\left[\left(1-\alpha^2\right)(1-\mu) - 2(1+\mu)\ln\alpha\right]\end{aligned} \tag{9}$$

Based on the superposition principle, Eqs. (9) and (1) are superposed. Subsequently, the maximum stresses of the SSCP under pressure, uniform moment, and uniform shear force are obtained after simplification as follows:

$$(\sigma_r)_{\max} = (\sigma_\theta)_{\max} = \frac{3(3+\mu)}{32}\frac{PD_2^2}{\delta^2} + \frac{6WL_G}{\pi D_2 \delta^2} + \frac{3Q_i D_2 \alpha\eta}{4\delta^2} \tag{10}$$

where $\eta = (1-\alpha^2)(1-\mu) - 2(1+\mu)\ln\alpha$.

Equation (10) denotes the theoretical stress solution of a bolted flat cover with double metal sealing rings. The results are mainly determined by pressure, bolt pretension, and the linear load of the inner metal sealing rings.

2.3 Comparison of the theoretical and numerical results

The TMSR pressure vessel adopts a flat cover as the upper head that is connected with the flange via 32 bolts. In the middle of flat cover and flange, double metal C-rings are installed as shown in Fig. 2. The design parameters of the flat cover under operation conditions are as follows: P = 0.5 MPa; δ = 54.96 mm; D_2 = 1129.8 mm; D_1 = 1058.6 mm; D_b = 1221 mm; $Q_i = Y_1$ = 200 N/mm; $W = 1.876 \times 10^6$ N; E = 172 GPa; and μ = 0.31.

By using ANSYS software, the numerical simulations are performed via FEA to calculate the stress intensity of the TMSR flat cover. A 1/4 symmetric model is constructed given the geometric symmetry in the finite element analysis (see Fig. 3a). The displacement along the Z direction of the circle center line for the outer metal sealing ring is restrained (UZ = 0). Two symmetric displacement boundaries are applied on the symmetric planes. Internal pressure P, bolt pretensions W, and the linear load Y_1 of inner metal sealing ring are loaded on the model (see Fig. 3b). Radial stress (σ_r) of the TMSR flat cover by FEA is shown in Fig. 3c. It indicates that the maximum radial stress value (σ_{rmax}) is equal to 121.22 MPa and occurs at the center of the upper surface of the flat cover.

In order to verify the derived equation, the theoretical results of σ_r along the r direction of TMSR flat cover are calculated based on Ref. [2] and Eqs. (7) and (8). Additionally, the theoretical results are compared with the FEA results, and they consider the following two loading conditions: (a) $P + W$, in accordance with a single metal gasket; (b) $P + W + Q_i$, in accordance with double metal sealing rings.

The radial stress distribution curves obtained by theoretical and numerical methods, respectively, are shown in Fig. 4. As shown in the figure, the theoretical results are consistent with the FEA results in view of the stress distribution characteristics. Additionally, the σ_{rmax} value of the flat cover occurs at the center point of the upper surfaces under the two loading conditions. With respect to a flat cover with the same thickness, the σ_{rmax} value obtained from the theoretical calculation is 7.2% higher than the FEA results. The force analysis above indicates that the modified theoretical equation simplifies the connection of the sealing ring to an ideal simply support type, and this leads to theoretical solutions that are more conservative relative to the numerical solutions.

Moreover, the reaction force of the inner metal sealing ring changes the radial stress distribution of the flat cover, and this causes a stress concentration in the position of the inner metal sealing ring. Furthermore, the σ_{rmax} value with Q_i is approximately 12% higher than that without Q_i, which indicates that the influence of double metal sealing ring on the stress of the flat cover is more serious than that of a single metal gasket. Therefore, it is necessary to distinguish

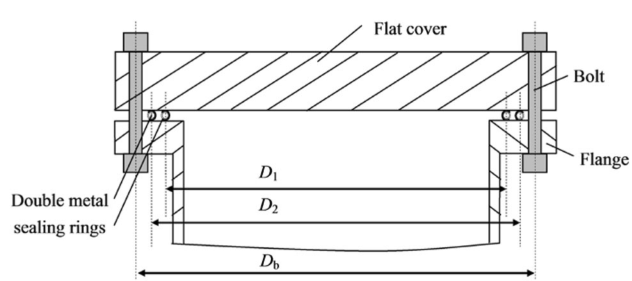

Fig. 2 Two-dimensional sketch of the TMSR flat cover

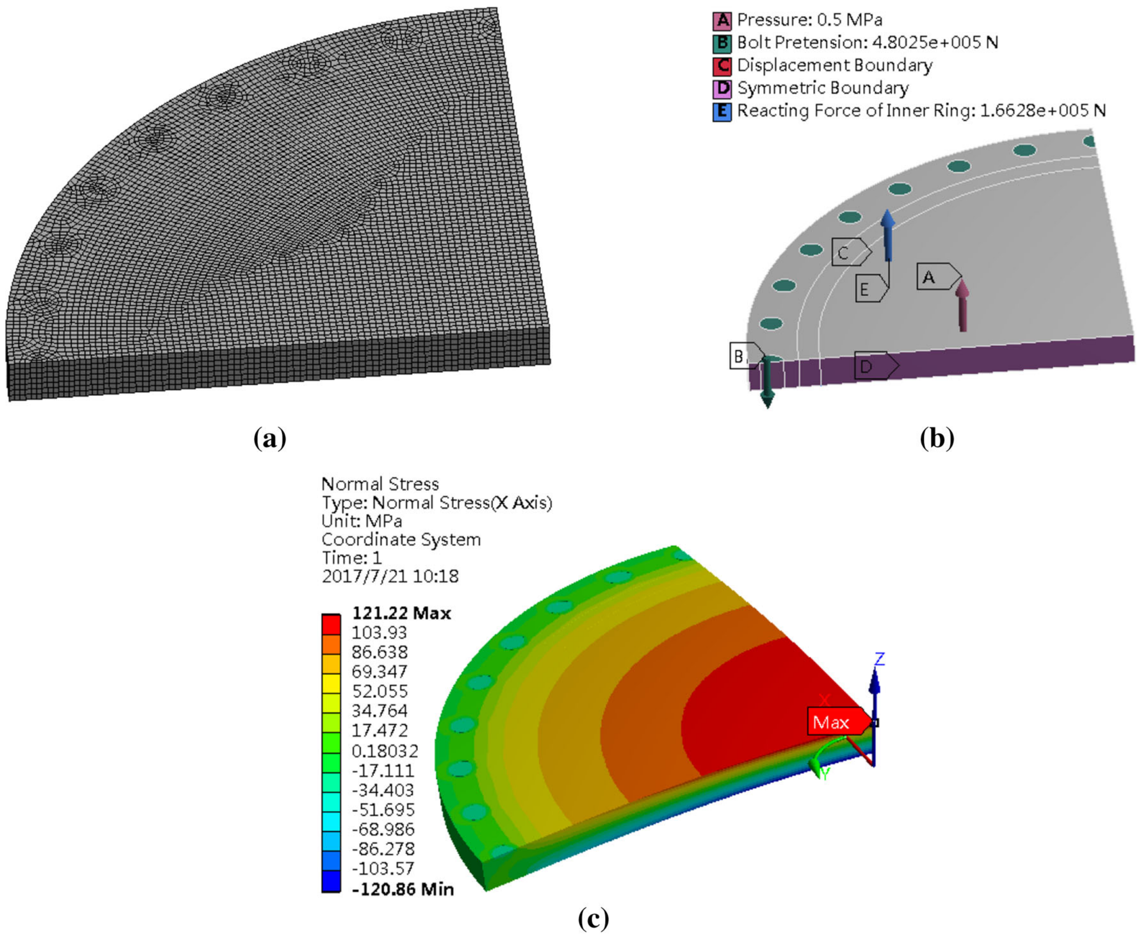

Fig. 3 (Color online) FEA model and results of the TMSR flat cover. **a** EEA model; **b** boundary and loads; **c** FEA results of radial stress

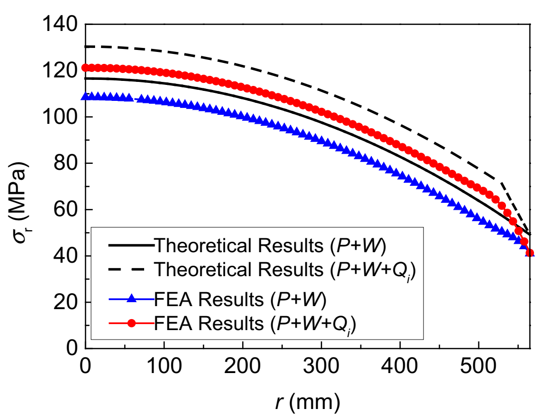

Fig. 4 (Color online) Radial stress distribution curves along the radius direction of the TMSR flat cover

the stress and thickness calculation equations of a bolted flat cover with double metal sealing rings with a single metal gasket during the design process of the pressure vessels.

3 Thickness calculation of the bolted flat cover with double metal sealing rings

3.1 Thickness calculation equations in the design codes

The thickness calculation equations in present design codes, such as GB150 and ASME codes, are shown in Table 1. In the study, unified symbols are adopted to express the equations in Table 1 to ensure consistency throughout the study.

The equations are obtained from Eq. (1) by assuming a bolted flat cover sealed by single metal gasket. Therefore, strictly speaking, the thickness calculation equations in the design codes are not applicable to the bolted flat cover with double metal sealing rings. If an approximate estimate is required to calculate the thickness of the bolted flat cover with double metal sealing rings by using the equations in design codes, we then assume $D_c = D_2$ and use the sum of linear loads of inner sealing ring and outer sealing ring to calculate the W value. For example, W under the operation

Table 1 Thickness calculation equations of the bolted flat covers in the design codes

Design codes	Calculation equations
GB150-2011	$\delta = D_c\sqrt{\frac{KP}{S\phi}} = D_c\sqrt{\frac{0.3P}{S\phi} + \frac{1.78WL_G}{S\phi D_c^3}}$
ASME VIII-1	$\delta = D_c\sqrt{\frac{0.3P}{S\phi} + \frac{1.9WL_G}{S\phi D_c^3}}$
ASME III-NC	$\delta = D_c\sqrt{\frac{0.2P}{S} + \frac{1.27WL_G}{SD_c^3}}$

condition is obtained as follows: $W = \frac{\pi}{4}D_2^2P + \pi(D_1 + D_2)Y_1$ [1].

3.2 Proposed thickness calculation equation

Based on Eq. (10), the thickness calculation equation of the bolted flat cover with double metal sealing rings is derived as follows:

$$\delta = D_c\sqrt{\frac{K^*}{S\phi}}, \tag{11}$$

where $K^* = \frac{3(3+\mu)}{32}P + \frac{6WL_G}{\pi D_2^3} + \frac{3Q_i\alpha\eta}{4D_2}$, and this denotes the modified structural characteristic coefficient. It must be noted that it is necessary to consider both the operation condition and preloading condition for P, W, S, and Q_i. Furthermore, μ = 0.3 for most pressure vessel materials. Thus, the parameter K^* is re-expressed as follows:

$$K^* = 0.3P + \frac{1.9WL_G}{D_c^3} + \frac{1.97Q_i\alpha}{D_c}\left[0.26(1-\alpha^2) - \ln\alpha\right]. \tag{12}$$

Next, the above calculation equations are applied to TMSR flat cover with double metal sealing rings. The δ values of the cover are calculated by two methods and compared as follows: (1) the approximate estimate for the calculation by using the design equations in Table 1 and (2) the calculation by proposed thickness calculation equation [Eq. (11)]. All the results are listed in Table 2, and they indicate that the calculation results (assuming Y_1 = 200 N/mm) of the flat cover by Eq. (11) are 7.3, 5.9, and 30% higher than the approximate results by GB150, ASME VIII-1 code, and ASME III-NC code, respectively.

3.3 Influence of the double metal sealing rings on the thickness

The effect of design pressure and bolt pretension on thickness is not examined in the study henceforth. In the following section, only the influence of double metal sealing rings on the thickness of bolted flat cover is discussed.

3.3.1 Influence of the linear load

Equation (11) is used to calculate the δ values of the TMSR flat cover under different linear loads Y_1 as shown in Fig. 5. It indicates that the δ values increase with increases in Y_1 in an approximately linear manner. With respect to low-pressure vessels (P = 0.5 MPa), medium-pressure vessels (P = 5 MPa), and high-pressure vessels (P = 15 MPa), the δ values of the flat cover increase by 10, 1.5, and 0.5%, respectively, when Y_1 increases by 100 N/mm. Hence, for high-pressure vessels, the linear load of the metal sealing rings is not the main factor that influences the thickness of the flat cover. However, it is necessary to not ignore the effect of linear load for low-pressure or atmosphere pressure vessels. Given the low-pressure characteristics of TMSR pressure vessel, the use of metal sealing rings with lower linear load is recommended to reduce the thickness of the flat cover to ensure the sealing performance of the vessels.

3.3.2 Influence of the spacing between rings

The metal sealing rings are generally installed within the inner diameter (D_i = 980 mm) of the pressure vessel, and thus the influence of the spacing β between rings ($\beta = R_2 - R_1$) on the thickness δ was considered when $D_i/2 \leq R_1 \leq R_2$ as shown in Fig. 6. It is observed that the δ values of the flat cover increase with increases in the spacing β. When β = 0 (namely, $R_1 = R_2$), it implies that double sealing rings with the same diameter or a single sealing ring with double linear load are arranged at the position of the outer sealing ring on the flange. In these types of cases, the bolt pretension is calculated as: $W = \frac{\pi}{4}D_2^2P + 2\pi D_2Y_1$. Additionally, given α = 1, $K^* = 0.3P + \frac{1.9WL_G}{D_c^3}$ is derived based on Eq. (12). Therefore, Eq. (11) is equivalent to the equation in ASME VIII-1 code. The same thickness values (δ = 55.25 mm) are obtained by using these two equations when β = 0.

The conclusion indicates that the spacing between rings should be reduced to the maximum possible extent, and this decreases the thickness of flat cover to a certain extent.

Table 2 δ values of the TMSR flat cover (mm)

Equations in the design codes			Modified equation
GB150-2011	ASME VIII-1	ASME III-NC	
54.21	54.96	44.90	58.18

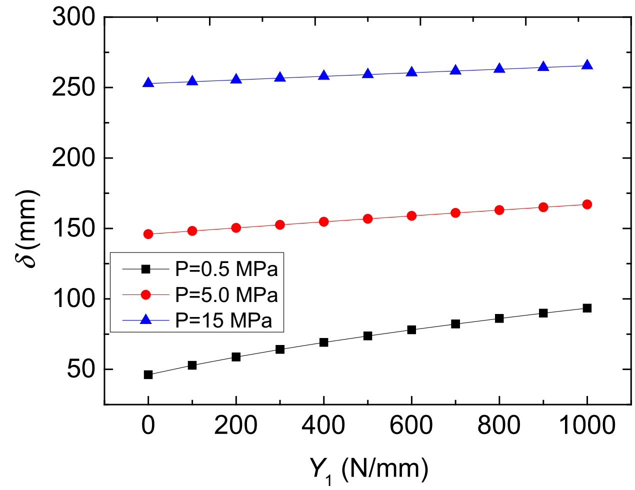

Fig. 5 (Color online) Influence of the linear load on the thickness of the TMSR flat cover

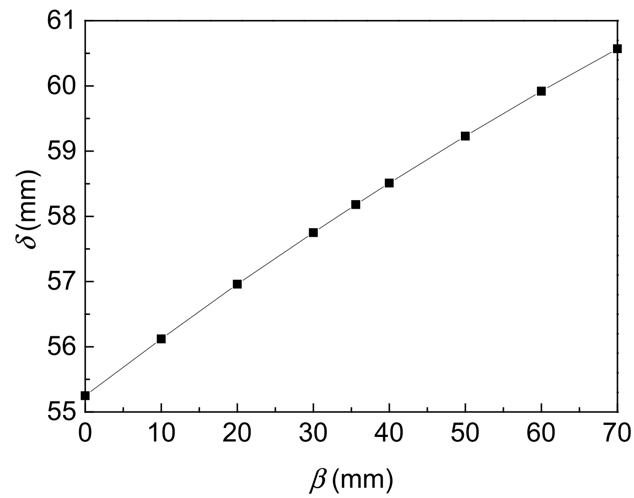

Fig. 6 Influence of the spacing between rings on the thickness of the TMSR flat cover

Therefore, with respect to the TMSR flat cover, it is necessary to minimize the spacing between rings to ensure a lower thickness.

4 Conclusion

In the study, the equations to calculate maximum stress and thickness for the bolted flat cover with double metal sealing rings are proposed. Furthermore, the influence of double metal sealing rings on the thickness of bolted flat cover is investigated and discussed. Based on the above analyses, the following conclusions are obtained:

1. The influence of a double metal sealing ring on the stress of the flat cover exceeds that of a single metal gasket. The equations proposed in the study describe the maximum stress of bolted flat cover with double metal sealing rings more accurately when compared to the equations proposed in design codes.
2. The theoretical results of the proposed maximum stress equation are in agreement with the FEA results.
3. The proposed thickness calculation equation of the bolted flat cover is more accurate and reasonable when compared with the equations proposed in design codes for double metal sealing rings, which are effectively used for supplementing and developing the design codes of pressure vessels.
4. The linear load and the spacing between rings significantly affect the thickness of the bolted flat cover for low-pressure or atmospheric pressure vessels. In order to save material and reduce the thickness of the flat cover, it is important for designers to select appropriate metal rings and minimize the spacing between the rings.

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