Evaluation of the Bolted Flange Connection with PTFE-blended Gasket under High-temperature and Long-term condition

1. Introduction

The bolted flange connections with gasket have been used under high temperature and long-term conditions in oil plant, chemical plant, power plant and so on. In Japan, various asbestos gaskets used to be widely used because of excellent heat resistance, sealing performance, strength, ease of use, and low cost till 2008. The many studies for asbestos gaskets[1-5] have been conducted, clarifying the characteristics of the connection with asbestos gasket such as sealing performance. In Japan, the use of asbestos products was restricted in 2008, requiring non-asbestos products to be used.[6] As a result, non-asbestos gaskets have been developed and improved.

The asbestos gaskets are categorized into two major types: the spiral wound gasket containing asbestos filler and the compressed asbestos fiber sheet gasket. For the substitution of asbestos, asbestos for spiral wound gaskets was replaced with flexible graphite, and it caused no major problems. On the other hand, the compressed aramid fiber sheet gasket, the flexible graphite sheet gasket and the PTFE-blended gasket have been developed[7]. The compressed sheet gaskets containing aramid fibers shows low resistant to heat because they contained a lot of rubber, and the flexible graphite sheet gaskets are so fragile and easy to scratch. Therefore, in Japan, the PTFE-blended gasket was improved further and is now widely used. The former PTFE-blended gaskets showed poor creep characteristics, whereas the newly developed PTFE-blended gasket offers improved creep characteristics. However, the mechanical characteristics including the stress–strain curve of gasket, fundamental leakage characteristics (JIS B 2490), and creep characteristics for these gaskets have not been available. In addition, there has been insufficient verification as to whether this connection with PTFE-blended gasket has superior sealing performance compared with the conventional connection with asbestos gasket.

Previous studies have investigated the connection with PTFE-blended gasket for its sealing performance at room temperature, flange hub stress, change in axial bolt force (load factor), and the contact gasket stress distribution. The results showed that the sealing performance of the PTFE-blended gasket is quite superior to that of connections with the compressed asbestos fiber sheet gasket.[8] However, its performance at high temperatures is not well known.[8] Therefore, research on the mechanical properties of the connection including creep characteristics and sealing performance under high temperatures and long-term condition are required.

The objective of the present paper is to examine the mechanical characteristics of bolted pipe flange connections with PTFE-blended gaskets under elevated temperature using FEM calculations and experiments. Firstly, the fundamental characteristics of the PTFE-blended gasket such as stress–strain curves, thermal expansion coefficient, and fundamental leakage characteristics are measured. In addition, the creep characteristics at high temperatures are measured. In FEM calculations, the change in axial bolt force, the flange hub stress and the contact gasket stress distribution of bolted pipe flange connection with PTFE-blended gasket at some temperature are calculated. And then, the leak rates ware estimated from the contact gasket stress distribution and relationship between the leak rate and contact gasket stress. For verification of the FEM method, the experiments to measure the change in axial bolt force, the flange hub stress and the leak rate at each temperature are carried out.

In this study, the test gasket is No.GF300 in Nippon Valqua Industries, ltd.. The No.GF300 includes no rubber and no material degradation occurs in high temperature and long-term conditions.

2. Experiment set up

Figure 1 shows the experimental setup for connection. The change in axial bolt force, the flange hub stress and the leak rate are measured using this set up. The nominal size of pipe flange is ASME/ANSI class300 2inch and the flange material is Stainless Steel 304[9]. The connection is heated 3℃/min using electric cartridge heaters. The flange temperature is measured and controlled using the thermocouple and the flange hub stress is measured using the strain gage. The axial bolt force was measured using the strain gages attached to shank of bolt. The tightening is performed according to JIS B 2251:2008 "Bolt tightening procedure for pressure boundary flanged joint assembly".

Leak rate was measured using the pressure drop method and calculated by equation (1)

$$L = \frac{MV}{tRT_1}\left(P_1 - \frac{T_2}{T_1}P_2\right) \quad (1)$$

where, L is leak rate (Pa·m³/s), M is molar mass (kg), V is volume within equipment (mm³), t is measurement time (s), R is gas constant (J/kg·K), T_1 is initial temperature (℃), T_2 is measurement temperature (℃), P_1 is initial internal pressure (MPa) and P_2 is measurement internal pressure (MPa).The nominal size of gasket is ASME/ANSI class 300 2 inch with thickness of 1.5mm. The internal pressure is 2MPa, the flange temperatures are chosen as room temperature, 100℃ and 200℃. The initial axial bolt force is 16.4kN correspond to mean contact gasket stress 35MPa.

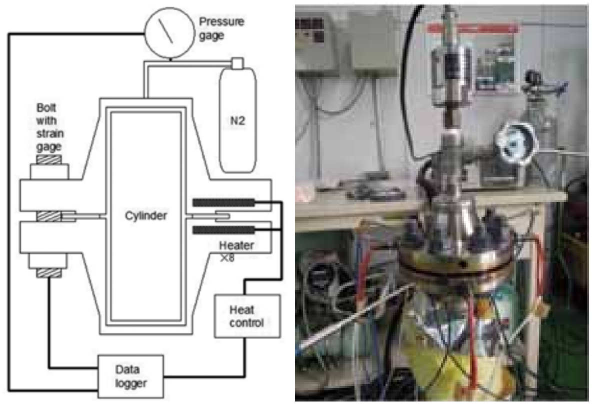

Figure1 experimental set up for connection

3.Gasket property measurement

Prior to FEM calculations, the gasket properties such as stress-strain curve, fundamental leak rate, thermal expansion coefficient and creep are measured.

3-1) Stress-Strain curve

Figure2 shows the schematic of experimental setup for measuring the sealing performance of the gasket (JIS B 2490). It can be heated by electric cartridge heaters. Figure3 shows the stress-strain curve at room temperature, 50℃, 100℃, 200℃ and 300℃ measured. The strain increases as test temperature increases and it can be seen the temperature dependency. It is because that the gasket material was softened in high temperature.

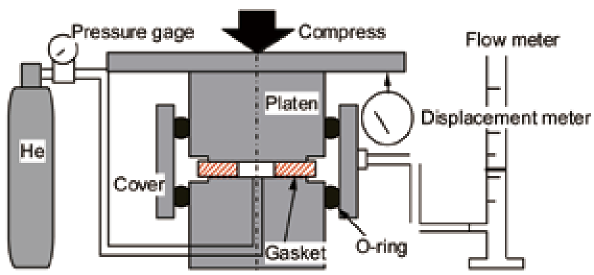

Figure2 Schematic of experimental setup for measuring the sealing behavior of the gaskets (JIS B 2490)

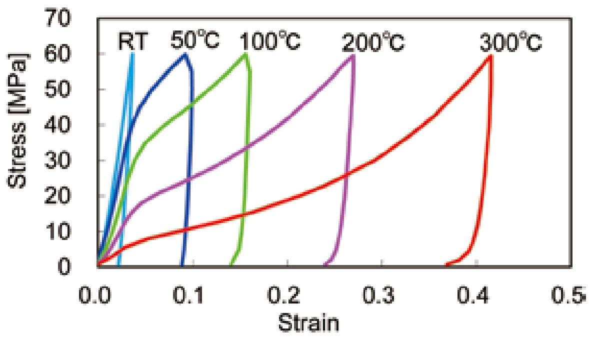

Figure3 Stress-strain curves of gasket

3-2) Sealing performance

The relationship between the fundamental leak rate and the contact gasket stress at room temperature and only re-load step at 200℃. The experimental setup was shown in Figure2 and the test gas is helium gas 2MPa.

Figure4 shows fundamental leak rate at room temperature obtained from the experiment. When the contact gasket stress is 20MPa or greater, it can be measured because that the value was less than lower limit of 5 x 10^{-5} Pa･m^3/s.

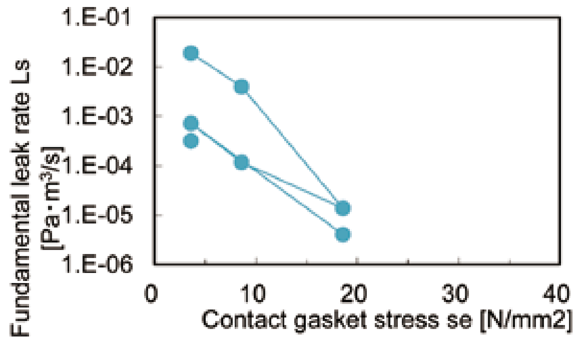

Figure4 Relationship of gaskets between leak rate and contact gasket stress at room temperature in a platen test

Figure5 shows the leak rate in unloading process at 200℃, the initial contact gasket stresses are chosen as 19.8MPa, 25.5MPa and 35.0MPa. From comparison between results of Figure4 and Figure5, it can be seen that the sealing performance at high temperature is better than at room temperature. The result indicates that sealing performance increases as the temperature increases. This is suggested that because the softened gasket material is able to fill the micro gaps of flange faces at high temperature.

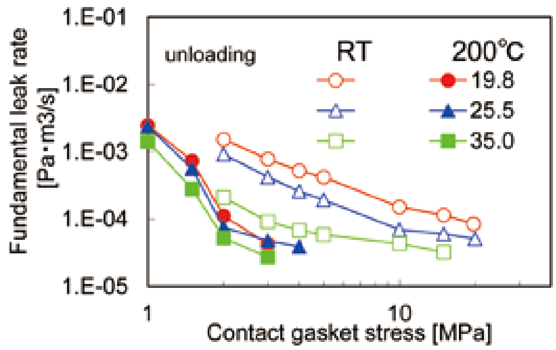

Figure5 Measured relationship between the fundamental leak rate and the contact gasket stress in unloading step at RT and 200℃

3-3) Thermal expansion coefficient

Figure6 shows thermal expansion coefficient measured by thermal mechanical analysis (TMA). It can be said that the thermal expansion coefficient increases with higher temperature.

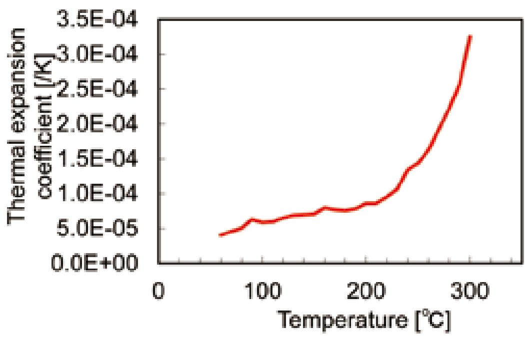

Figure6 Thermal expansion coefficient of gasket

3-4) Creep

The creep characteristics of gasket are measured by the setup shown in Figure7, for evaluation of gasketed connection in long-term condition. The dimensions of test gasket are ϕ22mm and ϕ58mm, test gasket stresses are chosen as 12.5MPa, 25.0MPa, 35MPa, and the temperature is 200℃. Figure8 shows the measured creep strain behaviors of the gasket. The abscissa is elapsed time, and the ordinate is creep strain. This figure indicates that the creep strain increased over time. So creep strain increases as gasket stress increases and it show the stress dependency. This behavior was formulated to equation 2 and inputted to FEM calculations.

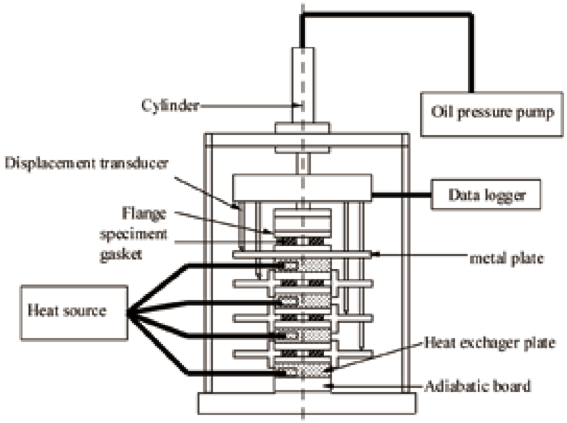

Figure7 Equipment for testing the creep of gaskets

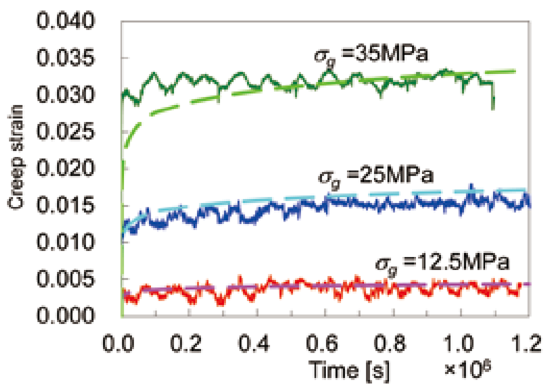

Figure8 Measured creep strains of gaskets

$$\overline{\varepsilon_c} = a \cdot \sigma^n \cdot t^j \quad (2)$$

where $\overline{\varepsilon_c}$ is creep strain rate (/s); σ is stress (MPa); t is measurement time (s); and a, n, and j are constants obtained by experiment (a = 1.61×10^{-5} (/MPa), n = 1.25, j = −0.915).

4. FEM calculations

The FEM calculations are conducted using ABAQUS. Figure9 shows the FE model for bolted flange connection with gasket. Taking into account the symmetry of the connection, 1/32 part (1/2 in axial direction, 1/16 in circumferential direction) of connection is analyzed. Bolts and nuts are united, and screws are omitted. Also, nut shape is simplified from hexagonal to circular.

Figure10 shows the boundary conditions. The uniform bolt stress is applied to the cross sectional area in the bolt at initial tightening. In Step 2, heat and internal pressure are applied to the inside of the connection. Flanges and bolts/nuts are modeled with elasticity-heat transfer elements. The gasket is modeled with elasticity-plasticity-heat transfer-viscosity elements. Table1 shows the characteristics of each material.

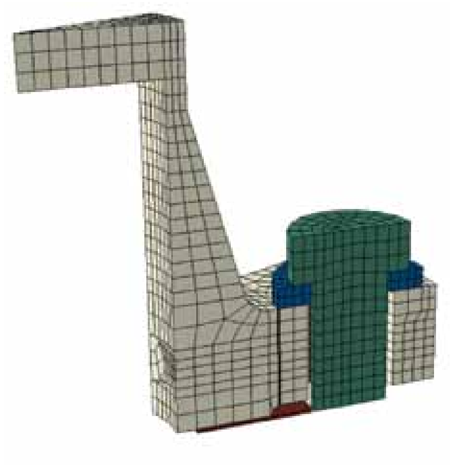

Figure9 FE model for pipe flange connection with gasket

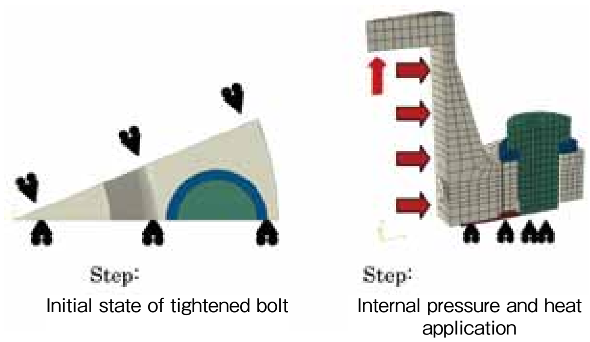

Figure10 Boundary conditions

Table1 The characteristics of each material

	Flange	Bolt	Gasket
Modulus of longitudinal elasticity [GPa]	200	200	Fig.3
Poisson's ratio	0.3	0.3	0.45
Linear expansion coefficient [/K]	1.12 E-05	1.09 E-05	Fig.6
Heat transfer coefficient [W/m·K]	4.4 E-02	1.1 E-02	2.5 E-05
Specific heat [J/kg·K]	500	500	1000
Density (room temperature) [kg/m^3]	7800	7800	2.3

5. Experiments and Results of FEM Analysis

5-1) Changes in Axial Bolt Force

Figure11 and 12 show the changes in axial bolt force obtained by FEM calculations and experiments at 100°C and 200°C respectively. The solid lines show the FEM results, the dotted lines show experimental results. And the change in flange temperature is shown in same figure. The initial axial bolt force is chosen as 16.4kN. The flange is heated, kept for 24 hours, cooled to room temperature. The heated and cooled cycles are 4 times.

From figure 11 and 12, it can be seen that the change in axial bolt force are influenced from temperature of the connection. In initial heating, the axial bolt force decreases substantially, because the gasket strain increases due to the temperature dependency of stress-strain curve of gasket material, that is, the gasket thickness decreases. Axial bolt force increased and decreased in accordance with increasing and decreasing temperature due to the difference in thermal expansion coefficient between each component. In heating at 200℃, the change in the axial bolt force is larger than that at 100℃ and also the reduction in the axial bolt force is larger in cooling. In cooling, the axial bolt force is reduced to 2kN, by which the average gasket stress is 4.3MPa. However, no leakage is observed.

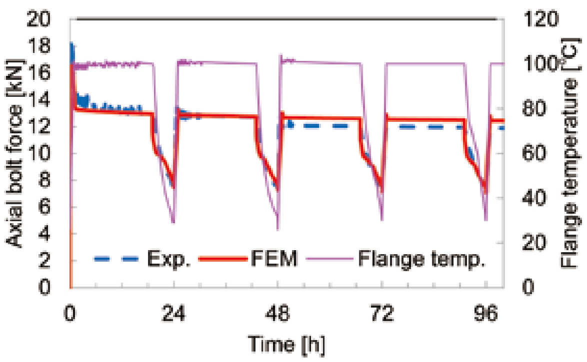

Figure11 Changes in axial bolt force at 100℃

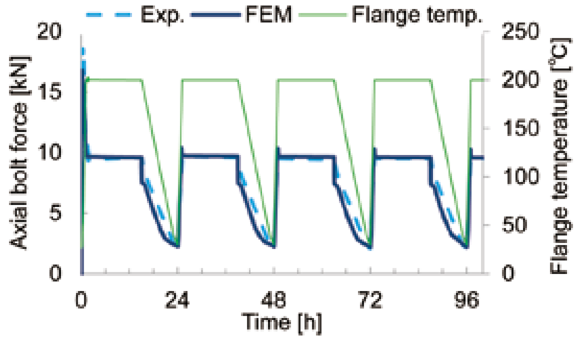

Figure12 Changes in axial bolt force at 200℃

5-2) Hub Stress of Flanges

Figure13 shows the flange hub stress at initial tightening and under high temperature. The figure also shows value calculated according to the Boiler & Pressure Vessel Code, Section VIII, Division 1.[14] The measured results are fairly good agreement with the FEM results, the method of FEM calculations are verified.

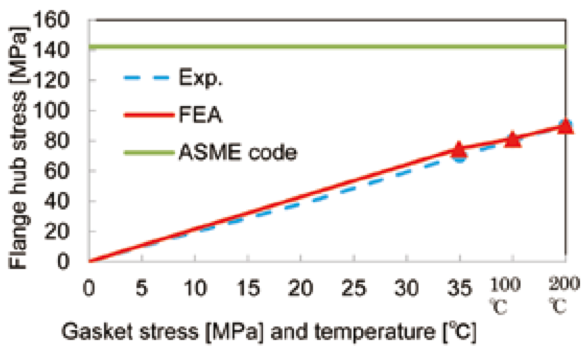

Figure13 Flange hub stress

5-3) Contact Gasket Stress Distribution and Leak Rates

Figure14 shows the obtained contour figure of contact gasket stress distribution for the gasket in initial bolt tightening, and the cases where the connection is heated to 100 and 200℃, respectively. The around outside of gasket did not contact the flange face. So the contact gasket stress is zero.

In these figures, it can be said that the change in contact gasket stress distribution in the circumferential direction is negligible. As the result, the contact gasket stress increases at the outer edge of the gasket because the flange rotation occurs. The results at the elevated temperature, show that the outside of gasket is deformed by compression due to the heating and a contact force by a bolt.

Figure15 shows the leak rate from the gasket interfaces is estimated using the contact gasket stress distribution obtain from the FEM and the fundamental leak rate shown in Figure4 and 5 [12)13)]. The abscissa is contact gasket stress, the ordinate is the amount of gas leakage per unit contact diameter. A fairly good agreement between the estimated results and the experimental results is observed. This confirms the validity of the method for estimating the amount of leakage from the FEM calculations and the fundamental leak rate.

5-4) Estimation of the sealing performance in long-term condition

The bolted connection with gasket is used in high temperature and long-term condition, so it is important to evaluate the sealing performance in high temperature and long-term condition. Figure16 shows the change in contact gasket stress in ten years estimated from results of FEM calculations. The leak stress (when allowable leakage is 1.7×10^{-4} Pa·m³/s) is also shown in same figure, the leakage occurs when the contact gasket stress decreases less than that value. The connection size is ASME/ANSI class 300 2inch, the fluid temperature is 200℃ as above evaluations. The shutdown is every two years, so it is considered in FEM calculations. When the initial contact gasket stress is chosen as 25MPa, the contact gasket stress fall down less than leak stress, and then it is estimated that the leakage occur. On the other hand, when the initial contact gasket stress is chosen as

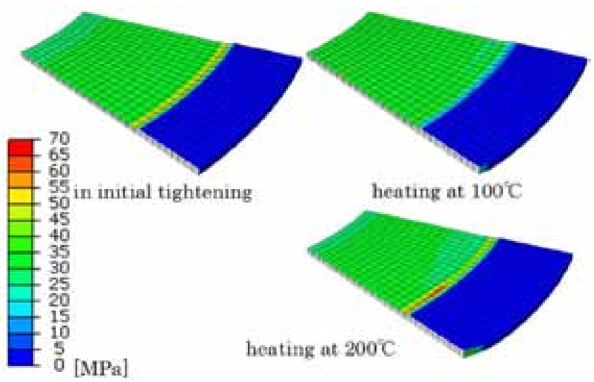

Figure14　Contact gasket stress distributions obtained by FEM calculations

35MPa, the contact gasket stress keep over leakage stress, it can be considered that the sealing is kept.

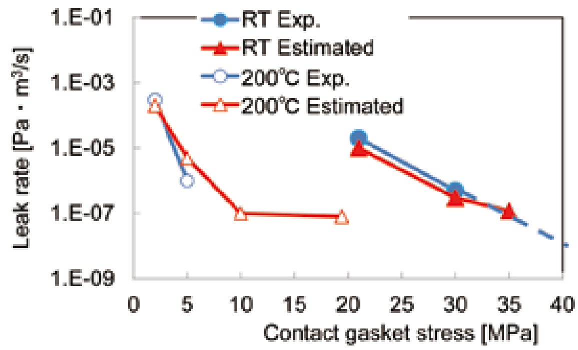

Figure15　Comparison of leak rates of connections between the experimental results and estimated results.

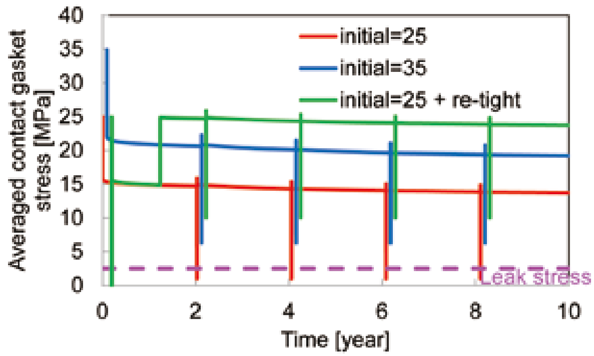

Figure16　Change in contact gasket stress of connection in ten years estimated by FEM calculations

6. Conclusion

In this present paper, it is shown that bolted pipe flange connection with PTFE gasket (No.GF300) keep good sealing performance in high temperature and long-term condition by using experiments and FEM calculations. The results obtained are as follows.

(1) The fundamental characteristics of PTFE-blended gasket were measured experimentally such as the relationship between gasket stress and displacement and its temperature dependency, the relationship between the leak rate and contact gasket stress, thermal expansion coefficient and creep property.

(2) The change in axial bolt force of bolted connection with PTFE-blended gasket is effected substantially by heat cycle and the connection with No.GF300 gasket shows the good sealing performance in 200℃ heat cycle condition. In addition, the flange hub stress was lower than the value calculated using ASME code.

(3) The leak rate from the connection with PTFE-blended gasket was estimated from the contact gasket stress distribution obtained by FEM calculations and the relationship between leak rate and contact gasket stress obtained by experiments, and compared with the experimental value to verify the robustness of our prediction method.

(4) It is proposed the method to estimate the long-term behavior of bolted flange connection with PTFE-blended gasket (No.GF300) under high temperature. And it is shown that the connection with No.GF300 gasket keeps safety for 10 years when the initial contact gasket stress is 35MPa, and also that re-tightening resulted in additional safe.

7. References

1) Takaki, T., Satou, K., Yamanaka, Y., Fukuoka T.: "Effects of Flange Rotation on the Sealing Performance of Pipe Flange Connections," ASME PVP Vol. 478 (2004) pp. 121–128

2) Takaki, T., Fukuoka, T., Yamanaka, Y.: "Finite Element Simulation of Bolt-Up Process of Pipe Flange Connections," Valqua Technology News, No. 2 (2002), pp. 5–13

3) Sawa, T., Ogata, N., Nishida, T.: "Stress Analyses and a Sealing Performance Evaluation of Pipe Flange Connections with Spiral Wound Gaskets under Internal Pressure," Proceedings of the Japan Society of Mechanical Engineers (Ver. A), Issue 671 of Vol. 68 (2002), pp. 1120–1128

4) Kobayashi, T., Nishida, T., Yamanaka, Y.: "Effect of Creep-Relaxation Characteristics of Gaskets on the Bolt Loads of Gasketed Joints," ASME PVP Vol. 457 (2003), pp. 111–118

5) Kobayashi, T., Nishida, T., Yamanaka, Y.: "Consideration on the Representations of Sealing Behavior of Gaskets: Effects of the Internal Pressure and the Gasket Width," ASME PVP Vol. 457 (2003), pp. 133–138

6) Industrial Safety and Health Law No. 318 (2008)

7) Nippon Valqua Industries, Ltd. Non-Asbestos Gasket, Catalogue No. ZY03 (2011)

8) Sato, K., Muramatsu, A., Kobayashi, T., Sawa, T.: "FEM Stress Analysis and Sealing Performance of Bolted Flanged Connections using PTFE Blended Gaskets under Internal Pressure," PVP 2015-45268, Proceedings of ASME PVP 2015 Conference (2015)

9) ANSI/ASME B 16.5, "Pipe Flanges and Flanged Fittings" (1996)

10) Japanese Industrial Standards: JIS B 2251 "Bolt tightening procedure for pressure boundary flanged joint assembly" (2008)

11) Japanese Industrial Standards: JIS B 2490 "Test Method for Sealing Behavior of Gaskets for Pipe Flanges" (2008)

12) Omiya, Y., Sawa, T., Takagi, Y.: "Stress Analysis and Design of Bolted Flange Connections under Internal Pressure," PVP 2014-28606, Proceedings of ASME PVP 2014 Conference (2014)

13) Omiya, Y., Sawa, T.: "Stress Analysis and Sealing Performance Evaluation of Bolted Pipe Flange Connections with Smaller and Larger Nominal Diameter under Repeated Temperature Changes," PVP 2014-28730, Proceedings of ASME PVP 2014 Conference (2014)

14) ASME Boiler & Pressure Vessel Code Section VIII, Division 1: "Rules for Construction of Pressure Vessels" App. 2 (2004)

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