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화재 안전용 볼밸브의 열·구조 연성해석

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Thermal-structural Coupled Field Analysis for Fire Safety Type Ball Valve

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ABSTRACT

The safety of transporting equipment in a cryogenic condition is one of important problems under the circumstances that the application weight of natural gas is gradually increasing. As a larger disaster may be generated by leakage of oil or gas from valves in case of fire occurrence of a ship, the present research applied a numerical analysis method on thermal stress distribution and deformation, etc. to the design of ball valves satisfying fire safety test's specification(API607) to prevent this. In addition, the present research progressed fire safety tests and compared the test result with numerical analysis results. The Max stress by parts was confirmed through thermal analysis of major parts to evaluate safety. The fire safety test was progressed according to the regulation of API607.

Key Words : Cryogenic Ball Valve, Leakage, Numerical Analysis, Thermal Stress, Fire Safety Test

1. Introduction

In recent years, The demands of crude oil and LNG gas carriers are increasing due to growing energy demand of world countries, and especially, because the natural gas almost doesn't emit carbon dioxide and sulfurous oxide, etc. In case of combustion of natural gas, it is getting attention as alternative energy of petroleum.

However it is difficult to transport or store natural gas in a gas state due to very big volume, the equipment transporting and storing the liquified natural gas gradually needs, and as the application weight of natural gas gradually increases, the demand of equipment controlling this and transportation equipment is increasing[1,2].

In case of fire occurrence of a gas ship, because the leakage of oil or gas occurs from valves, a larger disaster could be generated. It is required that the values used in the crude oil and LNG gas carriers satisfy the fire safety test specification to prevent this.

Accordingly, in case of valves mounted in a ship,

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only valves with verified safety according to the fire safety test specification is selected to prevent additional accidents due to a fire, and the present paper aims to apply the design of actual ball valve by numerically analyzing thermal stress distribution and deformation, etc. on thermal shock.

2. Theory

The finite element equation on three-dimensional load is the same as the equation(1)[3].

$$\frac{\partial\sigma_{xx}}{\partial x}+\frac{\partial\sigma_{xy}}{\partial y}+\frac{\partial\sigma_{xz}}{\partial z}=0$$
$$\frac{\partial\sigma_{yx}}{\partial x}+\frac{\partial\sigma_{yy}}{\partial y}+\frac{\partial\sigma_{yz}}{\partial z}=0$$
$$\frac{\partial\sigma_{zx}}{\partial x}+\frac{\partial\sigma_{zy}}{\partial y}+\frac{\partial\sigma_{zz}}{\partial z}=0 \quad (1)$$

The stress and strain is the same as the equation(2), and here, D is a stiffness matrix, and ε is a strain vector.

$$\sigma = D\varepsilon \quad (2)$$

In addition, the relationship equation between strain and displacement can be shown like the equation(3).

$$\epsilon=\begin{pmatrix} \frac{\partial u_x}{\partial x} \\ \frac{\partial u_y}{\partial y} \\ \frac{\partial u_z}{\partial z} \\ \frac{\partial u_y}{\partial z}+\frac{\partial u_z}{\partial y} \\ \frac{\partial u_z}{\partial x}+\frac{\partial u_x}{\partial z} \\ \frac{\partial u_y}{\partial x}+\frac{\partial u_x}{\partial y} \end{pmatrix} \quad (3)$$

In order to numerically analyze the finite element method, if the equation(3) is made as a Weak form, it is the same as the equation(4).

$$\int_{\Omega}^{\overline{u}^T} \Delta\sigma d\Omega = 0 \quad (4)$$
$$\overline{u^T} = \left[\overline{u_x}, \overline{u_y}, \overline{u_z}\right]$$
$$\sigma = \begin{vmatrix} \sigma_{xx}\sigma_{xy}\sigma_{xz} \\ \sigma_{yx}\sigma_{yy}\sigma_{yz} \\ \sigma_{zx}\sigma_{zy}\sigma_{zz} \end{vmatrix}$$
$$d\Omega = dxdydz$$

If the theorem of Green is used, it can be shown like the equation(5), and $\overline{\varepsilon}$ is a virtual strain vector and Γ means a boundary.

$$\int_{\Omega}^{\overline{\varepsilon}^T} \sigma d\Omega - \int_{\Gamma}^{\overline{u}^T} t d\Gamma = 0 \quad (5)$$

The stress vector is shown like the equation(6) to substitute a boundary condition.

$$t = -k(u-u_g)+t_b \quad (6)$$

Here, ku is a case that there is an elastic body in the boundary, u_g is when the displacement was given to the boundary, and t_b is a stress vector on the boundary. T he equation(7) was obtained by substituting the equation(6) for the equation(5), and it is as follows.

$$\int_{\Omega}^{\overline{\varepsilon}^T} D\varepsilon d\Omega - \int_{\Gamma}^{\overline{u}^T} ku d\Gamma = \int_{\Gamma}^{\overline{u}^T} (ku_g + t_b) d\Gamma \quad (7)$$

The finite element equation is the same as the equation(8), and the stiffness matrix K and external force vector f can be respectively shown like the equation(9) and equation(10)[4].

$$Kd = f \tag{8}$$

$$K = \sum_{i=1}^{e} \left(\int_{\Omega_e} B^T D B d\Omega_e + \int_{\partial\Omega_{e\cap\Gamma}} N^T K N dT \right) \tag{9}$$

$$K = \sum_{i=1}^{e} \left(\int_{\Omega_{e\cap\Gamma}} N^T (t_b + k u_g) d\Gamma \right) \tag{10}$$

3. Thermal-structure FSI analysis of ball valve for Fire-safety

3.1 Analysis and finite element model

The numerical analysis was carried out by using ANSYS[5], which is a commercial program. The finite element model is the same as in Fig. 1 and used all STRUCTURED GRID and NON-STRUCTURED GRID, and its numerical analysis was performed by defining a Contact condition of a state that sliding is possible.

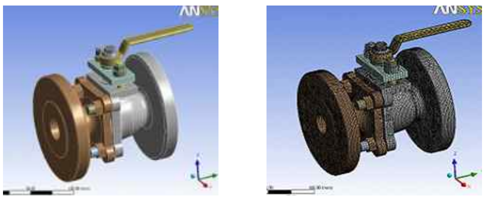

Fig. 1 Grid system and model of ball valve

3.2 Thermal analysis

The pressure applied to the inside is 16bar(1.6MPa), and the contact condition in the initial condition(18℃) and ambient condition of 980℃ were applied by considering the case of fire occurrence. Fig. 2 is a thermal analysis result after being exposed to the ambient condition of 980℃ for 30 minutes, and Fig. 3 shows that the convection condition of Transient Thermal is applied.

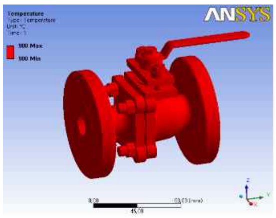

Fig. 2 Thermal distributions

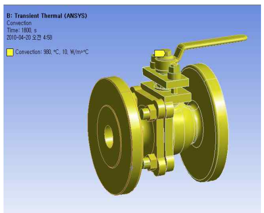

Fig. 3 Transient Thermal

3.3 Thermal-structure FSI analysis

The thermal-structure FSI analysis considering thermal stress due to temperature difference of between the inside and outside of a valve based on the result of thermal analysis was carried out[6,7]. And the imposed displacement's constraint condition was applied like Fig. 4 to give the same condition as an actual phenomenon.

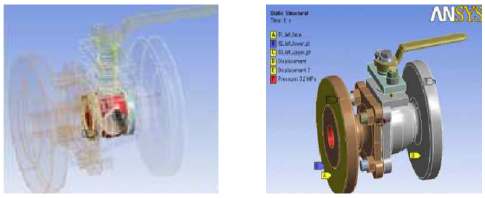

Fig. 4 Displacement conditions

This research analyzed analysis results according to each parts like Fig. 5 by referring to Max Stress in stress result analysis which is one of major examination targets of thermal-structure FSI analysis of a ball valve.

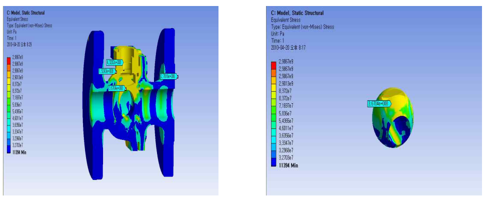

Fig. 5 Analysis result of ball valve

As an analysis result, the Max Stress occurred at an upper end of Ball, a cover of valve and a connecting part of the body. But it was confirmed that the Max Stress is 432MPa without exceeding 586MPa which is the allowable stress range of SUS316.

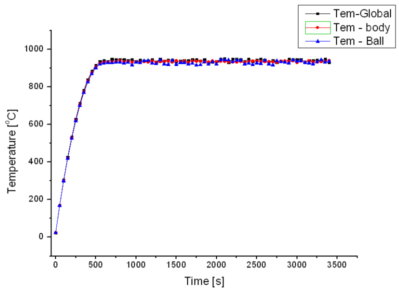

Fig. 6 Graph of Temperature distributions

Fig. 6 is a temperature change graph by thermal-structure FSI analysis of overall valve & body and Ball.

4. Fire-safety test(API607)

It is required that the ball valve for fire safety satisfies the fire safety test specification. Therefore, an experiment was executed for verification of design safety of a ball valve for fire safety based on the fire safety test assessment (API607) regulation and it is shown in Fig. 7.

4.1 Experimental method and procedure

The fire safety experiment method was progressed by the API607 regulation as follows, and its content is as follows.

Fig. 7 Fire safety test

4.2 Mimetic diagram of equipment

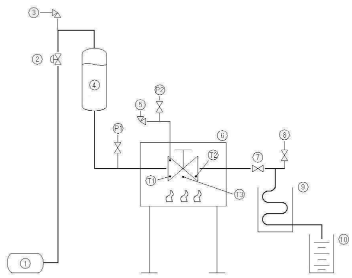

Fig. 8 Typical fire-test system using compressed gas as the pressure source

Heat the test valve body up to 760-980℃ by the burner. Preserve the temperate of more than 705℃ at the two of thermocouples.

One took a test of numerical analysis about the thermal stress and deformation of Seat and Ball inside the valve in case it is exposed to the high temperature of 900℃ for 30minutes. The leakage of the liquid is considered to be very little because there are the thermal stress with the increase of heat strain from the high temperature and little structural deformation at the part of design of Seat and Ball inside the valve. At the Fire-safety test to a Ball valve which is applied the result of numerical analysis, the result of the Seat Leakage Test is that Leakage rate is 0.3mL/min, which is very much less than an allowable leakage rate for leakage of the inner liquid. The study considers that the design safety of the ball valve is proved in a method of numerical analysis.

Fig. 9 Graph of global temperatures

In addition, Fig. 9 is a temperature change graph of overall ball valves measured in case of a fire safety experiment.

It can confirm temperature change of the inside and outside attached to a thermal couple and change of average temperature. After heating a valve and maintaining fixed temperature (900℃) for 30 minutes, its leakage test was executed after cooling it for 10 minutes. The leakage test result can be confirmed in Table 1.

As a result of confirming leakage rate of a valve after a test, it was confirmed that its leakage rate is 8mL and doesn't exceed the allowable leakage rate.

Table 1 Experimental conditions

	Press ure	Allowable leakage rate (mL/min)	Leakage volume (mL-30min)	Leakage rate (mL/min)
Test 1	2	89	8	0.3
Test 2	2	89	8	0.3
Test 3	2	89	10	0.3

5. Conclusion

The present research verified design safety of ball valves according to the fire safety test specification, performed the thermal-structure FSI analysis through analysis theories to grasp performance properties of a ball valve for fire safety and obtained the following results through the fire safety test and result's examination.

1. The finite element modeling was executed to make the ball valve for fire safety coincide with actual geometrical shape.
2. The thermal-structure FSI analysis was carried out at 16bar, at 18℃(internal temperature) and at 980℃ (external temperature).
3. The Max Stress occurred at major parts of a valve was 422MPa and doesn't exceed 586MPa which is a range of allowable stress, and the Max Stress was referred 1. to assess its stress analysis results.
4. The thermal and stress distribution obtained through the present research is about to be applied to optimal structural design of a ball valve, and it provided a basis for 1. a research to be executed in the future.

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