Table 1 Test sequence I (For non-metallic gaskets)

Step	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
σ N/mm^2	5	10	20	10	5	20	30	40	20	10	5
P MPa	2										

Table 2 Test sequence II (For spiral wound gasket)

Step	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
σ N/mm^2	12.5	25	50	25	12.5	50	75	100	50	25	12.5
P MPa	4										

MPa for sheet gaskets and spiral wound gaskets, respectively. Compressive load of gasket is calculated by

$$W = A_g \sigma . \tag{7}$$

The testing procedure is also shown in Fig. 2. In the testing procedure, the gasket is loaded to half of the maximum gasket stress, then, unloaded until one eighth of the maximum gasket stress. The gasket is loaded again to the maximum stress, then, unloaded again. This testing procedure simulates the assembly process and the working condition of gaskets.

The internal pressures are 2 and 4 MPa for sheet gaskets and spiral wound gaskets, respectively. The gasket is left for 5 minutes when the gasket stress is changed. Then, the leak rate is measured using a burette. It takes about 15 minutes for each measurement. Leak rate measurements for the 11 steps can be completed approximately within 3 hours.

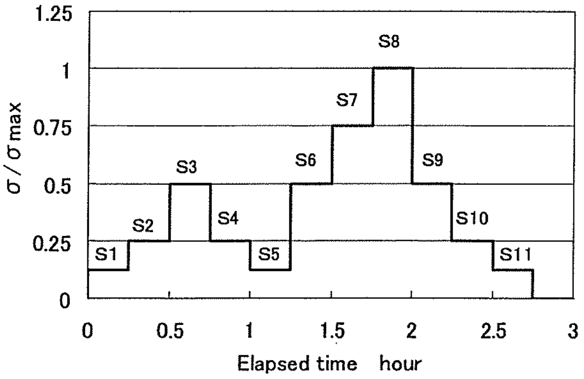

Figure 2 Testing sequence of gasket

Data processing and graphical representations of test data

Effective gasket stress is calculated using the following equation:

$$\sigma_e = \frac{W - \pi d_i^2 P / 4}{A_g} . \tag{8}$$

where, the load W and the internal pressure P are measured values.

The test results are summarized in the following graphs:

- Effective gasket stressσ_e – deformation of gasket δ_a
- Fundamental leak rate L_s – Effective gasket stressσ_e
- Fundamental leak rate L_s – deformation of gasket δ_a

TEST RESULTS

Figure 3 shows the fundamental leak rate L_s as a function of the gasket stress obtained using the loading-unloading sequence shown in Fig. 2. The tested gasket is compressed non-asbestos fiber sheet gasket #1995(Nichias Corporation), of which thickness is 1.5 mm. The inner and outer diameters of contact surface of gasket, d_i and d_o, are 61 and 96 mm respectively.

The leak rate is expressed by the unit Pa · m^3/sec throughout this paper. The leak rate decreases with increasing the gasket stress in the assembly process. When the gasket is unloaded at about 20 MPa, which corresponds to a working condition, the leak rate stays less than that in the assembly condition. Leak rates for S5 through S10 could not be measured because the leak rates were well under the measurable limit of a burette. It can be seen that the leak rates for loading and unloading cycles are different each other. As shown in this result, the sealing behavior is complex and is difficult to formulate.

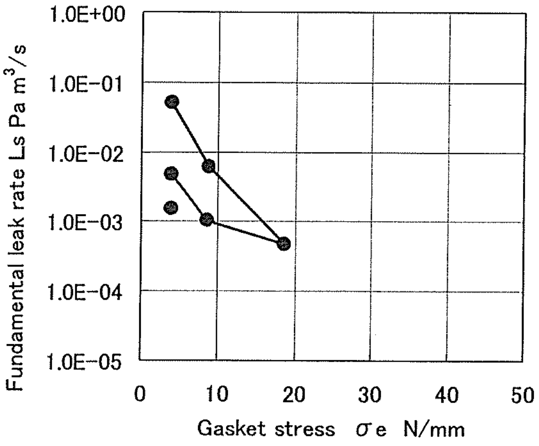

Figure 3 Sealing behavior as a function of gasket stress

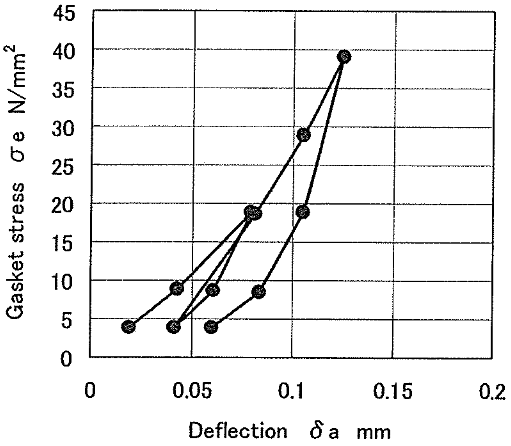

Figure 4 Stress-deflection curve of gasket

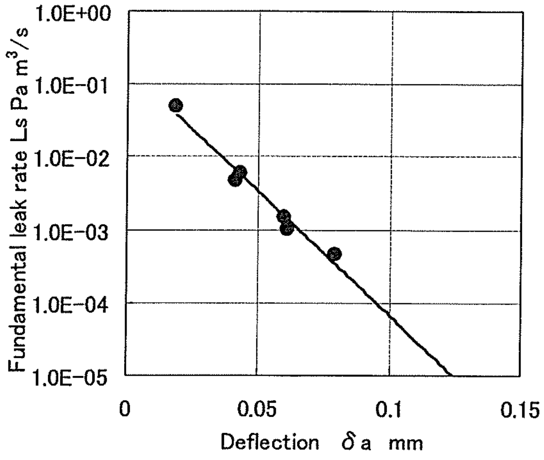

Figure 5 Sealing behavior as a function of gasket deflection

Figure 4 shows the stress-deflection diagram of the tested gasket during the seal test. As shown in the figure, the inclination increases as the gasket is compressed. This means that the gasket becomes stiffer. When the gasket is unloaded at about 20 MPa, a large plastic strain is observed compared with the recovery of the elastic strain. The reason for this is thought that the compressed fiber sheet gaskets are porous in nature. Once they are compressed, the material cannot be recovered due to its porous structure.

It has reported that the leak rate has a close relation with the gasket strain or deflection [4, 5]. The leak rate is arranged by the deflection of the gasket and the relation between them is shown in Fig. 5. The leak rate is indicated using a log scale. The solid line is an approximated result mentioned later. As shown in the figure, experimental results in the assembly process and those in the working condition almost coincide each other and fall onto one straight line on a semi-log graph. This fact strongly suggests that the leak rate of gasket is directly related to the gasket deflection. The reason for this is thought to be as follows: many micro leak paths through the section of gasket exist because the gaskets used in this study are porous. It is thought that the cross sectional areas of the micro leak paths govern the leak rate and the strain or deflection of gaskets is a direct measure of the cross sectional area of the micro leak paths. Thus, the leak rate has a good correlation with the gasket strain or deflection. As the relation between the leak rate and the gasket deflection is linear on a semi-log plot, the leak rate can be expressed by the following equation:

$$L_n = 0.1675 \cdot e^{-78.22\delta_a} \quad [\mathrm{Pa \cdot m^3/s}]. \qquad (9)$$

The calculated result by Eq. (9) is also plotted in Fig. 5. The experimental data are well approximated by Eq. (9).

CONCLUSIONS

This paper discusses the gasket testing procedure HPIS Z104 to obtain fundamental sealing behavior of gasket established in Japan. It is shown that the fundamental sealing behavior can be well characterized using the proposed testing procedure.

The future project is to develop experimental formulas to indicate the sealing behavior of gasket for various kind of gaskets based on measured data obtained using the testing procedure HPIS Z104.

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APPLICATION OF PLASTIC REGION TIGHTENING BOLT TO FLANGE JOINT ASSEMBLY

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ABSTRACT

Elastic region tightening based on torque control method is conventional method of tightening a bolt. Axial force of the bolt is controlled by a torque wrench, however, it is not easy to achieve uniform bolt tightening force. When torque method is applied to flange joint assembly, the scatter of the bolt tightening foeces are large. They might cause the leakage of the internal fluid from a flange joint. Recently, plastic region tightening is remarked for critical applications, which provides good uniformity in bolt preloads and high preloads compared with the elastic region tightening.

In this research, the plastic region tightening is applied to flange joint assembly and its superiority in uniformity of the bolt tightening force is demonstrated. For the tightening tests, JPI-4inch flange, spiral wound gaskets and M16 bolts were used. Axial force and elongation of all bolts in the flange were measured. Bolts were tightened by modified HPIS flange tightening procedure which incorporates the angle control method into the clockwise tightening sequence.

Experimental results show that variations of the axial force in the plastic region was smaller than those in the elastic region. The influence of the elastic interaction on the axial force in the plastic region is also small. It is concluded that the application of plastic region tightening to flange joint assembly is effective for the leak-free joint and that the nominal diameter of the bolt can be reduced.

INTRODUCTION

A flange joint with a gasket is widely used for the joint of the piping and the pressure vessel in various plants. The pressurized fluid contained are often under high temperatures and harmful. It is difficult to prevent the leakage completely, therefore there is a risk that the leakage causes an accident. Many researches have been carried out to establish a method of design and assembly procedure of the leak-free flange joint, though it has not been reached.

Conventional tightening method of the flange joint tightened with multi-bolts is elastic region tightening by the torque control method with torque wrench. In the elastic region tightening method, variation of the friction coefficient under tightening affect the uniformity of the tightening force. Additionally, flange joint assembly brings some problems and difficulties; the tightening force variation due to elastic interaction, uneven flange gaps and the relaxation of the gasket. They may cause ununiformity in the gasket stress and result in the leakage of an internal fluid from the flange joint.

In the automotive industry, the plastic region tightening is in attracted as practical tightening method in which the target of tightening force is yield point or plastic region. The plastic region tightening has advantages as follows; higher tightening force, less variation of the tightening force. The yield tightening force is determined by the mechanical properties of the material and the effect of the friction coefficient of the bolt is small. The plastic region tightening prevents advantageously the fatigue fracture and the relaxation of the joint and may increase the reliability of the joint. The diameter of the bolt is reduced, the number of the bolt is decreased or the strength class of the bolt is lowered. For the critical application, therefore, high performance and cost reduction are achieved compatibly.

The plastic region tightening has been applied to various fields. In the automotive industry, it is applied to the parts where frequent disassembly and reassembly are not required such as the cylinder head bolt and the connecting rod bolt in the engine assembly, and its superiority is demonstrated. In an architectural field, it is applied to friction grip bolts. Many researches have been done to clarify the superiority of the plastic region tightening and to establish a strength design of the joint.

Table 1 HPIS tightening procedure [2].

Step	Loading
Install	Hand tighten all bolts, then tighten 4 or 8 equally spaced bolts with gradually increased tightening torque to 100% of target torque on a cross-pattern tightening sequence. Check flange gap around circumference for uniformity.
Tightening	Tighten all bolts with tightening torque to 100% of target torque on a rotational clockwise pattern for specified iterations (6 passes for 10 inch and greater flange, 4 passes for others).
Post-tightening	If necessary, wait a minimum of four hours and tighten by the previous step, but 1 or 2 passes.

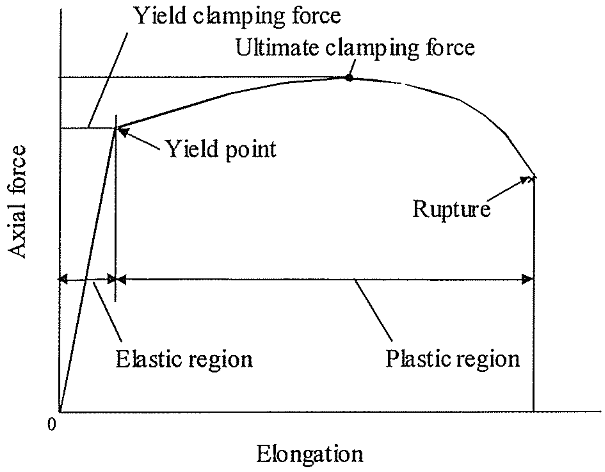


Fig.1 Relation between axial force and bolt elongation under tightening.

Table 2 Tightening control method.

Tightening control method	Index	Tightening area	Tightening coefficient Q
Torque control method	Tightening torque	elastic region	1.4-3
Angle control method	Tightening angle	elastic region	1.5-3
		plastic region	1.2
Torque gradient control method	Tightening torque gradient for tightening angle	elastic limit	1.2

Today, the advantages of the plastic region tightening has been noticed. However, the characteristics of joints with multi-bolts tightened to the plastic region such as the flange joint is not yet shown.

In this research, the plastic region tightening is applied to flange joint assembly. Tightening procedure for the multi-bolt joint according to the plastic region tightening method is proposed and the superiority in the uniformity of the bolt tightening force is demonstrated. The uniformity of the bolt tightening force contributes to the leak-free service of the flange joint. Since the plastic region tightening obtains higher tightening force compared with the elastic region tightening, it enables the bolt and the flange joint to be downsized.

OVERVIEW OF THE BOLT TIGHTENING PROCEDURE FOR FLANGE JOINT ASSEMBLY

Although the importance of bolt tightening force control is recognized and the torque control method is applied widely, it is difficult to achieve accurate tightening force. The friction coefficient may varies even if the torque wrench is carefully used, and it follows that the scatter in tightening force becomes at least ±17% [1].

JPVRC BFC committee has proposed a new tightening method (HPIS procedure, namely clockwise pattern tightening method[2]), with the aim of a simple and effective procedure which achieves uniform bolt preloads and accurate flange alignment [2].

Table 1 shows the steps of the HPIS tightening procedure. The bolts are tightened to 100% of the target torque in all steps to decrease the number of tightening steps, except for the install step to prevent the flange misalignment by snugigng and tentative tightening. In all steps, the clockwise-pattern bolt tightening sequence is employed with the aim of a simple procedure to prevent human errors.

HPIS tightening procedure (Clockwise-pattern tightening method) achieves a comparable uniformity of the bolt tightening force, while the total tightening steps/rounds required for the joint assembly is decreased, compared with ASME method which employes the torque increment steps and a cross-pattern bolt tightening sequence[3]. HPIS procedure reduces both the cost and the human errors to avoid the complicated specification on the torque increment rounds and the tightening sequence, so that the method is practical with effectiveness and simplicity [2],[4].

THE CONCEPT OF PLASTIC REGION TIGHTENING

Table 2 shows various tightening control methods. The torque control method is applied to the elastic region tightening. The angle control method and the torque gradient method are applied to the plastic region tightening. The tightening factor

$Q = F_{f\max}/F_{f\min}$ shown in Table 2 means a scatter in the tightening force. The value of Q for the plastic region tightening including the yield point tightening is smaller than that for the elastic region tightening.

Figure 1 shows the relation between axial force and elongation of bolt under tightening to rupture.

Plastic region tightening is a method of tightening to the plastic region where the tightening force is greater than the yielding load (yield clamping force in Fig. 1) of the bolt. The tightening force of the bolt, which depends on its mechanical properties and the friction coefficient, is 80-90% or more of the tensile strength of the bolt. Since the control of strength of the bolt is easier than the control of friction coefficient, the scatter of tightening force by the plastic region tightening is smaller than the elastic region tightening. The plastic region tightening method has higher efficiency of the strength utilization of the bolt.

For the plastic region tightening, the tightening force is not controlled by the torque control method, therefore, an angle control method, i.e. the control of the rotational angle of the nut, is employed. Since the slope of curve at plastic region shown in Fig.1 is small, effect of the error of the rotational angle on the scatter of the tightening force is small.

ESTIMATION OF YIELD TIGHTENING FORCE BASED ON RIGID-PLASTIC MODEL

Estimation method of yield tightening force of bolts based on rigid-plastic model was proposed by Tsuji et al. [5], [6]. It is possible to estimate the yield tightening force in the plastic region tightening by the use of the material constant obtained by uniaxial tension of the bolt. The yield tightening force F_{fy} of the bolt is expressed as

$$F_{fy} = \frac{\pi d_S^{\,2} \sigma_{ys}}{4\sqrt{1+3\left\{\frac{3}{2}\frac{d_2}{d_S}\left(\frac{P}{\pi d_2}+1.155\mu_s\right)\right\}^2}} \qquad (1)$$

where d_2 is pitch diameter, d_S is diameter of net cross-sectional area, P is pitch, σ_{ys} is yield stress and μ_s is friction coefficient of thread.

Bolts with reduced shank of hollow cylinder were used for the tightening test in order to adjust the yield tightening force. The yield tightening force of the bolt with reduced shank is also calculated based on the solution extended to a hollow cylinder.

For the rigid-plastic hollow cylinder, the yield criterion under the combined loads of axial tension and torque is expressed as follows :

$$\left(\frac{F_{fy}}{F_y}\right)^2 + \left(\frac{T_{sy}}{T_y}\right)^2 = 1 \qquad (2)$$

where F_{fy} is axial tension and T_{sy} is torque. The value of F_y and T_y are yield point loads when the hollow cylinder is subjected to axial tension only and torque only, and expressed as follows :

$$F_y = \frac{\pi}{4} d_E^{\,2}(1-k^2)\sigma_{ys} \qquad (3)$$

$$T_y = \frac{\pi}{12} d_E^{\,3}(1-k^3)\tau_{ys} \qquad (4)$$

where σ_{ys} is the yield stress (under uniaxial tension), d_E is outer diameter of reduced shank body and $k = d_e/d_E$ is diameter ratio of hollow cylinder. Shearing yield stress $\tau_{ys} = \sigma_{ys}/\sqrt{3}$ is derived from von Mises yield criterion.

Since thread torque T_s is proportional to the axial force of the bolt F_f, the relation between yield tightening force F_{fy} and yield thread torque T_{sy} is expressed as

$$T_{sy} = F_{fy}\frac{1}{2}\left(\frac{P}{\pi}+1.155\mu_s d_2\right) \qquad (5)$$

Knowing μ_s, F_{fy} is obtained from Eqs. (2)-(5) as follows :

$$F_{fy} = \frac{\pi d_E^{\,2}(1-k^2)\sigma_{ys}}{4\sqrt{1+3\left\{\frac{3}{2}\frac{d_2}{d_E}\frac{(1-k^2)}{(1-k^3)}\right\}\left(\frac{P}{\pi d_2}+1.155\mu_s\right)^2}} \qquad (6)$$

When σ_{ys} = 900MPa obtained from uniaxial tension test is substituted for Eq.(6), F_{fy}=42.8kN. Calculated yield tightening force is decreased by 8% compared with the yielding load 45.1kN obtained by the uniaxial tension.

PRELIMINARY TIGHTENING TEST OF BOLT

INDICATOR TYPE OF BOLT

Characteristic of plastic region tightening of the bolt used is examined before the tightening test of the flange joint.

Figure 2 shows the indicator type of bolt for the measurement of the bolt elongation. Nominal diameter of the bolt is M16. The material of the bolt is SNB7, and of the nut is S45C. The middle part of the bolt was machined to a reduced shank body. A through hole of the diameter 6mm is drilled and a indicator rod of diameter 4mm is passed through the bolt to mea-

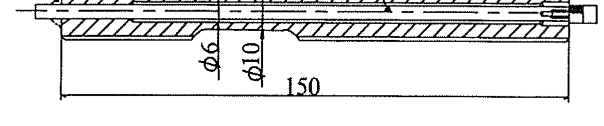


Fig.2 Indicator-type of bolt.

sure the bolt elongation. An edge of the rod is fixed by welding, and a flat gage head is set on the other edge.

TIGHTENING TEST CONDITIONS

Figure 3 shows a assembly of a bolt and a elongation detector and Fig. 4 shows a setup for the plastic region tightening test of the bolt. Voltage change of a potentiometer by the displacement of the indicator rod is measured with a digital multimeter and recorded by a PC. A load cell which measures the tightening force is placed between nuts. The lubricant used in the test is a dry coating spray of MoS_2 (molybdenum disulfide) used in many plants.

Firstly, the bolt is tightened by hand lightly. After that, the bolt is tightened untill the bolt breaks by the angle control method using a torque wrench with a ten times torque amplifying device.

CHARACTERISTIC OF BOLT UNDER THE PLASTIC REGION TIGHTENING

Figure 5 shows the test result of the plastic region tightening of a set of the SNB7 bolt and the nut. Figure 5 (a) shows the relation between the nut rotational angle and the bolt tightening force and (b) shows the relation between the bolt elongation and the bolt tightening force. The bolt yielded when its elongation reached to 0.3 mm, and ruptured at 2.1 mm in elongation. The yield tightening force is 47.9kN, determined by 0.2% permanent set of the reduced shank body length. These behaviors are similar to those of general high-strength bolt tightened to the plastic region.

To obtain the relation between the nut rotational angle and the bolt elongation, the compression compliance of the joint should be taken into account, besides the pitch of the bolt. Since the compression compliance of the flange joint is large due to the gasket and the flange rotation in the case of the following flange tightening test, the target value of the tightening angle should be chosen to make sure that bolt is settled into the plastic region.

TARGET VALUE OF NUT ROTATIONAL ANGLE

Figure 6 shows the method to determine the target value of the nut rotational angle θ_N. In order to minimize the influence of the variation of the nut rotation angle on the tightening

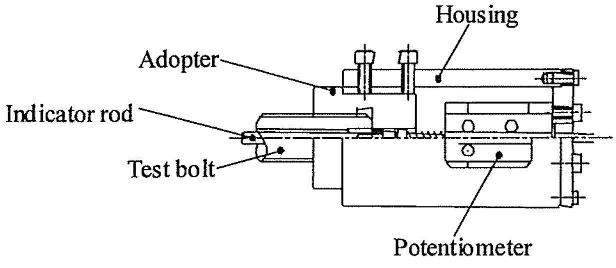
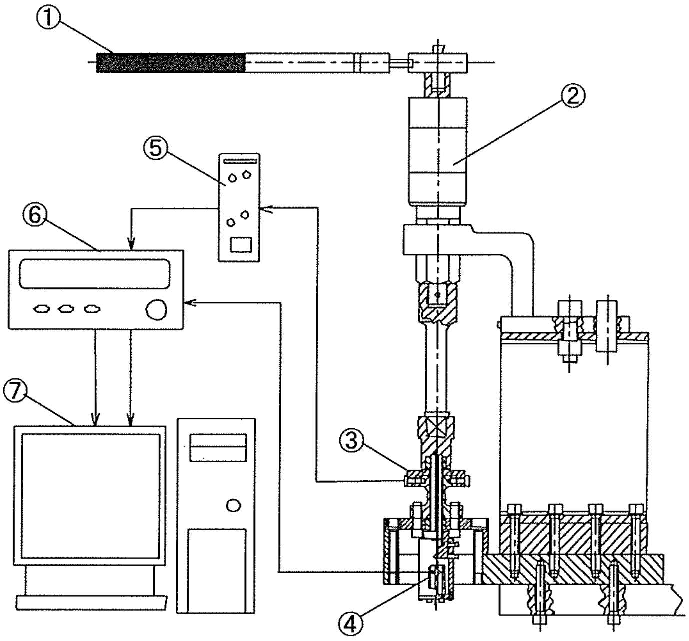


Fig.3 Assembly of bolt and elongation detector.

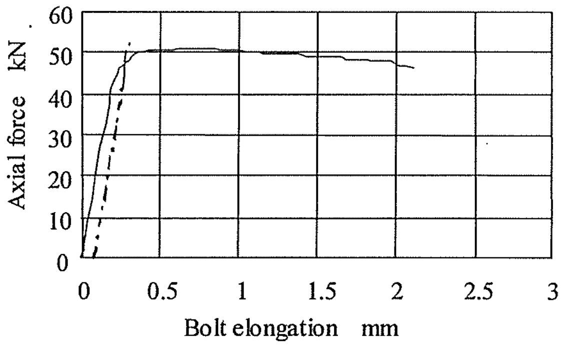


① Torque wrench ② Ten times torque amplifying device

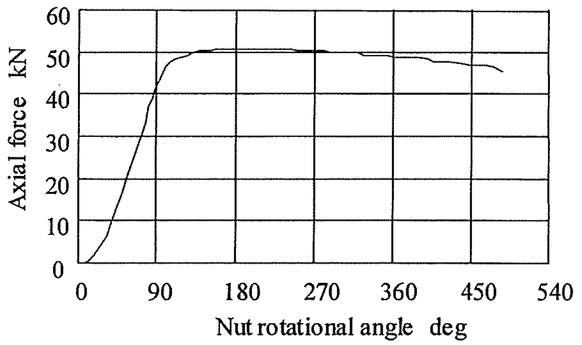
③ Load cell ④ Potentiometer ⑤ Strain amplifier

⑥ Digital multi-meter ⑦ Personal computer

Fig.4 Setup for plastic region tightening test.



(a) Relation between axial force and bolt elongation.



(b) Relation between axial force and nut rotational angle.

Fig.5 Result of plastic region tightening test.

force, θ_U shown in Fig.6 seems to be suitable for the target value. Necking of the bolt starts just after the maximum point θ_U, so that the weakening effect of the reduction in the cross-sectional area is dominant and the tightening force decreases until the bolt ruptures. It might be undesirable to generate necking immediately after tightening. Considering the assembly efficiency in the site and the reuse of the bolt, nut rotational angle should be as small as possible. Then, the mean value of θ_Y and θ_U, is considered as the optimum target value of the nut rotational angle θ_N,

$$\theta_N = \frac{1}{2}(\theta_Y + \theta_U) \qquad (7)$$

The value of θ_N is set to 420 degrees by the preliminary flange tightening test, taking into account of the compliance of the actual flange joint.

PLASTIC REGION TIGHTENING TEST OF THE FLANGE JOINT

SETUP FOR TIGHTENING TEST

Figure 7 shows a setup for the plastic region tightening test of the flange joint. Bolt tension is controlled by the angle control method where a torque wrench and a ten times torque amplifying device are used for tightening operation. Tightening force of each bolt is measured using a load-cell with strain gages and the flange gaps are measured by a vernier caliper. Elongation of the bolt is measured using the potentiometer. Measured data are recorded by a personal computer through a digital multimeter. The test flange is the 4 inch class 150 lb (material: SFVC2A), raised face slip-on welding type flange specified in JPI (Japan Petroleum Industry). The test bolt (stud) is nominal diameter of M16 with nuts (bolt material: SNB7, nut material: S45C). Figure 8 shows a test gasket, spiral wound gasket (SWG) made of non-asbestos filler with an outer ring (No.591, Nippon Valqua Co.).

TEST CONDITIONS

Tightening test procedure follows the slightly modified HPIS procedure which employs a rotational clockwise pattern tightening sequence, to achieve an assembly efficiency and the joint reliability. The angle control method is used for tightening instead of the torque control method. As an install step, bolts are hand tightened, and are tightened by a cross-pattern tightening sequence with a snug torque corresponding to 10kN of the bolt axial force. As a main step, bolts are tightened in a rotational clockwise pattern sequence and the nut rotational angle is 60 degrees. Since the tightening force is 49kN when the bolt completely reaches the plastic region by the preliminary test, target value of the nut rotational angle is set to 420 degrees, corresponding to 7 passes. Lubricant used in the test is a dry coating type spray of MoS_2 (molybdenum disulfide) applied to many plants.

RESULTS AND DISCUSSIONS

Figure 8 shows the result of the tightening test of the flange joint: Figure 8 (a) shows the relation between the pass number and the bolt elongation and (b) shows the relation between the pass number and the axial force. The axial forces of all bolts are measured during the tightening process. The bolt elongation increases in proportion to the pass number from pass No.1 to pass No.4. The rate of the bolt elongation increment changes when the bolts reaches the plastic region (Fig. 8 (a)). In pass No.5, the bolt axial force becomes 40kN and reaches the yield

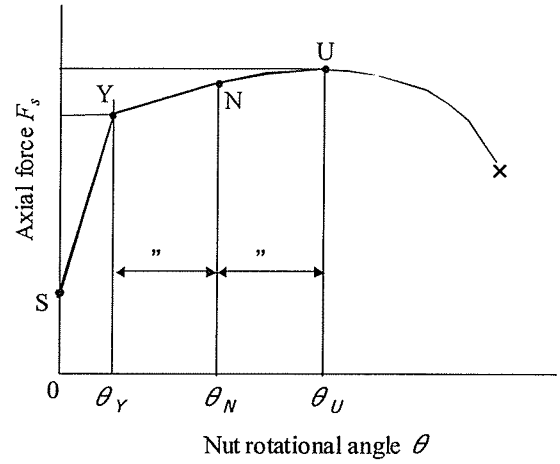
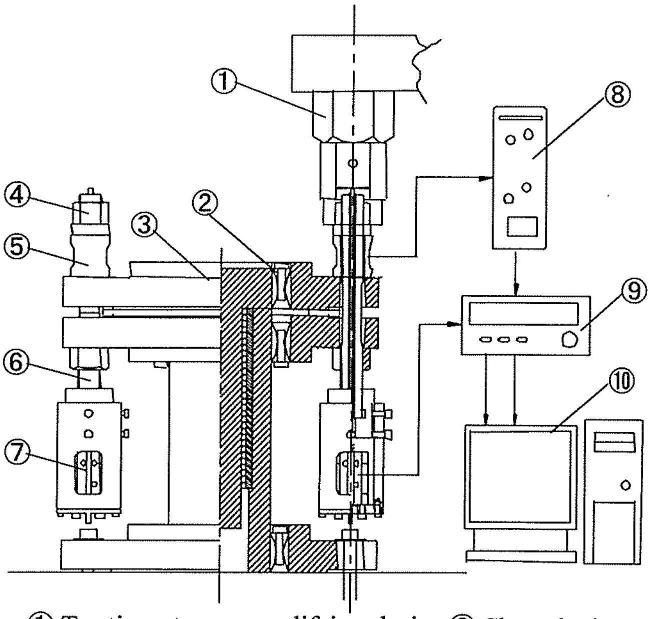


Fig.6 Determination of target of nut rotational angle.



① Ten times torque amplifying device ② Clamp lock
③ Flange joint ④ Hexagon nut ⑤ Load-cell
⑥ Bolt ⑦ Potentiometer ⑧ Strain amplifier
⑨ Digital multimeter ⑩ Personal Computer

Fig.7 Setup for flange tightening test.

point. In pass No.6, all bolts reach the plastic region. Their final axial force, namely tightening force are about 45 kN at θ_N. Scatter of axial force is 10% or less when tightening was completed. The uniformity of bolt tightening forces obtained by the test is equivalent or superior to that of the elastic region tightening. A favorable result is obtained compared with the data of HPIS procedure for the elastic region tightening. In the case of the bolted joint tightened by many bolts such as the flange joint, the scatter of the bolt axial force is small by the plastic region tightening.

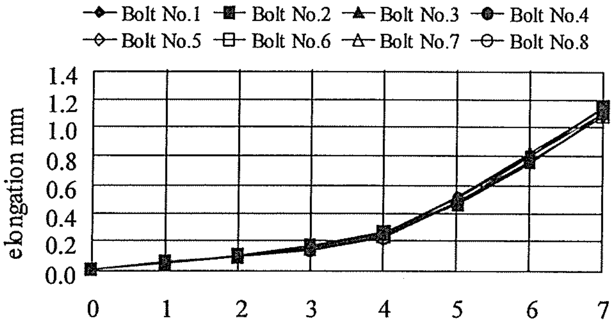
Figure 9 shows the elastic interaction in the tightening processes: Fig. 9 (a) shows variation of the bolt axial force in the pass of the elastic region and (b) shows variation of the bolt axial force in the pass of the plastic region.

When two adjoined bolts have been arranged relatively closely, the influence of the elastic interaction on the variation of the bolt axial force is significant under the elastic region tightening (torque control method). The influence of the elastic interaction appears in the elastic region under the plastic region tightening by the angle control method as well as the elastic region tightening by the torque control method. When bolts reach the plastic region, tightening of a bolt does not influence the axial force of the neighboring bolts. An increase in the axial force is very small in the plastic region, so that the influence of the elastic interaction is also small. It is effective in the uniformity of the bolt tightening force.

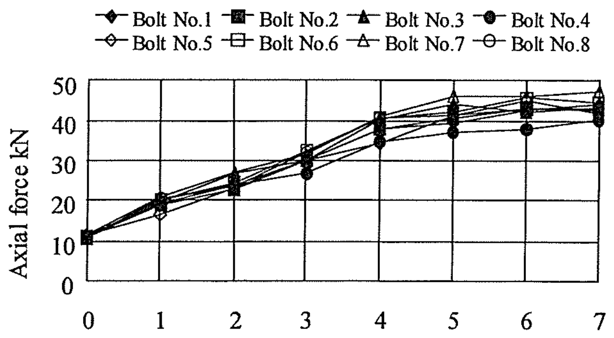
The flange gaps are measured at four points of the flange circumference in order to check the uneven clamping. Ununiformity of flange gaps measured are from 0 mm to 0.4 mm.

These data are the comparable to the data of the elastic region tightening by HPIS procedure. Uneven clamping does not appear in the plastic region tightening.

In this research, bolts with the reduced shank of cross-sectional area $A_E = 50.3$ mm^2 are used to adjust the tightening force and their yield clamping forces are 50 kN. Standard tightening force for the combination of the test flange and the gasket is 35kN. Assuming that the number of bolts and the strength class of bolts are constant, equal tightening force can be achieved by using M8 bolts (stress area $A_S = 36.6$ mm^2). Application of plastic region tightening to the flange joint is able to downsize the bolts and the flange due to higher tightening forces and their uniformity.

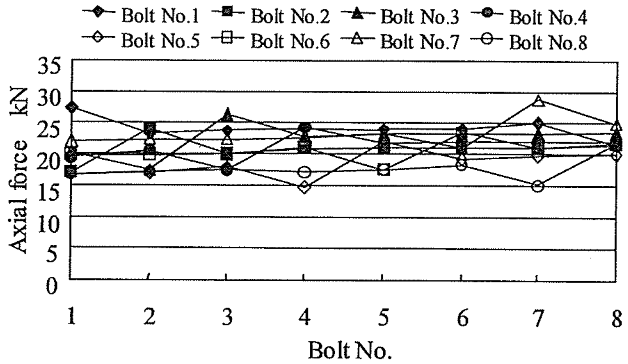


(a) Relation between pass number and bolt elongation.

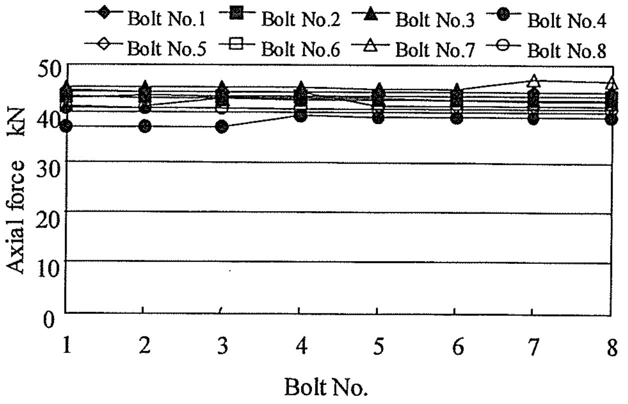


(b) Relation between pass number and bolt elongation.

Fig.8 Result of tightening test of flange joint.



(a) Pass at elastic region. (Pass No.2)



(b) Pass at plastic region. (Pass No.6)

Fig.9 Variation of axial force during one pass.

CONCLUSIONS

This paper described the application of plastic tightening bolt to the flange assembly. The following results were obtained.

1. The behavior of the plastic region tightening of the bolt made of SNB7 was examined. There was no difference between the SNB7 bolt and the high strength bolt for the automotive application.
2. The estimation method of the yield clamping force of the bolt with reduced shank of hollow cylinder was proposed.
3. The flange joint was tightened to the plastic region of the bolt by the modified HPIS tightening procedure with the angle control method.
4. Under the plastic region tightening, the influence of the elastic interaction appeared in the elastic region as well as the elastic region tightening by the torque method. When bolts reached the plastic region, tightening the bolt does not influence the axial force of the neighboring bolts. Uniform tightening force is achieved, so that scatter of final tightening force was 10% and less.
5. When the plastic region tightening is applied to the 4 inches standard flange joint, equivalent tightening force can be achieved by using M8 bolts in place of M16 bolts.

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フランジ継手用ガスケットの常温・高温下における漏洩量評価

（J-EHOT 試験方法の提案）

Evaluation of Leakage of Gasket for Flanged Joint under Room Temperature and Elevated Temperature (Proposal of J-EHOT Test Procedure)

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Key Words: Gasket, Flanged joint, Leakage test, HOTT,ROTT, EHOT, Tightness,

1．緒言

管用ガスケットのシール性能をまとめ米国機械学会（ASME）内の圧力容器研究委員会（PVRC）は，新ガスケット係数（G_b, a, G_s）を提案している．その係数を導き出す常温試験である ROTT(Room Temperature Tightness test)(1)試験及び高温試験である HOTT(Hot Operational Tightness Test)(2試験)及び EHOT(Emission Hot Tightness Test)試験も公表されている．

一方，日本高圧力技術協会(HPI)の圧力設備のシーリング技術研究委員会(STOP)で独自の試験方法として常温でのガスケットの基本密封特性試験方法(3)（以下，HPIS ガスケット試験法と呼ぶ）を規定した．

本研究では HPIS ガスケット試験法を高温に拡張した試験方法 J-EHOT を提案した．300℃で J-EHOT 試験を実施し，うず巻形非石綿ガスケットの漏洩量を測定している．

2．HPIS ガスケット試験法

HPIS ガスケット試験法では，ガスケット寸法に依存しないものとして定義された基本漏洩量 L_s (Pa・m^3/s)を有効締付圧 σ_e(N/mm^2)と圧縮変形量 δ_a (mm) で評価する．L_s は次式で表される．

$$L_s = \frac{L}{k} \qquad (1)$$

ここで，漏洩量 L (Pa・m^3/s)，ガスケット形状係数 k である．基本漏洩量を用いることにより試験・実用面での汎用性が増す．k は次式で表される．

$$k = \frac{1}{d_o / d_i - 1} \qquad (2)$$

HPIS ガスケット試験法では試験手順の簡略化及び時間の短縮が試されている．図 1 及び 2 にうず巻形ガスケットにおけるガスケット締付圧の負荷シーケンスを示す．現在 HPIS では常温試験のみの規定である．

3．J-EHOT の提案

HPIS ガスケット試験法を高温に拡張した試験方法 J-EHOT(Emission Hot Tightness Test)を提案する． EHOT 試験では常温特性を ROTT，高温特性を HOTT で評価していたものを HOTT の後に ROTT を行うことにより高温でのエージング後のシール性能の変化によって劣化したガスケットがシール性能に及ぼす影響を確認できる．この試験法は実際のプラント運転状況を想定しているところに特長がある．

また，HOTT 試験だけでは高温下における評価が難しいため，高温下での評価に E-HOTT 試験の結果を加えることを提案する．J-EHOT 試験ではプラントにおいてのスタートアップ時とシャットダウン後の再起動時とのガスケットのシール性能評価を行うことができる．これにより漏洩レベルがどれくらい増えているか評価ができる．

試験はガスケットを試験装置に装着し，室温状態で図 1 の Pre-ROTT に従って Step を行う．その後，ガスケット温度を 300℃まで上昇させる．昇温後，試験内圧一定で 90 時間放置（エージング）する．エージングの間，漏洩量は 6 時間おきに測定する．測定には石鹸膜流量計を用いる．エージング終了後，除荷・負荷過程を繰り返し終了する．図 1 の Step では HOTT 試験において漏洩量の変化が見られなかったので，図 2 の Step において荷重除荷負荷の幅を大きくし，除荷回数も増加させた．高温試験終了後にガスケット温度を常温に戻し，Post-ROTT として除荷過程を行う．

4．試験装置及び試験ガスケット

図 3 に試験装置の構成を示す．試験ガスケットは油圧シリンダによって均一に圧縮される．プラテンには計 8 個のカートリッジヒータが埋め込まれており 450℃まで昇温が可能である．温度はプラテンに埋め込まれたシース形熱電対により測定している．また，冷却装置によりロードセル，油圧シリンダは熱による影響を受けない．作動流体は He ガスを使用する．試験ガスケット・プラテン周りはメタルベローズとメタル中空 O リングにより密封されており，漏洩した He ガスはメタルチューブを通り石鹸膜流量計へと導かれる．この流量計はガラス体積管内の所定距離内を石鹸膜が移動する時間から He ガスの漏洩量を測定するものである．ガスケットひずみの測定にはダイヤルゲージ及び高温用クリップゲージにて測定する．

試験ガスケットは 3 インチ内外輪付非石綿うず巻形ガスケット(ASME/ANSI Class 300 NPS3/No.8596,日本バルカー工業製)である．

本試験装置の優位性は，高温状態においてガスケット応力，ガスケット変位，He ガスの漏洩量，ガス内圧を同時に測定できる点にある．これにより実際のプラントの運転サイクル（スタートアップ，シャットダウン）に近づけた理想的な条件で試験でき，従来は不可能だったガスケットの長期劣化化の様子を測定可能にしている．

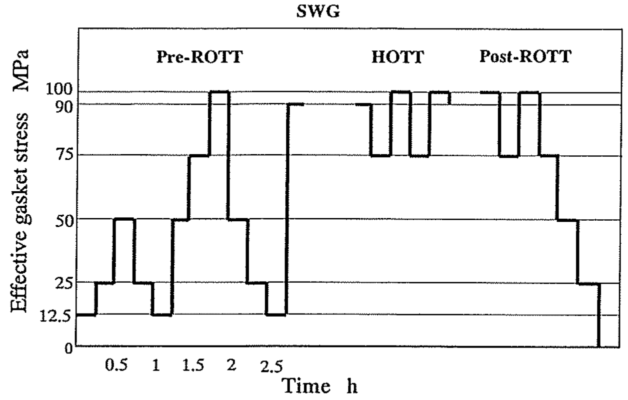

Fig. 1 Loading sequence of a gasket

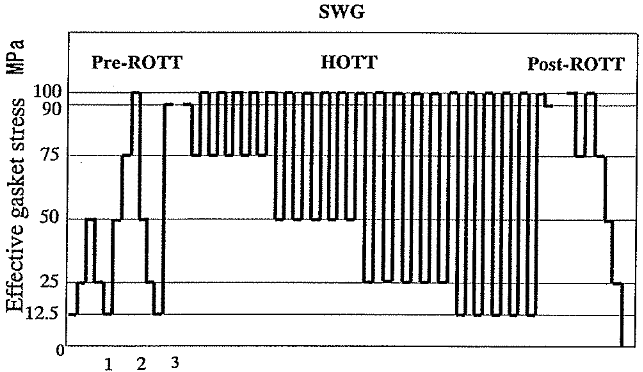

Fig. 2 Loading sequence of a gasket

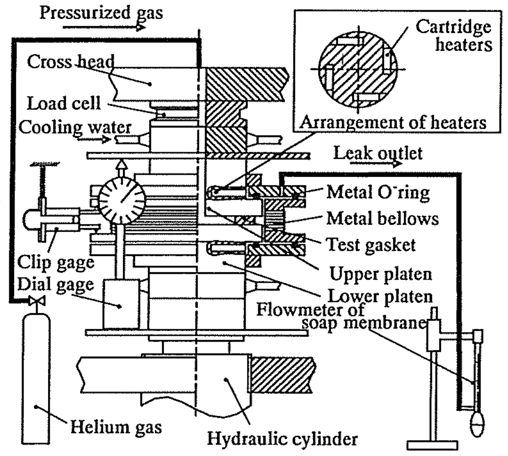

Fig. 3 Testing apparatus

5．試験結果

図4及び5にHPISガスケット試験/高温試験/常温試験の流れを基本漏洩量を対数とし，横軸に時間経過(Step)として示す．図4及び5から，常温試験Step3において漏洩量を測定することが出来ない．これは石鹸膜流量計の測定限界により測定不可能になったためである．また，その後のStepでも同様に測定限界に達している．そこで本研究では基本漏洩量2×10^{-7} (Pa・m^3/s)を下回る値を測定限界として位置づける．石鹸膜流量計を用いた非石綿うず巻き形ガスケットの常温試験では，このことを考慮に入れる必要がある．

プラント運転時の外乱を想定したガスケット応力の除荷過程を図4では2回，100，75(N/mm^2)の幅で，図5では5回づつ 100,75,50,25,12,5 でそれぞれ行ったが漏洩量はあまり変化が見られず図4及び図5共に約10^{-5}(Pa・m^3/s)で一定のシール性能が見られる．HOTT試験後のJ-EHOT試験によりスタートアップ時とシャットダウン後再起動時とのシール性能評価が得られた．これによりガスケットの漏洩レベルが2桁〜3桁上昇していることが確認できた．これは実際のプラントにおけるガスケットの使用条件を考慮したもので，初期締付からのシール性能評価が得られた．これにより，HPISガスケット試験方法を用いて，高温後常温におけるシール性能評価が可能であることが認められた．図4及び5から各試験の結果を比較すると途中のばらつきはあるが，基本漏洩量は高いレベルで最終的な収束を見せている．

以前の実験結果ではHOTT試験において漏洩レベルが大きく変化したものもある．これはガスケットの個体差であると考えられる．よって今後さらに実験を繰り返して高温の外乱のパターンの数はデータ数を増やす必要がある．

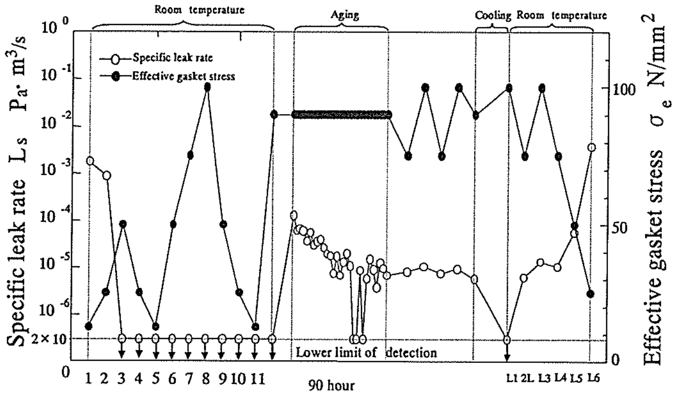

Fig. 4 Loading sequence diagram of a gasket

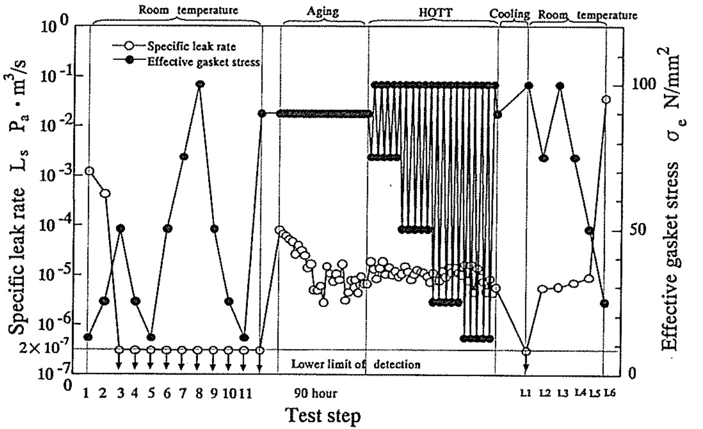

Fig. 5 Loading sequence diagram of a gasket

6．結言

高温後における管フランジ用ガスケットの基本密封特性試験を行った．以下に得られた成果を示す．

(1) HPISガスケット試験法を拡張した高温後のガスケット試験法（J-EHOT試験法）を提案した．

(2) 提案した試験方法により高温後常温における評価をガスケットの漏洩レベルの比較により，可能であることを明らかにした．

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ガスケット非石綿化の動向と密封特性試験方法の検討

圧力設備のシーリング技術研究(STOP)委員会
委員長　澤　俊行（広島大学）
○ 副委員長　辻　裕一（東京電機大学）

1．はじめに

石綿による健康被害が社会問題化しており，ガスケットの非石綿化が急務である．これに対応するため，新しい材質や形式のガスケットが開発されつつある．ここで，ガスケット係数（m, y）の測定方法が明確でないため，新材料，新形式のガスケットに対し根拠のある係数の決定ができないという問題が生じている．欧米ではフランジ継手からの微少漏洩抑制を目標としたフランジ設計規格が制定もしくは検討されており，これらの規格では(m, y)の代わりに使用される新ガスケット定数を決定するための密封試験方法が存在する．

本委員会では，独自の試験方法として HPIS Z 104「管フランジ用ガスケットの基本密封特性試験方法」を規格化し，さらにガスケット高温特性評価への拡張を検討している．

2．石綿ガスケットの規制に関する動向

2006 年 1 月に厚生労働省から石綿製品の代替可能性に関する検討結果が公表された. 新規の設備では石綿製品の使用を認めないこととなった．既存の設備では技術的に代替化困難な事例があるため，例外的にやむを得ない使用条件を禁止の除外とした．経済産業省からは，既存の設備についても 2008 年に，又は前倒しで全面的使用禁止という方針が出された. 表 1 に代替困難性の分類レベルを示す. 石綿ジョイントシートの代替品を始め多くのガスケットがレベルⅡの実証試験段階の製品と判断された. レベルⅡ製品の実証試験では，実使用条件下における健全性の評価と漏洩等のリスクの把握を行う．同時に，非石綿製品の施工、フランジ継手のトルク管理等の適切な使用方法の検討も挙げられている．

表 1　石綿製品の代替困難性の分類

レベルⅠ	代替可能な非アスベスト製品の新規開発，又は非アスベスト製品の製造に当たって製品設計及び評価が必要なもの
レベルⅡ	非アスベスト製品の安全性、信頼性に係る評価が必要なもの
レベルⅢ	代替化に際して経済性の向上が期待されるもの

3．常温及び高温におけるガスケットの基本密封特性試験方法

常温試験である HPIS Z 104 は，以下の方針により欧米の試験方法を改善している．

- 要求漏洩量レベルは石鹸水法の検出限界を包含し，さらに微少漏洩にも対応できる．
- ガスケットの使用実績から実用的な試験ガスケット締付圧と試験内圧を決定した．
- 異なる寸法のガスケットに対して，試験結果が適用できる方法を採用した．

試験では，試験ガスケットに圧縮荷重とヘリウムガス内圧を負荷し，ガスケット外周から漏出したガスを捕集し，漏洩量を測定する．ガスケット締付圧の負荷シーケンスは，組立て時及び運転時のガスケット締付圧状態を模擬している．

各試験ステップにおける漏洩量 L から，ガスケット寸法に依存しない基本漏洩量 L_s を次式で算出する．ここで k はガスケットの内外径比による形状係数である．

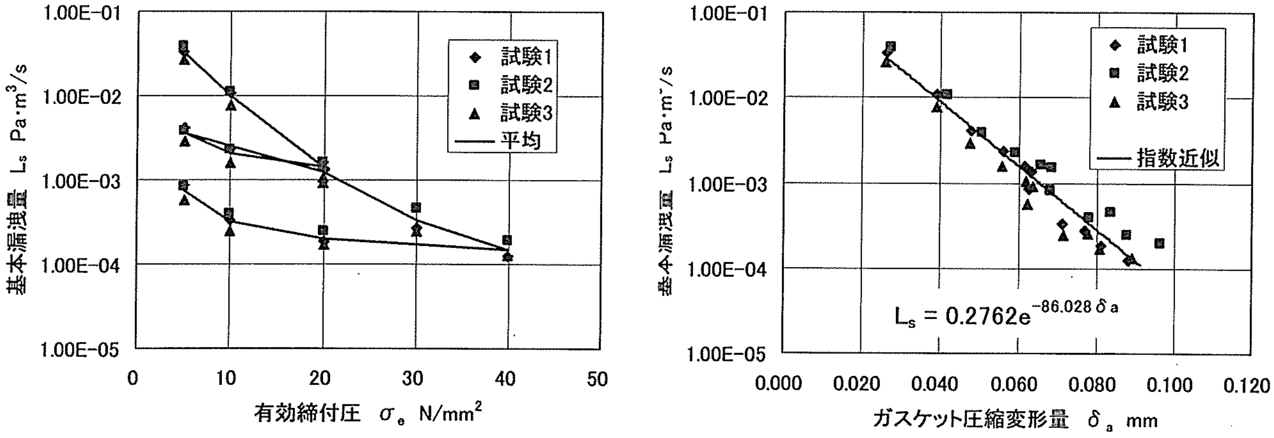
$$L_s = \frac{L}{k} \quad (\mathrm{Pa \cdot m^3/s}), \qquad k = \frac{1}{d_o/d_i - 1}$$

図２に試験結果の例を示す．有効締付圧 σ_e および圧縮変形量 δ_a に対する L_s を対数表示している．圧縮変形量で整理すると，L_s が一義的に直線関係で表示でき，漏洩量に及ぼす締付圧の履歴の影響を無くせる．

図３に常温試験／高温試験／高温後常温試験からなる一連の試験ステップで得られたガスケットの基本密封特性を示す．現在，常温における組立て／高温でのガスケットのエージングおよび外乱／シャットダウンを考慮できる標準的な試験方法の確立を目指している．

４．まとめ

今後この規格に基づく試験データの収集と解析を行い，漏洩を起こさないフランジ設計を行うための基礎データとなるガスケット定数を検討する計画である．高温密封特性評価に関しては，実機フランジにおける高温漏洩問題との関連が課題である．



(a) 基本漏洩量 L_s－有効締付圧 σ_e　　(b) 基本漏洩量 L_s－圧縮変形量 δ_a

図２　非石綿ジョイントシート（30K-40A）の密封特性試験結果

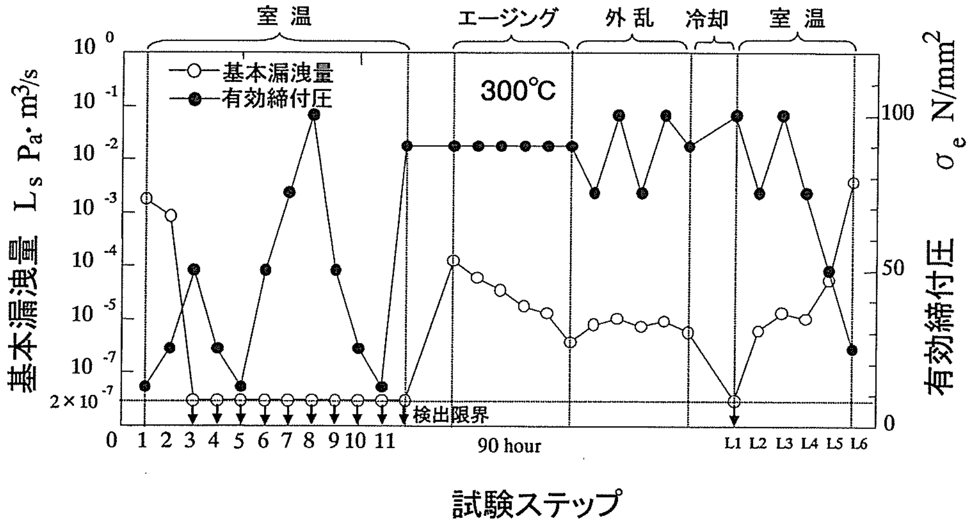


図３　高温ガスケット試験による基本密封特性（SWG: Class 300, NPS 3）