Influence of Bolt Tightening Methods on the Sealing Performance of Large Diameter Bolted Pipe Flange Connections

1. Introduction

Gasketed pipe flange connections are used in large numbers in pressure vessels and pipe connections in various industries. It is known that the sealing performance of the pipe flange connections depends not only on the gasket characteristics but also on the tightening method. According to The High Pressure Gas Safety Institute of Japan (KHK)[1], it is reported that about 67% of leakage accidents from gasketed pipe flange connections are caused by improper bolt tightening method. One of the factors of tightening failure is the elastic interaction occurring during bolt tightening. This is a phenomenon that affects each other when a large number of bolts are tightened. Each axial bolt force falls below the target bolt axial force, and individual bolt axial forces vary. As a result, an appropriate bolt axial force cannot be achieved, the gasket compressive force required for sealing cannot be obtained and leakage may occur. It is difficult to reduce the effects of this elastic interaction to zero, and measures are being taken to reduce the effects, such as increasing the number of circular tightening cycles or performing cross-tightening. However, all of them are based on experience and it is hard to say that sufficient technical studies have been done[2)-5)].

Under these circumstances, various standards have recently proposed bolt tightening methods for achieving an appropriate bolt axial force. In the United States, ASME PCC-1[6] Guidelines for Pressure Boundary Bolted Flange Joint Assembly was proposed in 2000 and revised in 2013 and 2019. In Japan, JIS B 2251[7] "Flange joint tightening method" was issued in 2008, and in 2018, "Flange method mounting technical specification" was published in China. However, the index used in these standards is the final bolt axial force and does not deal with the actually required sealing performance of the flange connections.

In Valqua Technology News Vol.37 in the previous report, the effect of tightening methods of ASME PCC-1[6] and JIS B 2251[7] using ASME class 150 4 inches small diameter and ASME class 300 24 inches large diameter flange connections sealing performance was examined and it was clarified that both of them are appropriate methods to exhibit adequate sealing perfromance[8]. However, although ASME PCC-1[6] shows several bolt tightening methods, the effects of these tightening methods on the sealing performance of the connections have not been studied.

This reportaims to investigate the effects of the tightening methods combined with Alternative #1, #2, and #3, which are newly added to ASME PCC-1[6] by using ASME class 300 24-inch flange connections, on the variation of bolt axial force, sealing performances, bolt tightening times, and wrench moving distances. In this report, the test was conducted using our high-performance gasket No. GF300 and expanded graphite filler spiral gasket No. 6596V.

2. Test method

2-1) Test equipment

Figure1 shows the pipe flange connection with a gasket used in this paper. The dimensions are 24 inches, which is the largest nominal diameter in the ASME standard, the pressure rate is class 300, the shape is W/N, the seat is RF, and the material is SUS304. It is known that the mechanical behavior of

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the flanged connections changes depending on the presence or absence of the pipe. In thisreport, we used equipment with a pipe of about 800 mm to study under conditions close to the actual equipment.

The bolts are made of SNB7, and 24 hexagon bolts of size M39 are used. Two strain gauges are attached to each bolt body so that the axial force of all bolts can be measured. The strain gauge of each bolt has been calibrated in advance, and molybdenum disulfide has been applied to the thread and seat of the bolt and nut. Helium gas was used as the test gas, and the internal pressure was 2 MPa. The leakage amount of the flange connection was measured by a pressure drop method. We measured the change in pressure with a pressure gauge and calculate using the following equation (1).

$$L=1\text{atm}\times\frac{MV}{\rho tRT_1c}\left(P_1-\frac{T_1}{T_2}P_2\right) \quad (1)$$

where

- L : Leakage per outer circumference of gasket, [Pa·m^3/(s·m)]
- M: Molar mass, [mg/mol]
- V : Inner volume of pipe flange connections, [ml]
- ρ : Density of test gas, [mg/ml]
- t : Measurement time, [s]
- R : Gas constant , (=8.314), [J/mol·k]
- T_1 : Absolute temperature at the start of test, [K]
- T_2 : Absolute temperature at the end of the test, [K]
- P_1 : Absolute internal pressure at the start of the test, [MPa]
- P_2 : Absolute internal pressure at the end of the test, [MPa]
- c : Gasket contact outer circumference, [m]
- *atm* : Standard atmospheric pressure (=0.101325), [MPa]

Figure2 shows an image of the work of tightening the pipe flange connection body. Bolt tightening is performed using a torque wrench with the target torque. Target gasket surface pressure was 40 MPa for gasket No. 6596V and 25 MPa for gasket No.GF300 and the target torque value T was determined from the following equation (2). Table 1 shows the target gasket stress and torque.

$$T=K\frac{\sigma_g}{N}A_gd \quad (2)$$

where

- T : Torque, [N・m]
- K : Nut factor, (=0.135)
- σ_g : Target contact gasket stress, [MPa]
- A_g : Contact gasket area, [mm^2]
- N : Number of bolts, [pcs]
- d : Bolt nominal diameter, [m]

In the experiment, the bolt axial force and the flange clearance are measured for each tightening cycle.

Figure1 Experimental setup of 24" pipe flange connection

Figure2 Image of tightening

Table1 Target torque, target axial bolt force and contact gasket stress

Size of pipe flange connection	Class300 24B	
Gasket	No.6596V	No.GF300
Suggested contact gasket stress [MPa]	50	35
Target contact gasket stress [MPa]	40	25
Target axial bolt force [kN]	98.4	85.6
Target torque [N·m]	520	451

2-2) Test gasket

The gasket dimensions used in this paper $\phi612\times\phi772\times t3.0$ for No.GF300 and $\phi603.2\times\phi628.6\times\phi685.8\times\phi717.6\times t4.5$ for No.6596V. Both are ASME class 300 24-inch diameter dimensions.

3. Tightening method

In this paper, we compared the variation of bolt axial force, sealing performance, and tightening time of the flange connection under seven types of bolt tightening methods.
Table2 shows each tightening method, and the outline of each tightening method is described below.

3-1) Tightening method JIS B 2251[7)]

In JIS B 2251 flange joint tightening method[7)], paragraph 4b) states that "if the number of flange bolts is 12 or more, 110% of the specified tightening torque shall be the target tightening torque. In this study, the measurement and examination are performed when the target torque is set to 110% in addition to 100%. 5.3b) Section 4) states that when a spiral-wound gasket is used, the gasket width is so narrow that one-sided tightening is likely to occur. To prevent this, tighten all bolts at the end of star pattern by 50% of the target tightening torque, and one round of tightening is performed by clockwise or counterclockwise tightening methods. For this reason,

Table2 Bolt tightening methods

Tightening methods	Target Torque	Gaskets		Step 1	Step 2	Step 3	Step 4	Total
JIS B 2251 110%	110%	No.6596V	Number of bolts	4	24	24	24	232 bolts
			Rounds	4	1	6	2	
			Pattern	Star	Circular	Circular	Circular	
		No.GF300	Number of bolts	4	24	24	—	208 bolts
			Rounds	4	6	2		
			Pattern	Star	Circular	Circular		
JIS B 2251 100%	100%	No.6596V	Number of bolts	4	24	24	24	232 bolts
			Rounds	4	1	6	2	
			Pattern	Star	Circular	Circular	Circular	
		No.GF300	Number of bolts	4	24	24	—	208 bolts
			Rounds	4	6	2		
			Pattern	Star	Circular	Circular		
ASME Legacy	100%	No.6596V No.GF300	Number of bolts	24	24	24	—	216 bolts
			Rounds	3	3	3		
			Pattern	Star	Circular	Circular		
ASME Alt.#1	100%	No.6596V No.GF300	Number of bolts	4	16	24	24	120 bolts
			Rounds	2	1	1	3	
			Pattern	Star	Star	Star	Circular	
ASME Alt.#2	100%	No.6596V No.GF300	Number of bolts	4	16	24	24	120 bolts
			Rounds	2	1	1	3	
			Pattern	Star	Star	Star	Circular	
ASME Alt.#3	100%	No.6596V No.GF300	Number of bolts	4	24	—	—	108 bolts
			Rounds	3	4			
			Pattern	Star	Circular			
3 Rounds	100%	No.6596V No.GF300	Number of bolts	24	—	—	—	72 bolts
			Rounds	3				
			Pattern	Star				

the tightening method of No.6596V is different from sheet gasket of No.GF300. In addition, in JIS B 2251[7], additional tightening was proposed in some cases, and the retightening was also carried out in this study.

A major feature of the tightening method[7] according to JIS B 2251 is that only four bolts (when the number of bolts is 24 or less) are temporarily tightened first, and in the final tightening, all bolts are circumferentially tightened. Since the final tightening is a simple circular tightening, it can be expected to reduce time and prevent mistakes such as forgetting to tighten.

3-2) Tightening method ASME PCC-1[6]

In ASME PCC-1[6], unlike JIS B 2251[7], the tightening method does not change depending on the gasket type. This study covers Legacy, which has been proposed previously, and Alternatives #1, #2, and #3, which have been newly added since 2013.

Legacy is a method of diagonally tightening all bolts and is the most widely used tightening method, but it has been pointed out that it takes a lot of time.

Alternative #1 and #2 are methods to reduce the number of tightening bolts in the first step by increasing the torque stepwise for four different bolts in Step 1 and Step 2.

Alternative #3 is a simple tightening method similar to JIS B 2251[7] where only four bolts are temporarily tightened and then circumferentially tightened.

The final steps of the four tightening methods described in ASME PCC-1[6] are "until the nut no longer turns," and the number of tightening times described in Table 2 is the result of the number of times the nut no longer turns in this test.

3-3) Tightening method 3 Rounds

In addition to JIS B 2251 and ASME PCC-1 tightening methods, a convenient way to make three cycles of cross tightening in stepwise is also examined.

4. Experimental results

4-1) Gap distribution between flange faces

Figure3 shows the gap distribution between the flange when tightening by seven methods. The results for the installed gasket No.GF300 are shown by solid lines, and those for No.6596V are shown by broken lines. When the gasket was No.GF300, the effect of the tightening method was minor. On the other hand, in the case of No. 6596V, almost the same results were obtained with the methods based on the standards of JIS B 2251[7] and ASME PCC-1[6], but with the 3 rounds method, the gap was slightly large and the compression amount was small.

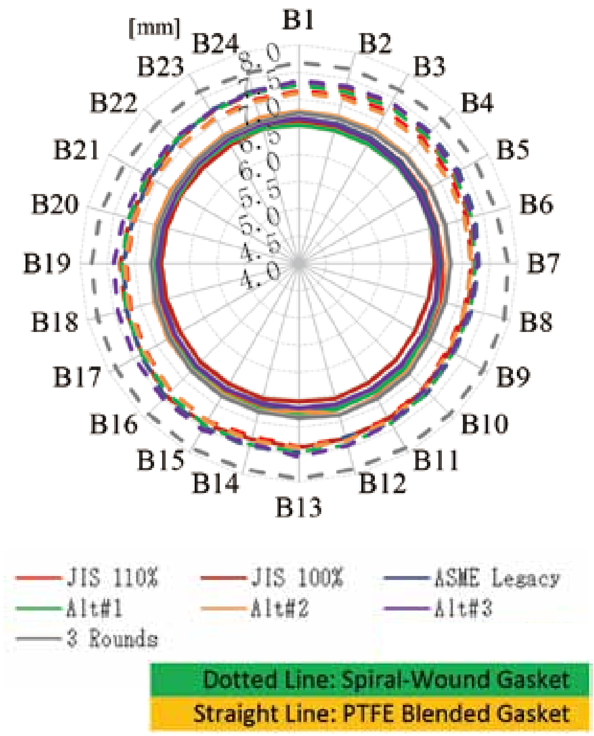

Figure3 Distribution of the flange gap

4-2) Bolt axial force distribution

Figure4 and 5 show the final bolt axial force distribution and the variation in axial force, respectively when the gasket was No.GF300. Regardless of the tightening method, variations in axial force are observed due to elastic interaction. In particular, the variation was large in the 3 Rounds method, and the tightening coefficient Q ($=F_{max}/F_{min}$) was 2.62. Regarding the minimum bolt axial force F_{min}, the target bolt axial force of 85.6 kN could not be achieved with all tightening methods due to the influence of elastic interaction. According to this, the value of Q in JIS 110% (Table2) is 1.31, and the value of Q in Alt#3 is 1.33, indicating the smallest value.

Figures6 and 7 show the final bolt axial force distribution and the results of variation in axial force, respectively when the gasket was No. 6596V. As in the case of No.GF300, the variation was remarkable by 3 Rounds method and one of the three bolts had zero axial force. In Figure 7, the value of Q becomes Q=1.47 in JIS 110%, showing the smallest value. In addition, the value of Q indicates that the tightening of No.6596V is larger than that of No.GF300.

4-3) Sealing performance

Figure8 shows the measurement results of the leak rate of the pipe flange connection tightened by each method. Regardless of the tightening method, the amount of leakage was smaller in the case where the gasket was No.GF300 than in the case where the gasket was No.6596V. The figure also shows the smallest bolt axial force F_{min} of 24 bolts. Comparing

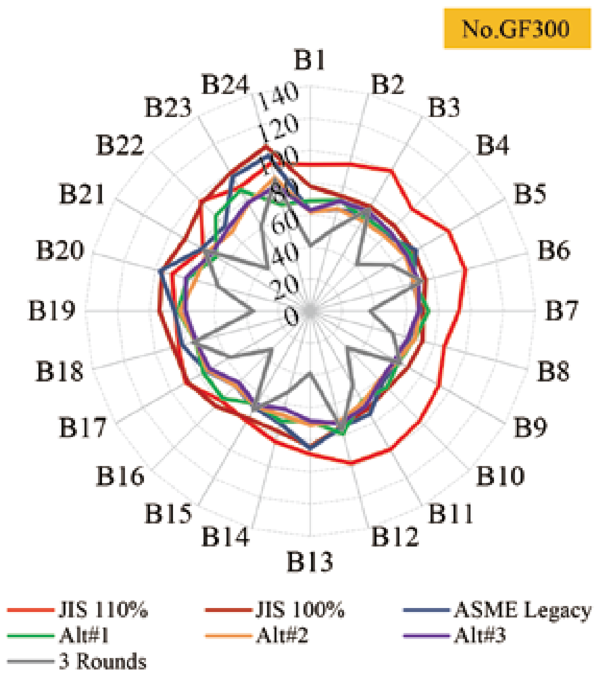

Figure4　Distribution of final axial bolt force (No.GF300)

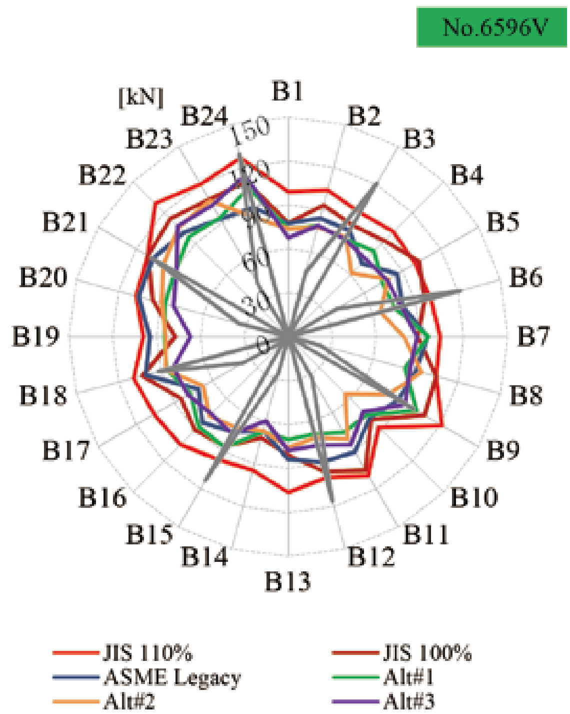

Figure6　Distribution of final axial bolt force (No.6596V)

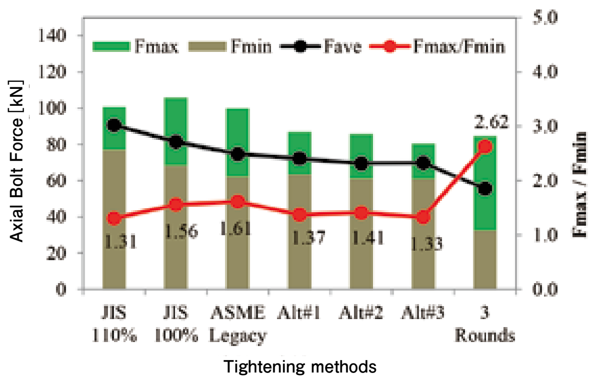

Figure5　Variation of final axial bolt forces (No.GF300)

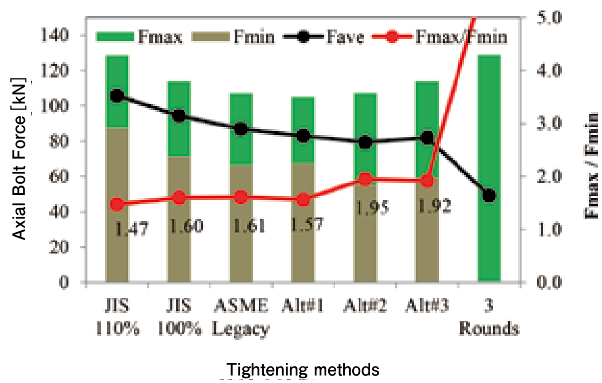

Figure7　Variation of final axial bolt forces (No.6596V)

the leak rate by each tightening method, it is understood that the leakage amount decreases as the minimum bolt axial force increases. Conversely, the smaller the minimum bolt axial force, the smaller the gasket contact stress locally and the larger the leakage amount. In other words, the minimum gasket contact stress has a large effect on the leakage. In the case of a pipe flanged joint with a gasket, if the bolt axial force is low in some parts, it is considered that leakage is likely to occur from the gasket contact surface in the vicinity. It has been shown that it is important to increase the minimum bolt axial force as much as possible to improve the sealing performance.

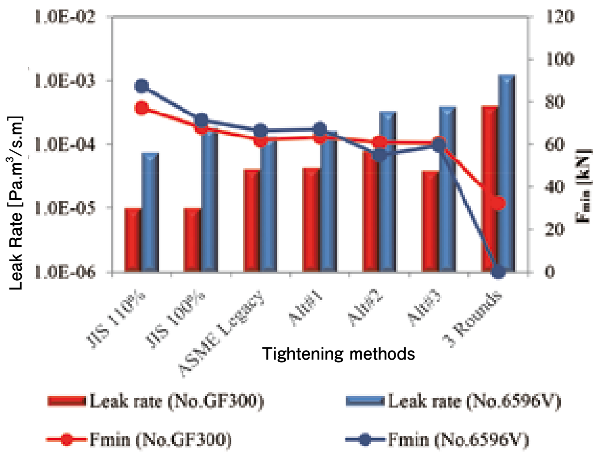

Figure8 Sealing Performance

4-4) Moving distance of wrench

Figure9 shows the moving distances of the wrenches when tightening in six different tightening methods. The moving distance is calculated not by the straight line distance between the bolt holes but by the shortest distance along the circumference. JIS B 2251 and ASME Alt#3 had relatively short moving distances. 3 Rounds method has a long moving distance in spite of the least number of tightening bolts. It can be said that the moving distance becomes shorter in the tightening method in which there are many circumferential tightening, and it can be said that the moving distance becomes longer in the tightening method in which there are many cross tightening.

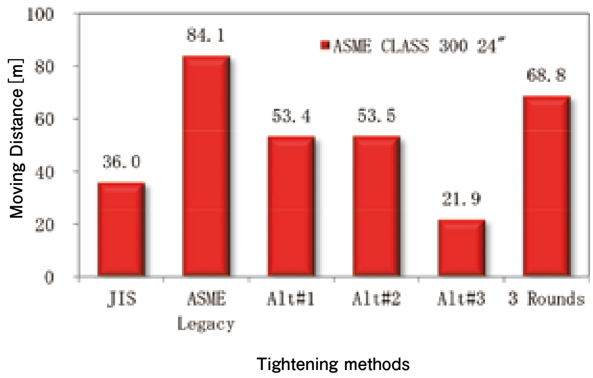

Figure9 Wrench's Moving distance

4-5) Tightening time

Figure10 shows the tightening time required for each of the six tightening methods. In this experiment, the gap between the flange faces was measured during the tightening, but the results in Figure 10 do not include the gap measurement time. JIS B 2251[7] and ASME PCC-1[6] Legacy, which has a large number of tightening bolts, have a longer tightening time, and the 3 Rounds tightening method with a smaller number of tightening bolts has the shortest tightening time. Although a torque wrench was used in this study, the tightening time may greatly vary depending on tools such as a hydraulic wrench and torque tensioner and the environment at the site.

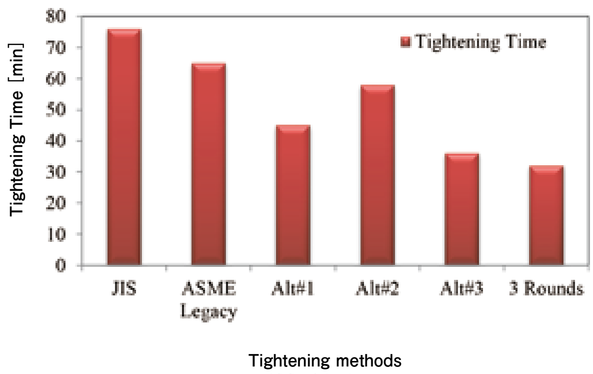

Figure10 Tightening time

5. Summary

In this paper, sealing performance, flange gap, bolt axial force, moving distance of torque wrench and tightening time of two gaskets of No.GF300 and No.6596V were used when tightened by seven different tightening methods, were measured using a large- diameter pipe flange connection, and the following results were obtained.

(1) No significant difference was found in the flange gap distribution according to these tightening methods.

(2) The sealing performance of pipe flange fasteners is affected by the tightening method and JIS B 2251[7] 110% tightening method has the least leak rate. Then, JIS B 2251[7] was 100%. Although it was observed that the 3 rounds tightening method was simple but the sealing performance was inferior.

(3) It was observed that the sealing performance of pipe flange joints are affected by the minimum bolt axial force and it is important to increase the minimum bolt axial force as much as possible to improve the sealing performance.

(4) As for the tightening method, the moving distance of the torque wrench tends to lengthen when the cross tightening is large, and as for the tightening method with a large number of tightening times, the tightening time tends to longer.

(5) JIS B 2251[7] and ASME PCC-1[6] Legacy and Alt #1 have relatively small leaks but require a longer tightening time. The 3 Rounds method has a relatively large leakage but the tightening time is less than half of JIS B 2251[7].

6. Conclusion

The American Society of Mechanical Engineers (ASME) has introduced a factor called assembly efficiency η. η is the ratio of the final axial bolt force to the target axial bolt force, and the value is less than 1. In other words, in actual design and construction, the target value of the bolt axial force is further increased by $1/\eta$. (JIS B 2251[7]) The basic idea of 110% is to tighten 10% larger. However, this is based on the bolt axial force and is not always appropriate, and it has been proposed to use the assembly efficiency based on tightness parameter[9]. It seems that there is room for improvement to a more efficient tightening method to improve the sealing performance required for the gasketed flange connection. We hope that this research will help the plant tightening work.

We were advised by Mr. Koichi Morimoto of Mitsubishi Chemical Co., Ltd. about this experiment. We would like to express my gratitude by noting.

7. References

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