"Fastener Troubles, Causes & Solutions" Series

Fluid Leakage of Pipe Flange: Analysis of Leakage in Low Temperature Fluid Pipelines

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Introduction

Leakage in fluid-transferring pipelines often occurs when the temperature of internal fluid is high. However, with increasing use of low temperature fluids recently in various applications, the leakage in low temperature pipelines sometimes becomes an issue. Therefore, it is highly demanded to clarify the mechanism of leakage in low temperature pipelines and establish the method for prevention. The low temperature fluid, which is most related to ordinary citizens, is liquefied natural gas (LNG), a primary component of city gas. The temperature of LNG is about minus 163℃, while the temperature of liquefied petroleum gas (LPG) is about minus 45℃. This article targets pipe flanges used for LNG pipelines, and explains the basic mechanism of leakage by using the results obtained by cooling tests and finite element analysis, and provides effective information on the prevention method.

Axial Force Variation in Bolted Joints Subjected to Low Temperature Thermal Loads

Figures 1(a) and **(b)** illustrate **the change of axial bolt force when the bolt receives thermal load from the initial fastening state**. In the case where the bolt, nut and fastened plates are made of the same material and heat is applied to the outer surface of the fastened plates, the elongation of fastened plates becomes larger than that of bolt-nut connection, thereby increasing the axial bolt force. On the contrary, if the fastened plates are cooled in the same manner, the axial bolt force decreases since larger contraction occurs in the fastened plates. Corresponding to the latter case, **Figure 2** shows **the flowing state of low temperature fluids in a pipe flange**. The temperature of the part near the inner surface of the pipe flange, which is in contact with inner fluids, is significantly dropped. In contrast, the temperature of the outer surface, at which bolts are installed, becomes fairly higher than that of the inner surface. As a result, the temperatures of all portions of the pipe flange decrease, but since the fastened plates contract more than the bolt-nut connection, it is presumed that the axial bolt force decreases. In the previous article of the series, it is explained that the reduced stiffness of gaskets greatly affects the reduction of axial bolt force in pipe flanges under high temperature thermal loads. On the other hand, the rate of stiffness variation in pipe flanges subjected to low temperature thermal loads is fairly smaller comparing to the case of being under high temperature thermal loads. The following chapters report the results of the quantitative evaluation of bolt force variation, obtained from the cooling experiment and finite element analysis.

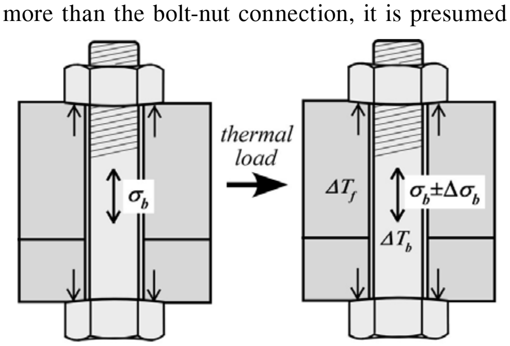

Fig.1 (a), (b)

ΔT_f , ΔT_b : temperature increase/decrease

$\Delta\sigma_b$: bolt stress variation

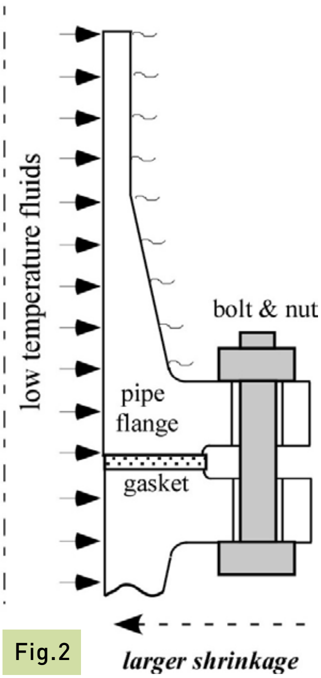

Fig.2

Cooling Experiment of Pipe Flange

Figure 3 shows an **overview of the experimental device**. The cylinder end of the lower pipe flange is manufactured to have a cover in order to keep the low temperature fluids poured in the pipe during experimentation. Liquefied nitrogen (LN2), which is relatively easy to handle, was used as the low temperature fluid. The temperature of LN2 is about minus 196℃, which is even lower than LNG. The pipe flanges used in

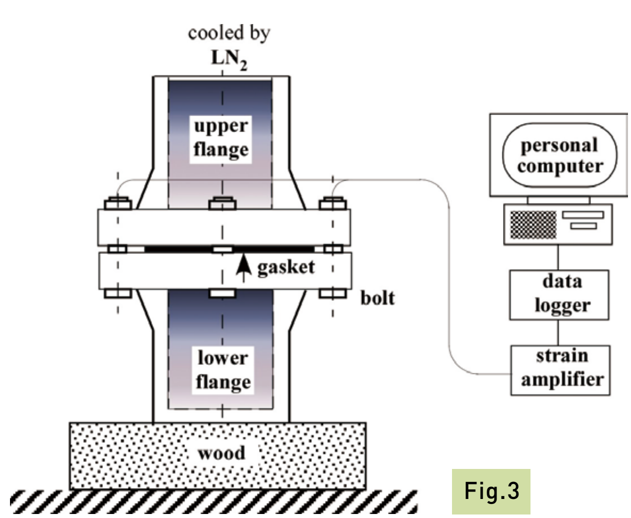

Fig.3

the experiment are manufactured to match Japanese Industrial Standard of nominal pressure of 20K and nominal diameter of 65. The pipe flanges are fastened with eight M16 bolts, and thermocouples and strain gages for measuring temperatures and axial bolt forces are attached to the four of them. A fluorine resin gasket for low temperature fluids is inserted between the upper and lower pipe flanges. With reference to the strain gage readings, the bolt is fastened until the axial stress reaches 100MPa. Then, the average contact pressure of gasket is around 22MPa. **Figure 4** shows **the pipe flanges during experimentation**. Quite a lot of frost is on the pipe. Since LNG boils and evaporates almost instantly, it is continuously poured into the pipe flanges to keep the liquid surface height during the experiment. **Figure 5** shows **the measured results of the bolt shank temperature and the axial bolt stress**. The axial bolt stress σb at each time is given by dividing it by the initial bolt stress σi. The horizontal axis is the elapsed time after the pipe flange was filled with LNG. After a sufficiently long time since the start of cooling, the bolt temperature is lowered to minus 155℃. Furthermore, the axial bolt stress is reduced to 65% of the initial value. These values cannot be negligible as far as the sealing performance of pipe flanges is concerned. In actual pipelines, the reduction rate of axial bolt force may change because of the different flowing conditions. In any event, it is presumed that the axial bolt stress significantly decreases. The supply of LNG is stopped after 18,000 seconds since the measurement is started, and then the bolt temperature returns to the initial value. After a sufficient period of time elapses, the bolt temperature returned to the room one, but the axial bolt stress only returned to 93% of the initial value. The cause can be attributed to the hysteresis property involved in the gasket compression characteristic.

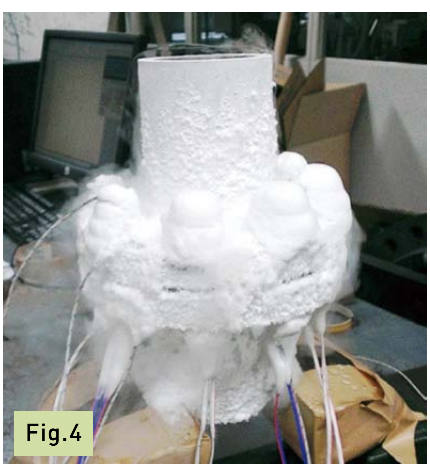

Fig.4

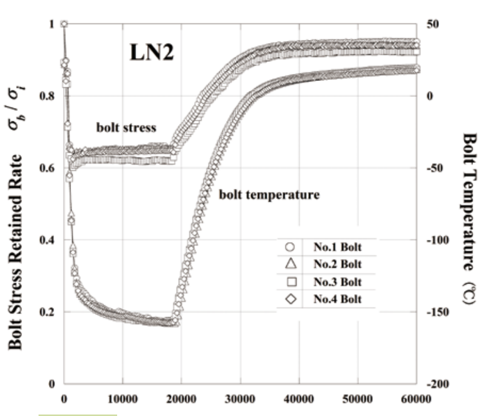

Fig.5

Finite Element Analysis of Axial Bolt Force Variation in Pipe Flanges

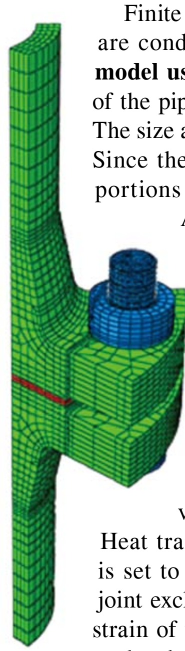

Fig.6

Finite element analyses corresponding to the cooling experiment are conducted in this chapter. **Figure 6** shows **a finite element model used in the analysis**. Considering the geometric symmetry of the pipe flange, one-eighth of the whole pipe flange is modeled. The size and shape of the model conform to the experimental device. Since the target of the analysis is not thread loosening, threaded portions are modeled assuming an axi-symmetric thread form. As the boundary conditions of the temperature field, the internal surface of the pipe flange is supposed to be heat transfer boundary that liquid nitrogen of minus 196℃ runs through. The outer surface is also set to be heat transfer boundary. The liquid nitrogen boils when poured into the pipe flange, so it is difficult to accurately estimate the heat transfer coefficient. Therefore, heat transfer coefficient is tentatively varied from 5,000 W/m^2K to 15,000 W/m^2K, and the value of 8,000 W/m^2K is selected, with which temperature variations close to the experimental results can be obtained. Heat transfer coefficient on the outer surface of the pipe flange is set to be 8 W/m^2K. Elastic material is assumed for the bolted joint excluding the gasket. The relationship between the stress and strain of the fluorine resin gasket is non-linear, showing hysteresis that behaves differently in loading and unloading processes. The mechanical behavior of gaskets is explained in detail in the referenced literature.

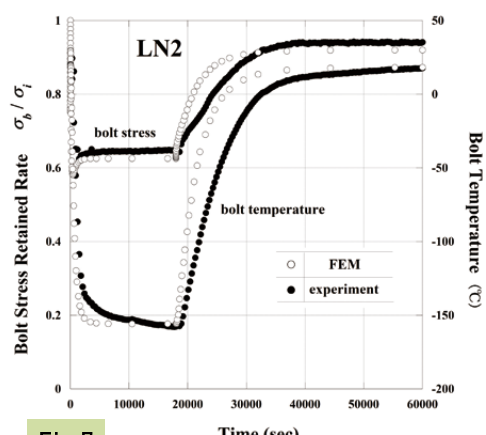

Fig.7

Figure 7 compares the analytical values of bolt shank temperature and axial bolt stress with the experimental ones. In the steady state, both bolt shank temperature and axial bolt stress, obtained analytically, agree fairly well with experimental results. On the other hand, after stopping the supply of liquid nitrogen, the analytical values and experiment ones slightly differ from each other in the process of returning to room temperature. This is because the liquid nitrogen is assumed to instantaneously disappear in the analysis, though its surface level in the pipe flange gradually lowers in the experiment. In any case, at the point that the minimum axial bolt stress occurs, both values agree pretty well; therefore, the analytical method used here can be considered effective. Additionally, regarding the frost attaching to the pipe flange, incorporating the frost into the original model and conducting the analysis, a difference is hardly recognized on the graph. Therefore, it is considered that the effect of the attaching frost is negligible.

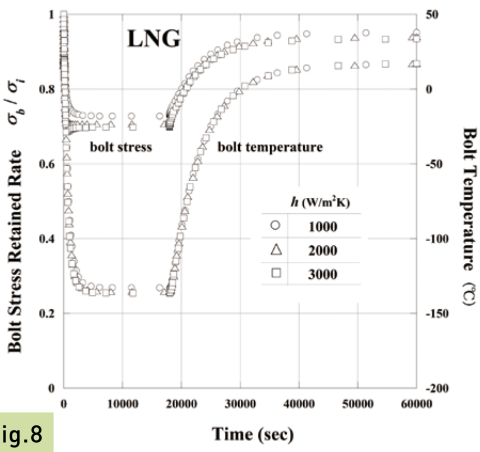

Fig.8

Finite Element Analysis of Axial Force Variation of Bolts Fastening Pipe Flanges

The analytical method, whose effectiveness is validated in the previous chapter, is applied to the case of the low temperature fluid being liquefied nitrogen gas (LNG). The main component of LNG is methane, so the physical property values of liquid methane are used in calculation. Heat transfer coefficient of the internal surface of pipe flange is calculated by the formula proposed for the turbulent flow zone in the pipe developed under forced convection.

$$Nu=0.023Re^{0.8}\,Pr^{0.4}$$

where Nu,Re,Pr are Nusert number, Prandtl number, and Reynolds number. Considering the fluid flow in the actual state, the flow velocity is supposed to be 0.5, 1.0, 1.5 and 2.0m/s, and then heat transfer coefficients become 1013, 1674, 244, 3071 W/m^{2}K respectively. Based on the results, in finite element analyses, the temperature of LNG is set to be minus 163℃, and heat transfer coefficient is changed as 1000, 2000, 3000 W/m^2. **Figure 8** shows **the numerical results**. After a sufficient cooling time, the bolt shank temperatures are around minus 135℃, and the bolt force retained rates are around 70%. The main reason causing the difference against the case of liquid nitrogen is the temperature difference between the two fluids.

Conclusion

It was shown in this article by cooling experiment and finite element analysis that axial bolt force reduces in the pipelines, through which low temperature fluids flow, as in the case of high temperature fluids, though the leakage mechanism is different. Although the results introduced here were obtained using the numerical models by assuming that low temperature fluids do not flow unlike actual pipelines, it reveals a non-negligible level of axial force reduction. It is said that axial bolt force reduction in actual pipelines occurs in two cases, i.e., when low temperature fluids start to flow and the fluid level rises, and when fluid transfer completes and the fluid level lowers. According to the numerical results conducted in my laboratory, in which the target pipeline with liquefied nitrogen running inside is placed horizontally, axial bolt force could drop below 40% while the fluid level rises. I also would like to explain this phenomenon if the occasion arises. ■

Reference

Fukuoka, T., Evaluation of Thermal and Mechanical Behaviors of Pipe Flange Connections for Low Temperature Fluids by Numerical Analysis and Experiments, Proceedings of the ASME 2016 Pressure Vessels and Piping Conference (2016), PVP2016-63212, Vancouver, Canada.