Evaluation of Basic Sealing Properties of the Pipe Flange Connection with Metallic Flat Gasket

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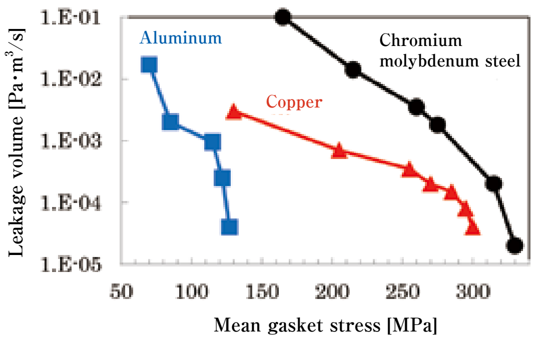
1. Introduction

It is known that the metallic gaskets such as metal flat gaskets and ring joint gaskets are widely used within the flange connection under high temperature and high internal pressure conditions in petroleum refining, petrochemical, and power plants. However, the some leakage accidents occur in the connections. The main reasons of those are considered that the mechanical characteristics and tightening method of the gasketed connection have not been clarified. Many previous studies for soft gasket such as the compressed fiber sheet gaskets, PTFE gaskets, and spiral wound gaskets have been performed in American Society of Mechanical Engineers (ASME), High Pressure Institute of Japan (HPI), universities, and manufacturers. However, there have been few studies on a flanged connection with the metallic gasket, so their behaviors remain unknown[1), 2)].

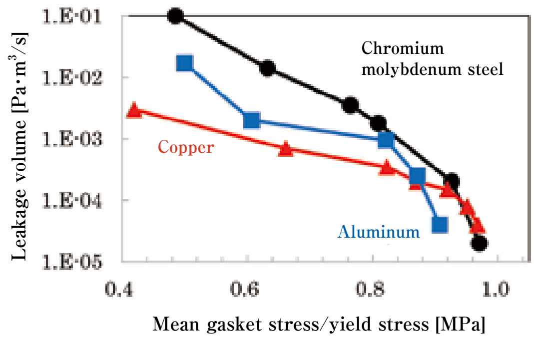
Kondo et al. reported the plastic strain on the gasket face made the sealing performance in metallic flat gasket improved[3)-7)].

The relationship between the leak rate of metallic flat gaskets made by chromium-molybdenum-steel, copper and aluminum and the mean contact gasket stress were shown in Figure1 (a). It was found the sealing performances were improved as Young's modulus and surface hardness of material decrease. In addition, when the ratio of mean contact gasket stress for the yield stress was related with leak rate, the leak rate decreased exponentially at the value of ratio is near 1.0 as shown in Figure1 (b). Those data indicated that the sealing performance of metallic gasket was influenced so much by the yield stress. However, most of prior studies have been discussed around the leakage of 1×10^{-4} Pa·m^3/s level due to the limitations of the measuring functions of evaluation equipment.

The objective of this paper is to discuss the leak rate of $1 \times 10^{-4} \sim 10^{-7}$ Pa·m^3/s for metallic gaskets. The sealing performance of the gaskets under compression was measured for two types of gasket materials (aluminum and copper) and three types of gasket width using platen by the experiments and the FEM calculations. In addition, the mechanical characteristics of pipe flange connection with metallic gasket were evaluated using the ASME/ANSI class 300 2-inch flange.



(a) The relationship between leak rate and mean contact gasket stress



(b) The relationship between the leak rate and the ration of the mean contact gasket stress for yield stress

Figure1 The sealing performance of metallic flat gaskets

2. Experimental Method

Figure2 showed the experimental setup of platen device in which metallic flat gasket was compressed for measuring an amount of leakage. The experimental setup was consisted of the compression tester (AUTO GRAPH 500KND; made by Shimadzu Corporation) consisted of the platen made of SUS304, a helium gas cylinder, a pressure gauge, a flow meter for amount of leakage and the displacement gages. The device for measuring leak rate could be alternately switched functions between a soap-film flowmeter and helium leak detector (made by ULVAC). When the leak rate was 1×10^{-4} Pa·m^3/s or lower, the measurement was performed using the helium leak detector. The materials of flat metallic gasket were aluminum (A1050) and copper (C1020). The sizes of gasket were $\phi25\times\phi20$ (outside×inside diameter), $\phi30\times\phi20$, $\phi40\times\phi20$, $\phi65\times\phi$ 55mm, and the gasket thickness was chosen as 3.0mm. The helium gas was applied to 4MPa after the platen with gasket is compressed, and then, the leak rate and displacements of gasket were measured. In a test sequence of compression and recompression, the contact gasket stress was changed in the following stepwise: 0 → 180 → 0 MPa for aluminum, and 0 → 450 → 0 MPa for copper.

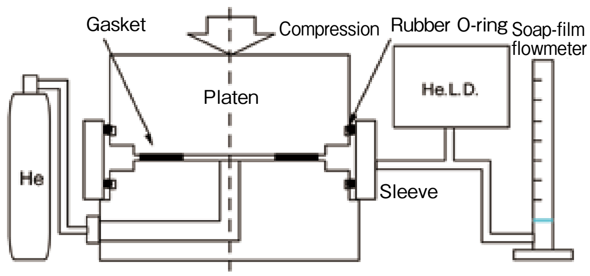


Figure2　Illustration of platen test equipment

3. FEM Calculations Method

The FEM calculations were performed for the platen test shown in section 2, using the numerical code ABAQUS. Figure3 showed the 3-D FE model of the platen test equipment with metallic flat gasket. Originally, an effective evaluation can be calculated with the axi-symmetric model, however, the 3-D model was employed to compare with one for the pipe flange connection. The gasket was modeled as elastoplastic element, and the Platens were modeled as elastic element. The platen was under compression, then the gasket stress, compression displacement and corresponding plastic strain were calculated. Here, the corresponding plastic strain is defined as:

$$\overline{\varepsilon^p}=\int\sqrt{\frac{2}{3}\left\{(d\varepsilon^p_{xx})^2+(d\varepsilon^p_{yy})^2+(d\varepsilon^p_{zz})^2\right\}+\frac{1}{3}\left\{(d\gamma^p_{xy})^2+(d\gamma^p_{yz})^2+(d\gamma^p_{zx})^2\right\}}$$

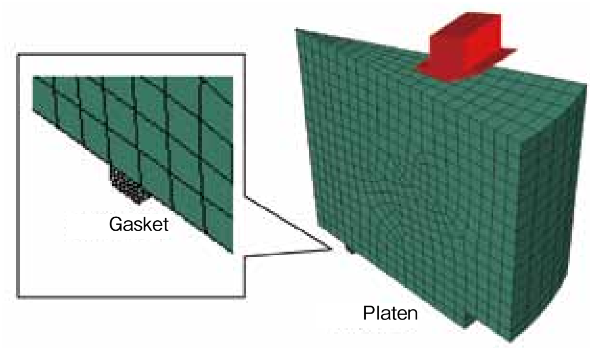


Figure3　FE model for platen testing

4. Results of Experiments and FEM calculations

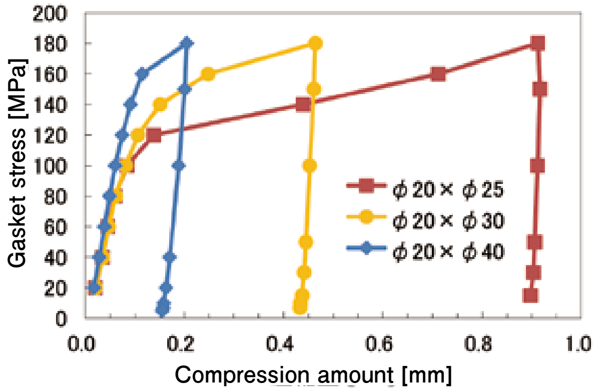
Figure4 showed the results of platen test for aluminum and copper gaskets. It was found that the deformation increased as the outer diameter of gasket decreased (as the gasket width decreased) in both materials. This was resulted in the influence of shape of gasket.

Figure5 showed the surface conditions of the aluminum flat gasket with a diameter of $\phi20\times\phi40$ and the platen after the compression test. It seemed that there were white discolorations at inner and outer side positions of gasket on both the gasket face and the platen faces. Those imply that the compressed aluminum gasket would have been deformed to inner and outer diameter and be sharpened by the friction with the platen faces because of remained small aluminum particles on the surface.

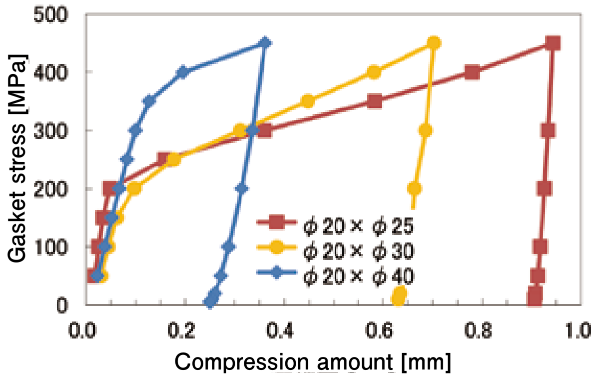
The relationship between leakage volume obtained from the platen test and the mean gasket stress was shown in Figure6. Use of a helium leak detector allowed the measurement of very small leakage volume of approx. 1×10^{-7} Pa·m^3/s. The measurement results for both aluminum and copper gaskets showed that application of a higher average gasket stress reduced the leakage volume and that a reduction of the mean gasket stress increased the leakage volume. Also, the reduction rate of leakage volume became more moderate at around 120 MPa for aluminum and at around 250 MPa for copper.

In general, the relationship between leakage volume and mean gasket stress is known unchanged even when the gasket width is changed. Therefore, the sealing properties of metal flat gaskets can be organized according to the mean gasket stress. During the unloading process, the leakage volume rapidly increased at approximately 30 MPa for aluminum gaskets and at approximately 50 MPa for copper gaskets. This was considered to have been caused by the loss of conformability of initial step of loading between the flange and gasket surfaces.

Figure7 showed the results of a Finite Element Analysis which replicated the platen test. The figure showed the distribution contours of gasket stress and corresponding plastic strain when the gasket material is aluminum and the gasket dimensions are $\phi20\times\phi25$. The figure indicated that the corresponding plastic strain rapidly increased when the mean gasket stress increased from 100 MPa to 120 MPa. At that time, the gasket might have undergone a marked plastic deformation to fill the very small roughness on the flange surface to improve sealing properties. This result indicates that plastic strain of a gasket surface is necessary for metal gaskets to exert their excellent sealing properties.



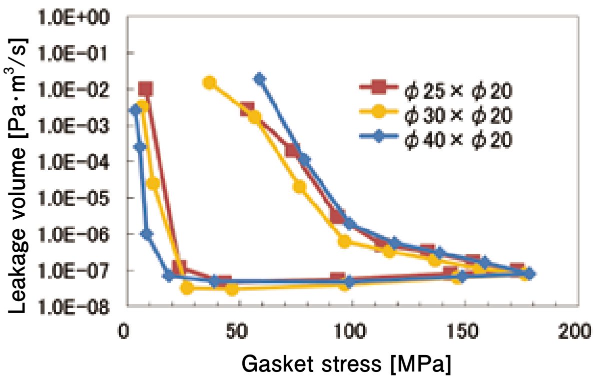
(a) Compression properties of aluminum flat gaskets



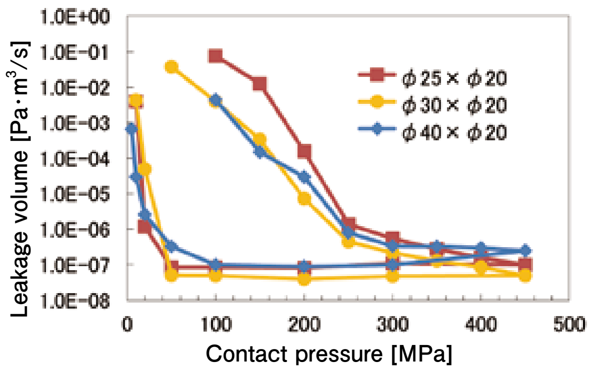
(b) Compression properties of copper flat gaskets

Figure4 Compression properties of copper flat gaskets

Figure5 Surfaces of gasket and flanges after compression test

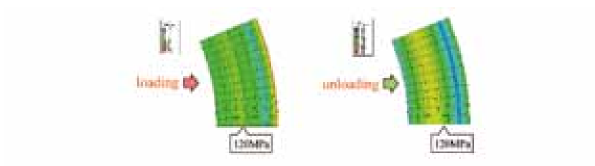


(a) Relationship between leak rate and contact gasket stress for aluminum flat gaskets

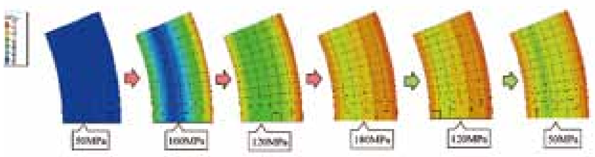


(b) Relationship between leak rate and contact gasket stress for copper flat gaskets

Figure6 Relationship between leak rate and contact gasket stress



(a) Contact gasket stress distributions



(b) Corresponding plastic strain distributions

Figure7 Distributions of contact gasket stress and corresponding plastic strain at each step obtained from FEM calculations

5. Evaluations of pipe flanged connection with the metal gasket

The previous sections described the evaluation using a platen, which enabled ideal homogeneous compression. In this section, the evaluation of characteristics using actual pipe flange connection was discussed.

Figure8 showed the test equipment for pipe flange connection, and figure9 showed the FEA model of the pipe flange connection with gasket. The connection sizes were chosen as ASME/ANSI class 300 2 inch and bolts were eight M16. Taking into account the symmetry of the connection, a one-thirty two part of connection was analyzed. In the FEM model, it was assumed that the nut was connected with a bolt and the screw thread of the bolt was not taken into account. In addition, for simplicity, the hexagonal nuts were replaced with a circle shape. The uniform bolt stress was applied to the cross sectional area in the bolt at initial tightening, while the displacements of the symmetrical plane were fixed in the axial direction. In the experiments, each axial bolt force was measured using the strain gauge attached to the shank of each bolt and the outputs are recorded in a data logger. The helium gas 4MPa was applied from cylinder and the leak rate is measured by pressure drop method.

Figure10 showed the leak rate from aluminum flat gasket with dimensions of $\phi 65\times\phi 55$ for the bolted flange connection (2inch) with metallic flat gasket which was described in dotted line and the measured result in the platen tests was described in line. Although the value of lower leak rate from pipe flange connection could not be measured by the pressure drop method, it was found that the leak rate of bolted flange connection behaved similar with that in the platen test because it was due to the flange rotation in the bolted flange connection and the plastic deformation occurred in lower average gasket stress region. The leak rate decreased substantially when the contact gasket stress was applied 100MPa. Figure11 showed the corresponding plastic strain distributions at that timing using FEM calculations. It indicated that the corresponding plastic strain was small when the contact gasket stress was 90MPa, however rapidly increased at contact gasket stress 100MPa. It was considered that the sealing performance increased so much under un-uniform stress compression in pipe flange connection because of increasing of the corresponding plastic strain.

The method of determining bolt preload for achieving allowable leak rate (less than 1×10^{-4} [$\mathrm{Pa\cdot m^3/s}$]) was proposed in reference [8]. This equation is described in Eq. (1).

$$F_{fmin} = b \times \sigma_{yield} \times \frac{\pi}{4}\left({d_2}^2 - {d_1}^2\right)/(N \times 1000) \quad (1)$$

where, d_2 is the outside diameter and d_1 the inside diameter of the gasket, N is the bolt number and b is the coefficient which indicates the initiation of the plastic deformation in the metallic gasket.

Figure12 showed the leak rate of 2" bolted flange connection, the abscissa was bolt preload from average gasket stress in Figure9 The triangle marks (○,△,□) showed the bolt preload calculated by Eq. (1) . The compressive yield strength of aluminum and copper gaskets were 120 and 250MPa, respectively. In addition, the factor of better sealing used was 0.8 in the previous paper [6]. The leak rate less than 1×10^{-4} [$Pa\cdot m^3/s$] can be obtained by the bolt preloads calculated by Eq. (1) . Thus, Eq. (1) was verified for determining the bolt preload to satisfy the allowable leak rate in bolted flange connection with flat metallic gasket.

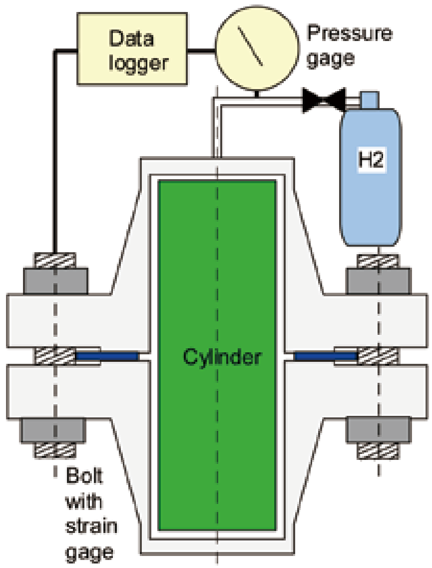


Figure8 Illustration of pipe flanged connection

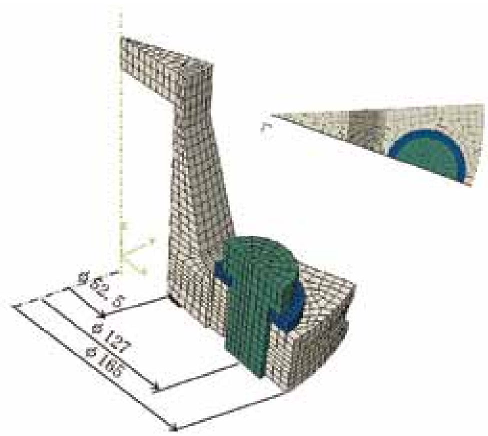


Figure9 FEA model of pipe flange connection with metal flat gasket

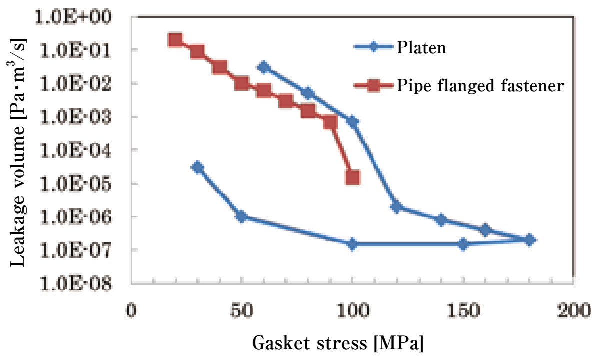


Figure10 Comparison of leak rate from platen test and pipe flange connection

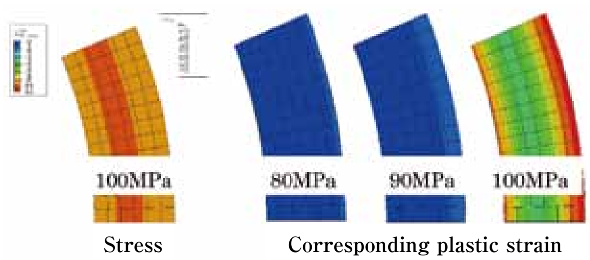
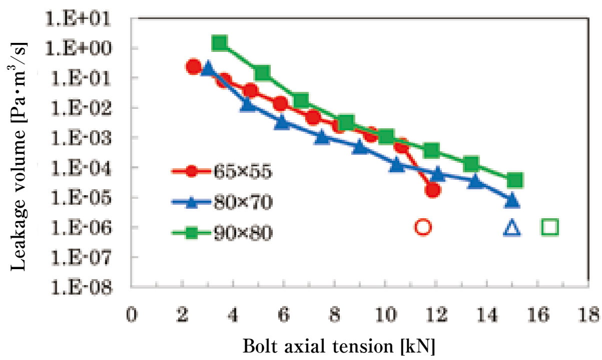
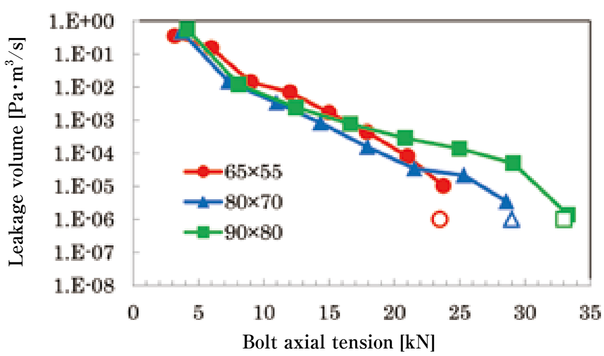


Figure11 The corresponding plastic strain distributions of aluminum flat gasket in pipe flange connection



(a) Aluminum flat gasket



(b) Copper flat gasket

Figure12 Measurement results and estimated results of leak rate for pipe flanged connection

6. Conclusion

In the present paper, the leak rate of 10^{-7} level for flat metallic gaskets which were compressed using the platen devise testing machine was measured. In addition, the leak rate in the bolted flange connection with flat metallic gaskets was also measured. The contact gasket stress distributions in both platen test and bolted flange connection with flat metallic gasket were analyzed using FEA calculations. The results obtained are as follows.

(1) The leak rate of the metallic gaskets which were compressed in the platen devices was measured in the 1×10^{-7}[Pa·m^3/s]) level using both methods of a soap film flow meter and a helium leak detector.

(2) In the platen device tests, it was found that the leak rate was independent of the dimensions of gaskets. In addition, the leak rate decreased with an increase of the gasket stress linearly to the leak rate level of 10^{-6} which corresponded to the gasket yield strength.

(3) In an ASME/ANSI class 300 2-inch pipe flange connection, sealing properties were also found to have been markedly improved when part of the gasket's contact surface had yielded.

(4) It was provided a method for calculating the axial tension required for initial bolt fastening of a fastener under a basic leakage volume of 1×10^{-6} Pa·m^3/s and compared calculated values with experimental results to verify the method.

7. References

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