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Research on the Assembly Pattern of MMC Bolted Flange Joint

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Abstract

In a Metal-to-Metal Contact (MMC) bolted flange joint the stress of sealing surfaces is constant. It canwithstand higherbolt load. So, under the operating conditions of high temperature, high pressure or their fluctuations, the sealing effect of MMC bolted flange joints is better than of floating (FLT) bolted flange joints. According to the structure characteristics of MMC bolted flange joints, a new tightening method (SH-Method) was recommended in this work.
The bolt forces during the tightening process of a MMC bolted flange joint with SH-Method were calculated and analyzed with the finite element analysis Software ANSYS. The calculating model and results were experimentally verified. Both calculating and experimentally results showed, the new tightening method 'SH-Method'has the advantages of fewer steps, simpler operation, more uniform bolt force, and better sealing effect, compared to the star pattern and the alternative pattern #3 of ASME PCC-1, in which only the pattern methods for FLT flange joints are recommended.

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*Keywords:*Bolted flange joint, Metal-to-Metal Contact(MMC), Tightening pattern, SH-Method, Sealing effect

1. Introduction

It is very important to study how to apply and control bolt preload in order to ensure to have a safe, reliable and long running of bolted flange joints. If the bolt force is too large, itcan lead to gasket crush and to leak failure. On the other hand, a too small bolt force can make the residual stress of the gasket not be enough to seal, and then also lead to leak failure. According to statistics, 50% to 80% of the leak was due to the inaccurate installation of bolt

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preloading. Therefore, to control the bolt force is one of the key points to guarantee the sealing performance in a bolted flange joint.

In bolted flange connections, all the bolts cannot be loaded simultaneously, but with a certain sequence, so that subsequently loaded bolts will affect bolts, which are loaded before, during clamping the flange. This effect causes the bolt load changes, which is called Elastic Interaction. For a gasket bolted joint, clamp load loss is mainly attributed to the elastic interaction between the fasteners, gasket, and joint[1-3]. Nasser and Alkelani[4] experimentally studied the clamp load loss due to elastic interaction and gasket creep relaxation in bolted joints under star or simultaneous tightening strategy. In a subsequent study[5], Alkelani proposed an elastic interaction model for the clamp load loss of a gasketed flange joint. This model can characterize the effects of gasket stiffness, gasket thickness, bolt spacing, and tightening pattern on the clamp load loss of a gasketed flange joint caused by the elastic interaction. To study the tightening strategy for the uniform bolted preload, Kumakura and Saito[6] studied the effect of tightening sequences for bolted flange joints using multiple bolts. The study experimentally showed the multi-pass tightening can make the bolt tension of each bolt more uniform.

The tightening methods for the preloading of bolted flange joints are proposed in ASME PCC-1[7] and JIS[8] standards. All these methods and studies mentioned above concern the floating bolted flange joints. There are no proposed tightening methods for MMC bolted flange joints. An optimizing tightening method for MMC bolted flange joints is presented in this work. The elastic interaction of bolt force is discussed. The influence of different tightening methods on bolt stress and sealing performance of MMC flange joints is also studied.

2. **Sealing principle of MMC bolted flange joints**

The contact stress on the sealing surface of a MMC type flange joint stays stable. It can withstand a bigger bolt preload force, and has better ability to resist damage than a FLT flange joint. So MMC type flange joints are widely used in the nuclear industry as well as in systems with high temperature, high pressure or high temperature and pressure fluctuation. Figs. 1 and 2 show the change of the structure and the loading of a MMC joint before and after it reaches metal-to-metal contact.At the first stage of bolt tightening, the MMC gasket is compressed at the surface of the graphite ring. The bolt load is taken by the graphite ring as the sealing surface (as shown in the left side of Fig. 1 and Fig. 2).With the increasing of the bolt force the metal outer ring begins to contact to the flange sealing surfaces, i.e., metal-to-metal contact (MMC) state is reached in the flange joint. At this time the bolt load is taken by the graphite ring and the metal outer ring. The surface stress on the graphite ring stays unchanged. The increased bolt force acts on the metal outer ring (as shown in the right side of Fig. 1 and Fig.2).

In the MMC bolted flange joints, there is generally a fixed pitch block or a limiting ring in the gasket. When the bolt preload is applied, the gasket is compressed. One part of the bolt force is transmitted to the sealing surface of the flange and gasket to prevent leakage; the other part of the force is taken by the fixed pitch block or the limiting ring to compensate a variety of gasket stress loss by the changing of the operating pressure, temperature or external loads.Compared withthe floating (FLT) bolted flange joints, there are many advantages of this sealing model, for example, the further deform of flanges is limited by the fixed pitch block or the limiting ring. It makes the stiffness of the flange joints be increased. Furthermore, the stress on the gasket sealing ring is not going to change if the operation conditions are unstable. The MMC bolted flange joint has also the better reliability and repeatability.

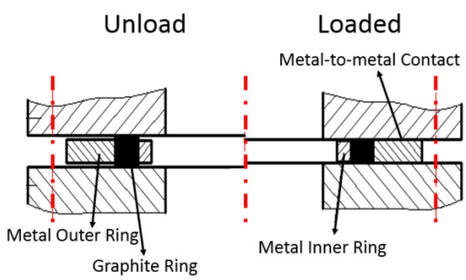

Fig.1. Metal-to-Metal contact (MMC) diagram.

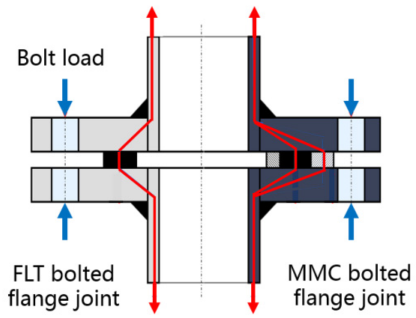

Fig. 2. Difference sealing performance betweenFLT and MMC type bolted flange joints.

Since July 1999, the German power plant began to study MMC flange connections. Bartonicek et al.[8] studied the effects of different temperatures on the MMC gasket sealing performance. But there is no study on the tightening methods of MMC bolted flange joints to be published.

3. **Tight patterns of bolted flange joints**

Here a new tightening method for MMC bolted flange joint, namely SH-Method, is recommended. As a comparison, the star tightening pattern and the alternative pattern # 3 in the ASME PCC-1 are also described and studied. A MMC bolted flange joint with 8 bolts is chosen as the study example in this work.

3.1. Star tightening pattern in the ASME PCC-1

The star tightening pattern is recommended by ASME standards as the best tightening method. In this method, the load of bolts is increased in three rounds to achieve 100% bolt preload through star tightening sequence, and then the bolts are tighten twice clock wisely in order to get a even distribution of bolt loads. Its tightening sequence is shown in Fig. 3, in which the label represents the tightening sequence of different bolts.

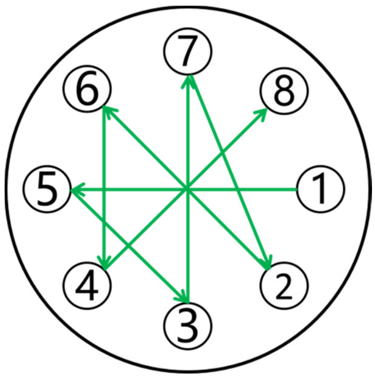

Fig. 3.Star assembly pattern.

First round: 20%-30% of target preload, tightening sequence: 1， 5， 3， 7—2， 6， 4， 8；
Second round: 50%-70% of target preload, tightening sequence: 1， 5， 3， 7—2， 6， 4， 8；
Third round: 100% of target preload, tightening sequence: 1， 5， 3， 7—2， 6， 4， 8；
Fourth round: 100% of target preload, clock wisely tightened；
Fifth round: 100% of target preload, clock wisely tightened.

3.2. Alternative pattern # 3 in the ASME PCC-1

The alternative pattern # 3 is the simplest way recommended in ASME standards. In this method, only 4 bolts are tightened at the beginning, and then the bolts are tightened clock wisely. It is no need to number each bolt with this method. The moving during the tightening operation of workers is also reduced. So, the assembly efficiency is increased. Its tightening sequence is shown in Fig. 4.

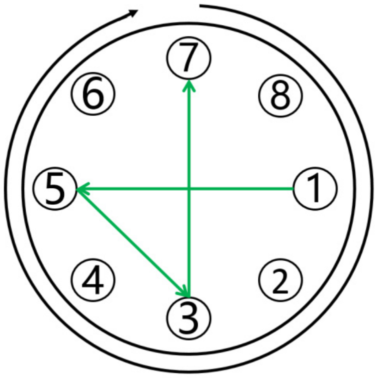

Fig.4. Alternative Assembly Pattern #3.

First round: 20%-30% of target preload, tightening sequence: 1，5，3，7；
Second round: 50%-70% of target preload, tightening sequence: 1，5，3，7；
Third round: 100% of target preload, tightening sequence: 1，5，3，7；
Fourth round: 100% of target preload, clock wisely tightened；
Fifth round: 100% of target preload, clock wisely tightened；

3.3. SH-Method: recommended here especially for MMC flange joints

According to the structural features of MMC gaskets, the gasket behaves at the first stage of the tightening as a soft gasket, namely all bolt preloads act on the sealing surface (graphite ring) of the MMC gasket. After three round tightening, the graphite ring is compressed to the same thickness as the metal outer ring. And then the MMC state is reached. After that, the joint is tightened as metallic hard gaskets. This tightening pattern is called SH-Method here. Its tightening sequence is shown in Fig. 5.

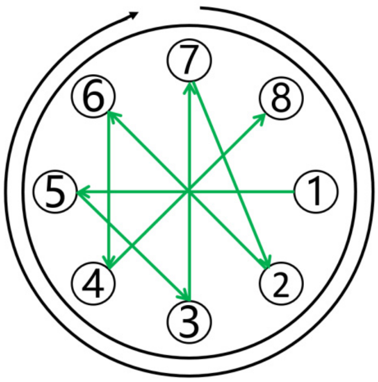

Fig. 5. SH-Method for MMC flange joints.

It is supposed the bolt load, which makes the gasket outer ring contact with the flange sealing surfaces (MMC), as F_{MMC}, and the target tightening bolt load as F_L. The tightening sequence of the SH-Method can be described as followings.

First round: 50% of F_{MMC}, tightening sequence: 1，5，3，7—2，6，4，8；

Second round: 110% of F_{MMC}, tightening sequence: 1，5，3，7—2，6，4，8；(This step is performed to achieve the metal-to-metal contact between the flange sealing surface and the outer ring of the MMC gasket, and to ensure to get an uniform contact stress.)

Third round: 110% of F_L, tightening sequence: 1，5，3，7—2，6，4，8；(To make the bolt loads more uniform)

Fourth round: 100% of F_L, clock wisely tightened；

Fifth round: 100% of F_L, clock wisely tightened.

4. Model of a MMC bolted flange joint

Here a pair of DN80-PN11 welded neck raised face steel pipe flanges are chosen as the calculate and experimental model. The material of these two flanges is 304 stainless steel. There are eight M20 stud bolts with 150mm long in this flange joint. The material of these bolts is 45 steel. The MMC graphite gasket with inner and outer ring is selected as the sealing element. The compression recovery performance curve (from experiment) of this MMC graphite gasket is shown in Fig. 6. The model of this flange joint is shown in Fig. 7.

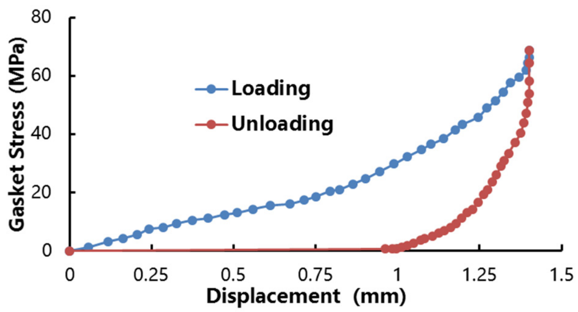

Fig. 6.compression resilience curve MMCtype gasket.

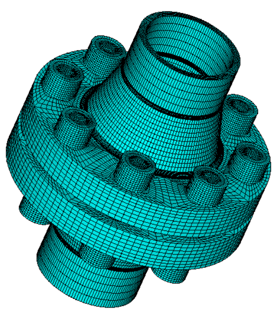

Fig. 7. MMC Flange Model for ANSYS Simulation.

5. **Calculation of bolt preload in the MMC flange joint**

When MMC flange joints are preloaded, the bolt load should be applied until contact between the outer ring and flange sealing surface reaches at the first stage. And then, enough additional bolt load should be exerted in order to compensate bolt load loosing because of internal pressure, temperature and theirfluctuation, as well as the external loading in the operation system. The calculation of the bolt preloading in a MMC flange joint is described as followings.

(1) Calculation of the effective contact gasket size, i.e. the effective gasket width, the effective gasket diameter and the effective gasket area;

(2) Calculated the minimum bolt preloading to reach metal to metal contact

The minimum bolt preloading to reach metal to metal contact (MMC) is called F_{GMMC}.

$$F_{GMMC} = A_{Ge} \times \sigma_{MMC} \quad (1)$$

Here A_{Ge} is the effective sealing area of the gasket;

σ_{MMC} is the gasket stress when MMC contact is reached.

The bolt load in every bolt at this time is F_{Bo}.

$$F_{B0} = F_{MMC} / 8 \quad (2)$$

(3) Bolt preloading in operation conditions

In operating conditions, the MMC contact should be remained to keep a stable sealing performance in the flange joints. So the contact stress in the graphite sealing surface of the MMC gasket stays unchanged.

The total axial force generated by the inner pressure p is F_p.

$$F_p = A_{Ge} \times p \quad (3)$$

So the minimum required total bolt load F_{Bp} is:

$$F_{Bp} = F_{MMC} + F_p \quad (4)$$

(4) Bolt preload with the consideration of the bolt load dispersion

During the installation process, the bolt preload fluctuations due to the dispersion of the bolt load should be compensated to ensure a reliable sealing.

With considering of the bolt load dispersion according to EN1591-1[9], the initial bolt load dispersions of a single bolt, namlyε_{1+} andε_{1-}, are calculated as followings, when the bolts are tightened using one torque wrench. Here the friction coefficient between the bolt and the nut is assumed as μ.

$$\varepsilon_{1+} = 0.1 + 0.5 \times \mu \quad (5)$$

$$\varepsilon_{1-} = 0.1 + 0.5 \times \mu \quad (6)$$

The bolt load dispersion of all bolts are ε_{1+} and ε_{1-}.

$$\varepsilon_{+} = \varepsilon_{1+} \times \left(1 + 3 / n_B^{1/2}\right) \quad (7)$$

$$\varepsilon_{-} = \varepsilon_{1-} \times \left(1 + 3 / n_B^{1/2}\right) \quad (8)$$

So the minimal and maximal bolt loads $F^{'}_{B0min}$ and $F^{'}_{B0max}$ are:

$$F^{'}_{B0min} = F_{BP} \div (1-\varepsilon_{-}) \quad (9)$$

$$F^{'}_{B0max} = F_{BP} \times (1-\varepsilon_{+}) / (1-\varepsilon_{1}) \quad (10)$$

In the calculation mentioned above, the other factors, which influence the gasket stress, for example, the stress relaxation, bolts creep, and temperature effect, and so on, are not taken into account. So the minimal and maximal bolt loads should be multiplied by a safety factor S, as the actual bolt preload.

6. Finite element analysis of the tightening process in the MMC flange joint

The tightening process of the MMC flange joint is calculated and analyzed with the software ANSYS here. Three tightening methods are used, namely, the star tightening pattern and the alternative pattern # 3 recommended in the ASME PCC-1, and also the SH-Method tightening pattern recommended in this work. In the tightening process, if the bolt load in each bolt is more than 90% of the target bolt preload, the bolt load distribution is assumed as uniform and the tightening process can be ended. The tightening effect with these three tightening pattern will be evaluated and compared by four parameters, namely, the number of loading round (RN) to achieve an uniform bolt load distribution, load dispersion (LD), number of tightening operation (TN) and moving number (MN) during tightening operation.

Number of tightening operation (TN) is the number to tight the bolts during the whole tightening process. Moving number (MN) is the number of moving times (or distance) for an operator during the tightening process. For the flange model with 8 bolts used here, one moving number (MN) is defined as moving one eighth circumference.

(1) Calculation results with the star tightening pattern

The changes of bolt preload with the star tightening pattern of ASME PCC-1 are shown in Fig. 8.

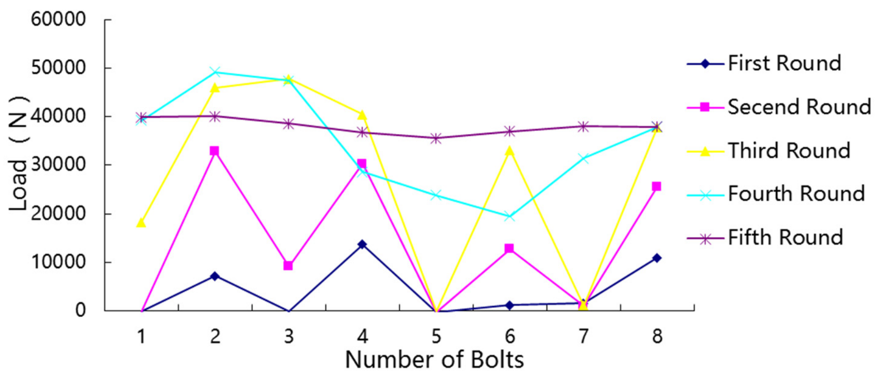

Fig. 8. Bolted load curve with Star tighten pattern method of ASME PCC-1.

The Fig. 8 shows that after 5 rounds tightening, the bolt force in every bolt reaches more than 90% of the target value. So the tightening operation can be ended. In the previous three rounds, the bolt loads distribute as a W-type curve. And in the last two rounds the distribution shows as a N-type curve. In the whole tightening process, TN is 40, and MN is 115 with the star tightening pattern of ASME PCC-1.

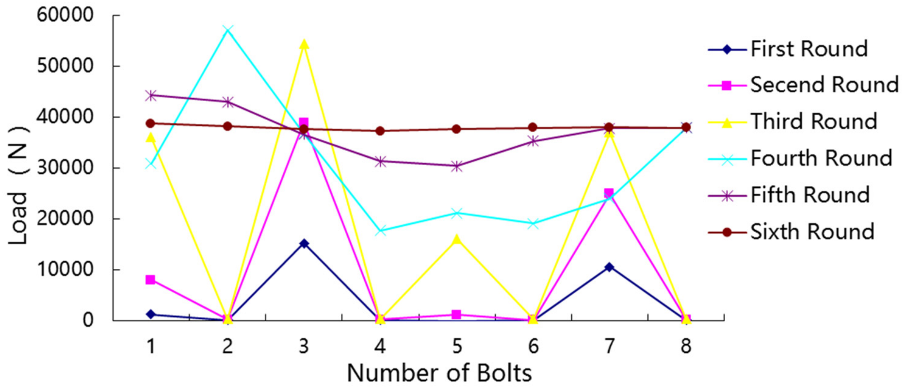

Fig.9. Bolted load curve with alternative assembly pattern #3 method of ASME PCC-1.

(2) Calculation results with the alternative pattern # 3

The Fig. 9 shows the changes of bolt load with the alternative pattern # 3 of ASME PCC-1. Till six rounds tightening, the bolt force in every bolt reaches 90% of the target value. In the previous three rounds, the bolt loads distribute as a W-type curve. And in the last rounds the distribution shows as a N-type curve. In the whole tightening process, TN is 36, and MN is 102.

(3) Calculation results with the SH-Method

The Fig. 10 shows the changes of bolt preload with the SH-Method, which is recommended in this work. After 5 rounds tightening, the bolt force in every bolt reaches more than 90% of the target value. In the previous three rounds, the bolt loads distribute as a W-type curve. And in the last rounds the distribution shows as a N-type curve. In the whole tightening process, TN is 40, and MN is 93.

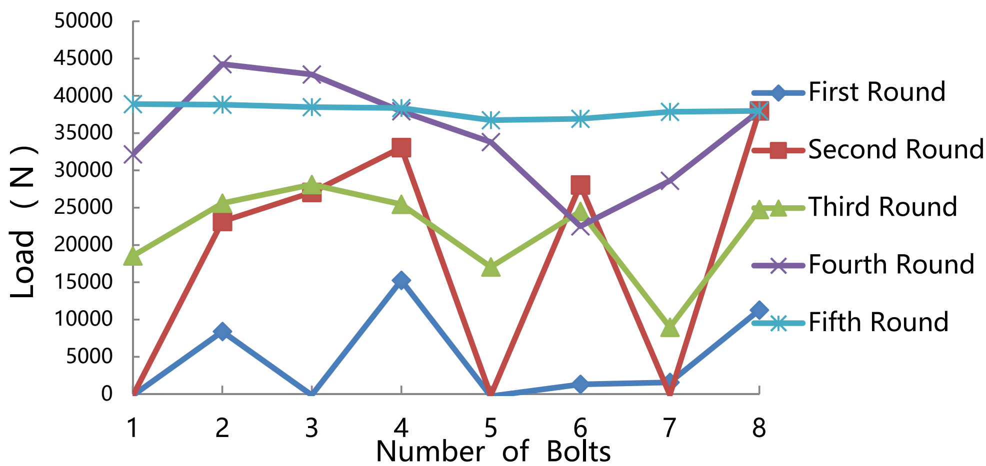

Fig. 10. Bolted load curve with SH-Method.

With comparing among the tightening results of the above studied three methods (see Table 1), the following conclusions can be drawn.

(1) For a MMC bolted flange joint, after 5 rounds the bolt force in every bolt reaches 90% of the target value with the SH-Method, just as the star tightening pattern of ASME PCC-1. While it need six rounds with the alternative pattern # 3 of ASME PCC-1.

(2) Comparing the dispersion of bolt force after 5 rounds, the dispersion value with the SH-Method is significantly less than the values, which using the star tightening pattern and the alternative pattern # 3 of ASME PCC-1.

(3) TN with the SH-Method is as same as with the star tightening pattern of ASME PCC-1, and slightly higher than with the alternative pattern # 3 of ASME PCC-1.

(4) MN with the SH-Method is significantly less than with the star tightening pattern and the alternative pattern # 3 of ASME PCC-1.

Table 1. Comparison of tight effect under three different Pattern Methods.

Tightening Pattern	LD		TN	MN
	RN=5	RN=6		
Star pattern of ASME PCC-1	1159		40	115
alternative pattern # 3 of ASME PCC-1	3675	315	36	102
SH-Method	634		40	93

In summary, for MMC-bolt flange joints, the tightening effect (LD, TN and MN) with the SH-Method is better than with the star pattern and the alternative pattern # 3 in ASME PCC-1. It shows, the tightening patterns recommended in ASME PCC-1, which are suitable for floating flange joints, are not good choices for MMC flange joints. For a MMC flange joint, the SH-Method recommended in this work can be choose according to the bolt load to reach the MMC statues.

7. **Tightening and leak experiment of a MMC bolted flange joint**

7.1. Instruction of the experimental device

The experimental device (Fig. 11) can be divided into parts, namely the bolted flange system, medium (N_2) supply unit, bolt strain real-time acquisition system, the leakage gas acquisition system. The bolt strain real-time acquisition system includes resistance strain gauges with the model BX120-3AA and a static resistance strain gauges with the model XL2118A24 (U). The bolts are tightened by a load torque wrench. The pressure drop in the system is measured by a differential pressure sensor with the model JYB-3151.

Fig.11. Measurement device for Bolt loads and flange leak rate.

The Bolted flange joint is composed of the upper and lower flanges (DN80-PN11, material:304 stainless steel), eight studs(M20, 150mm long, material:45 stainless steel), the upper and lower connection tubes and covers. The used gasket is a MMC graphite gasket with inner and outer rings.

7.2. Results of the tightening and leak experiment of the MMC flange joint

Table 2 shows the comparison between calculation and experimental results for the MMC flange joint using SH-Method to be tightened.

Table 2. Comparison between calculation and experimental resultsusing SH-Method.

Bolt Nr.	Bolt Load Difference,(Exp.-Cal.)/Exp., %				
	First round	Second round	Third round	Forth round	Fifth round
1	101	101	52	22	6
2	36	26	24	23	5
3	102	6	6	19	1
4	16	30	5	6	8
5	112	102	27	6	0
6	70	14	8	37	0
7	55	101	61	18	2
8	4	1	36	1	5
Average	62	48	27	17	3

From the data in Table 2, the initial period of tightening, bolt forces are scattered largely not only in the finite element calculation results but also in the experimental results. With the increasing of tightening round number, especially in the forth and fifth rounds, the bolt force get closer and closer to the target bolt force in both results. Moreover, the difference of the bolt force between the calculation result and the experimental result for the same bolt becomes smaller. The average value of this difference in the fifth round is only 3%. The results indicate that the finite element model and calculation results in this work can well reflect the actual situation, and the calculation results with ANSYS are credible.

The experimental results (the bolt load dispersion and leak rate) under three different tightening methods for the MMC flange joint are shown in Table 3.

Table 3. The comparison of the bolt load dispersion and leak rate under a different patterns.

Tightening pattern	bolt load dispersion	leak rate , cm^3/s
Star pattern of ASME PCC-1	3930.72	5.10E-03
alternative pattern # 3 of ASME PCC-1	4558.53	3.86E-03
SH-Method	1553.56	3.04E-03

It can be seen from Table 3, for a MMC type flange joint, the final bolt force dispersion and the leakage rate with the SH-Method tightening pattern are the lowest, comparing to the use of star pattern and the alternative pattern # 3 of ASME PCC-1. It is confirmed that the SH-Method has the best tightening effect, which is also shown in the calculation result with ANSYS.

8. Conclusions

The tightening methods for MMC bolted flange joints are studied in this work. According to the structural characteristics and sealing principle of MMC flange joints, the SH-Method, which has good tightening effect, less operation and less moving, is recommended as a suitable pattern for MMC flange joints. It is confirmed in both ANSYS calculation and experiments. The results are also compared with the star pattern and alternative #3 pattern in ASME PCC-1. The following conclusions can be drawn from this work:

（1） At the initial of tightening process, the MMC gasket presents the soft gasket characteristics, and after the metal to metal contact reaches, it shows the hard gasket features. At that time, the added loading is undertaken by the outer metallic ring of the MMC gasket. This should be considered when the tightening method is determined.

（2） Since the sealing principle in a MMC flange joint is not same as in a floating flange joint, so the patterns recommended in ASME PCC-1 are not suitable for it.

（3） The suitable pattern for a MMC flange joint, the SH-Method, is recommended in this work. The ANSYS calculation results showed, with the SH-Method, it needs less tightening rounds to reach the target bolt force, less number of tightening operation and less moving numbers, and the bolt load dispersion is lower, for a MMC flange joint, comparing to the star pattern and the alternative pattern in ASME PCC-1. The SH-Method shows a significant advantage in the tightening effect and tightening operations.

（4） The reliability of the finite element model and the ANSYS calculation results are confirmed by the experimental results. It is also verified the leakage rate in the MMC flange joint with the SH-Method pattern is lower than using a star tightening method and alternative method # 3 in ASME PCC-1.

ACKNOWLEDGEMENTS

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References

[1] G.D.Bibel,Experimental and Analytical Study of Elastic Interaction in a Pipe Flange, International Conference on Pressure Vessel Technology, Dusseldorf, Germany，1992.

[2] G.D.Bibel, R.Ezell, Bolted Flange Assembly: Preliminary Elastic Interaction Data and Improved Bolted-Up Procedures, Weld. Res. Counc. Bull., 408(1996), pp.1-27.

[3] G.Bibel,Tightening Groups of Fasteners in a Structure and the Resulting Elastic Interaction, Handbook of Bolts and Bolted Joints, J. H. Bickford and S. Nassar, eds., Marcel Dekker, Inc., NY, 1998, pp. 451-477.

[4] S. A.Nassar,A. A. Alkelani, Clamp Load Loss Due to Elastic Interaction and Gasket Creep Relaxation in Bolted Joints, ASME J. Pressure Vessel Technol., 128(2006), pp. 394-401.

[5] A. A.Alkelani,Gasket Creep Relaxation and Elastic Interaction in Bolted Joints, Ph.D. thesis, Oakland University, Rochester, MI, 2007.

[6] S.Kumakura, K. Saito, Tightening Sequence for Bolted Flange Joint Assembly, Proceedings of ASME Pressure Vessel and Piping Conference, PVP-457, Analysis of Bolted Joint, Cleveland, OH, July 20-24, 2003,pp. 9-16.

[7] ASEM PCC-1, 《Guidelines for Pressure Boundary Bolted Flange Joint Assembly》[S]. 2013.

[8] JIS B2205, 《Basis for calculation of pipe flanges》[S]. 2006

[9] M.Schaaf, J. Bartonicek, Calculation of Bolted Flange Connections[C]. Transactions of the 17th Conference on SMIRT. Prague, Czech Republic[s.n.]. 2003:17-22.

[10] EN1591-1, 《Flanges and their joints — Design rules for gasketed circular flange connections Part 1: Calculation》[S]. 2013.