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Structural Stability of High-temperature Butterfly Valve Using Interaction Analysis

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〈Abstract〉

A butterfly valve is a valve that adjusts flow rate by rotating a disc for about 90° with respect to the axis that is perpendicular to the flow path from the center of its body. This valve can be manufactured for low-temperature, high-temperature and high-pressure conditions because there are few restrictions on the used materials. However, the development of valves that can be used in a 600℃ environment is subject to many constraints.

In this study, the butterfly valve's stability was evaluated by a fluid-structured interaction analysis, thermal-structure interaction analysis, and seismic analysis for the development of valves that can be used in high-temperature environments. When the reverse-pressure was applied to the valve in the structural analysis, the stress was low in the body and seat compared to the normal pressure. Compared with the allowable strength of the material for the parts of the valve system, the minimum safety factor was approximately 1.4, so the valve was stable. As a result of applying the design pressures of 0.5 MPa and 600℃ under the load conditions in the thermal-structural analysis, the safety factor in the valve body was about 3.4 when the normal pressure was applied and about 2.7 when the reverse pressure was applied. The stability of the fluid-structure interaction analysis was determined to be stable compared to the 600℃ yield strength of the material, and about 2.2 for the 40° open-angle disc for the valve body. In seismic analysis, the maximum value of the valve's stress value was about 9% to 11% when the seismic load was applied compared to the general structural analysis. Based on the results of this study, the structural stability and design feasibility of high-temperature valves that can be used in cogeneration plants and other power plants are presented.

Keywords : butterfly valve, fluid-structure interaction analysis, finite element analysis (FEM), seismic analysis

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1. Introduction

A butterfly valve is a valve that isolates or regulates the flow where the closing mechanism takes the form of a valve disc. Butterfly valves are low-cost, lightweight and compact valves that can be operated easily, giving a satisfactory performance. A butterfly valve is usually comprised of a disc that can be rotated a quarter of a turn by a shaft running through it. The overall structure of the butterfly valve consists of a valve body, a butterfly disc, a retainer, a shaft, and seat.

The valve has a simple structure, occupies a smaller space than other valves, and is widely used in harsh environmental conditions such as low-temperature, high-temperature and high-pressure environment. In particular, when the energy of water vapor expanded by high pressure and temperature, such as a cogeneration plant is used, the flow rate is controlled by adjusting the disc rotation angle of the valve. Therefore, it is necessary to examine the safety of the valve system due to the influence of the fluid flowing in the pipeline. It is particularly essential to understand the flow characteristics according to the open angle of the valve disc. A butterfly valve is generally suitable for fluid flow, with a small differential pressure across the valve because the diameter of the pipe is large and the flow coefficient is large when the valve is fully opened. Also, the trend is that it has been used for special purposes such as flow control and the nuclear processing system of natural gas according to the development of materials.

Because of its value, advanced technology is required for the design and manufacture of the valve, and many simulations have been conducted on it.

Bae[1] studied the multi-objective optimal design of butterfly valves using ductility analysis and statistical methods while Lee[2] investigated fluid-structure interaction analysis for structural stability evaluation. In addition, he made a research that was conducted with the purpose of studying the validity of structural-interaction analysis, comparing it with single analysis in flow analysis. Lee et al.[3] performed strength evaluation using fluid-structural interaction analysis for cryogenic butterfly valves, especially obtaining the pressure distribution results according to the disc open angle. A paper on the structural safety evaluation of the super large butterfly valve using FSI technique was also presented by applying the dynamic result by flow analysis to the structural analysis.[4,5]

In the past, seismic verification was carried out through excitation with the force corresponding to the seismic force for the target structure. Recently, theoretical seismic proofing techniques and procedures have been systematized, and the design parameters for the earthquakes can be theoretically obtained.[6]

In this study, the strength of the high temperature butterfly valve was evaluated by applying the thermal-structure interaction analysis method at 600° C and the design pressure of 0.5MPa, and the stability of the valve by seismic load was decided.

2. Analysis Model and Method

As analysis for the development of the 600℃ high temperature butterfly valve, the safety of the valve system was evaluated by carrying out the fluid-structural interaction analysis for the disc, retainer, stem, and body parts which are the main parts of the butterfly valve. The strength evaluation is performed by comparing the stress obtained through the analysis with the allowable stress.

In the analysis, conducting the analysis about the open angle of the disc at 40° and 60° and in the case of full opening (90°), the pressure and flow rate were obtained under the design load. In general, the valves are frequently used when the disc open angle is about 60°. The case of the open angle that was small was excluded because a highly large flow rate with noise was generated and excessive load was given to the valve system. The results of pressure and other data obtained from the flow analysis were applied to the structure analysis according to the open angle of the disc, and the safety evaluation of the valve system was performed.

Table 1. Mechanical properties according to temperature

Description	Material	Yield Strength[MPa]		
		22℃	550℃	600℃
Body	A351 CF8C	205	98.3	57.7
Disc	A351 CF8C	205	98.3	57.7
Stem	A276 G347	345	247.6	241.1
Seat	Inconel 625	550	-	-
Retainer	A351 CF8C	205	98.3	57.7

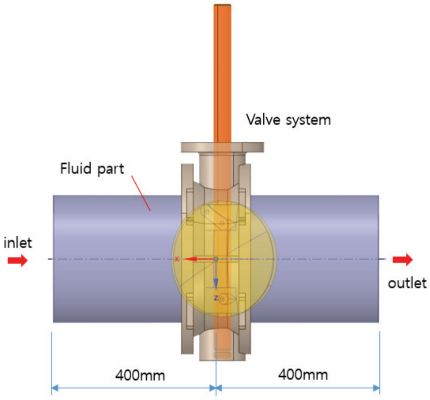


Fig. 1 Butterfly valve modeling for fluid-structural interaction analysis

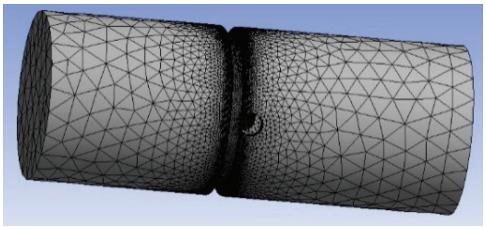


Fig 2. Finite element shape of fluid part

The yield strength of the main component material of the valve according to the temperature is shown in Table 1. Since Inconel is a material having high strength that can be used up to a high temperature of 980℃ due to the characteristics of the material, it is excluded from the stability analysis.

Figure 1 shows the modeling of the butterfly valve system for the fluid analysis.

For the fluid analysis, the inside of the virtual pipe was modeled, and its length was about 0.4m based on the valve stem. In fluid analysis, the inlet pressure was 0.5 MPa and the outlet pressure was set to atmospheric pressure.

3. Results of the Analysis

3.1 Fluid analysis

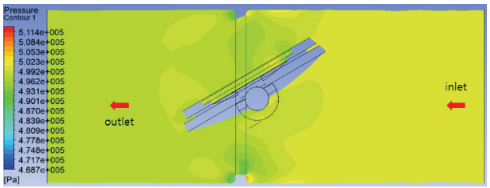
For the first figure, the fluid analysis is performed using the model and the pressure and flow velocity are analyzed according to the open angle of the disc at the design load. These results are then applied to the structural analysis through the interaction analysis method.

Figure 2 shows the finite element model for the flow analysis, and the analysis is performed with about 322,845 elements.

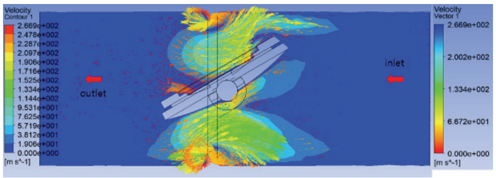
Figure 3 indicates the distributions of pressure and velocity for butterfly valve. As the disc open angle increases, the pressure tends to decrease. However, it can be seen that there is a section where the pressure is high in an extremely small part of the disc when the disc is completely opened. The smaller the disc open angle performs, the more uniform the pressure is distributed. The larger the angle of opening, the lower the velocity. It can be seen in the illustration that the velocity distribution change is more severe.

3.2 Fluid-structural interaction analysis

Figure 4 presents finite element modeling and constraint conditions for the fluid structural analysis. The analysis is performed



(a)pressure



(b)velocity

Fig. 3 Pressure and velocity distributions of valve(disc open angle at 60°)

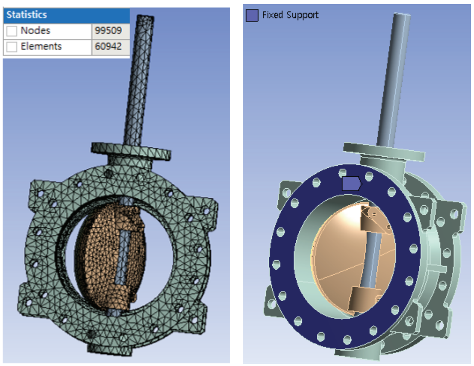


Fig. 4 Finite element shape of valve for fluid-structural analysis

with 99,509 nodes and 60,942 urea nodes. First of all, the design pressure load was applied to the flow analysis to derive the analytical results, then the results were reflected on the structural analysis.

Figure 5 shows the temperature and pressure obtained from the flow analysis results and the results are applied to the structural analysis. The maximum pressure inside the valve is about 0.502MPa, which is almost the same as the design pressure.

The temperature distribution is about 599.9℃, which is the same as the design temperature. The results of the flow-structure analysis mainly indicate the results of the analysis of the open angle of 60°, which is the most commonly used disc open angle when the valve is utilized.

Figure 6 shows the stress distribution obtained by the fluid-structure interaction analysis, and the results are obtained when the open angle is 60°.

The maximum stress occurs in the seat portion, and the value is about 18.33MPa. As mentioned above, the valve seat has a strength that can be used at a high temperature of 900℃ or higher; thus, it can be evaluated as stable. The maximum stress of the body and disc of the valve occurred at the part connected to the stem.

Table 2 represents the results of the safety evaluation of the maximum stress value obtained through the fluid-structural interaction analysis for the main parts of the valve under the environment of 600℃. Here,

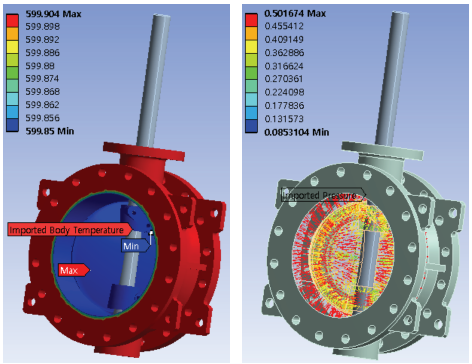
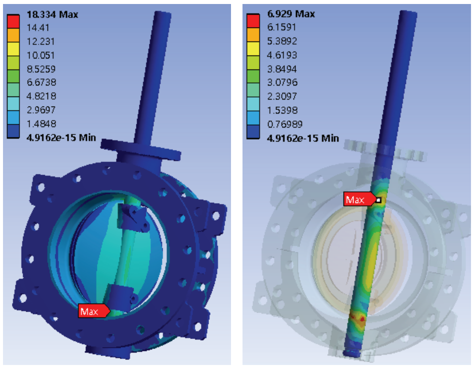
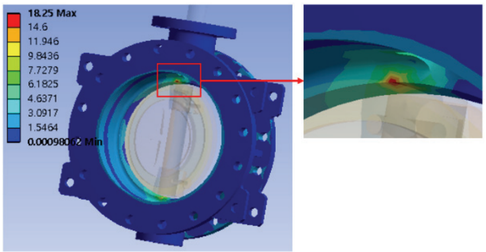


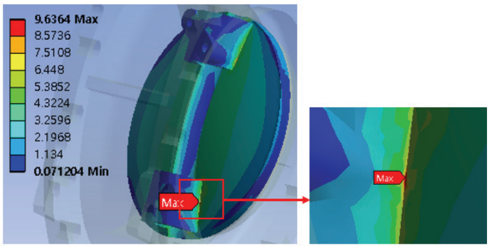
Fig. 5 Loading conditions of fluid-structural analysis



(a)Total (b)Stem



(c)Body



(d)Disc

Fig. 6 Stress distribution results at a open angle of 60°

Table 2. Stress results of fluid-structural interaction analysis (600℃)

Disc open angle(°)	Disc	Max. Stress [MPa]	Stress ratio	Safety factor
40	Body	25.71	0.45	2.2
	Disc	11.57	0.20	4.99
	Stem	9.36	0.04	25.8
60	Body	18.25	0.32	3.2
	Disc	9.64	0.17	5.98
	Stem	6.93	0.03	34.8
90	Body	6.09	0.11	9.5
	Disc	5.74	0.10	10.1
	Stem	3.71	0.02	65.0

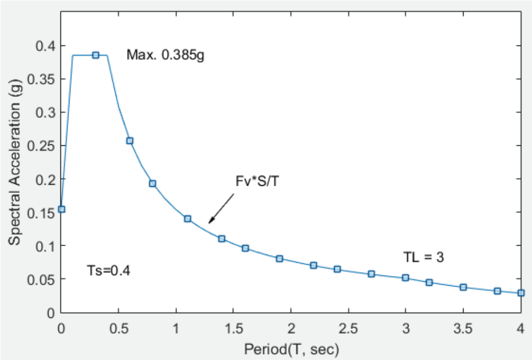


Fig. 7 Standard design response spectrum

the safety factor was defined as the following equation (1):

$$\mathrm{S.F.(safety\,factor)} = \frac{\mathrm{Yield\ strength}}{\mathrm{Caculated\ stress}} \tag{1}$$

4. Seismic analysis

For the seismic analysis of the high-temperature butterfly valve, the natural frequency was obtained by modal analysis of the target model. Generally, the first natural frequency of the valve is compared with the dominant frequency of the seismic force to decide whether to perform static seismic analysis and dynamic analysis. In this study, the stability of the valve was confirmed by performing the static seismic analysis because the obtained first natural frequency of the valve is larger than the dominant frequency of the earthquake.

4.1 Equivalent static load

The standard design response spectrum is derived as shown in Figure 7 using the site amplification factor obtained when the type of site and the seismic zone coefficient are 0.11g. The maximum acceleration(S_a) obtained by applying the risk factor can be obtained by the following equation.

$$S_a = 2.5F_a \times S \tag{2}$$

In this equation, and are the site amplification factor and valid ground acceleration, respectively. The mass of the valve is about 237.3 kg. For conservative evaluation, the equivalent static load when applying the maximum acceleration (0.385g) obtained in Figure 7 is determined by Newton’s second law as follows.

$$F = mS_a = 896.3\,[\mathrm{N}] \tag{3}$$

4.2 Seismic analysis

Figure 8 represents the load and restraint conditions for seismic analysis, and seismic analysis was performed by applying the seismic load obtained from Equation 2.

The seismic load was applied horizontally, and the operating conditions were 1.1 times the design pressure for seismic analysis.

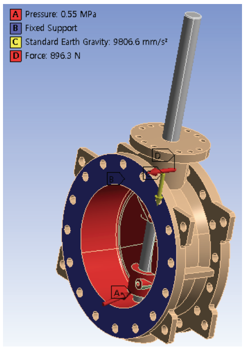
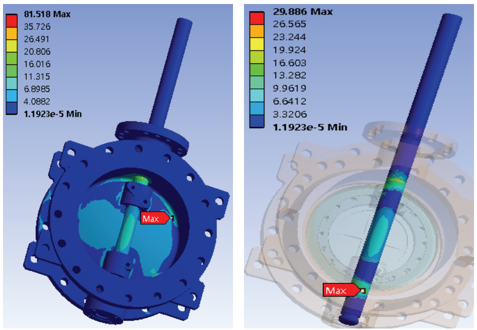
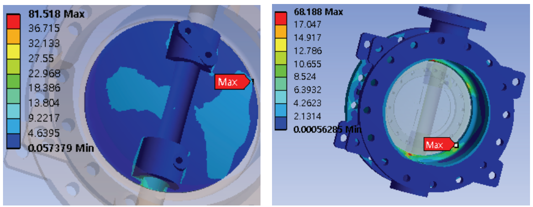


Fig. 8 Boundary condition for seismic analysis



(a) total (b) stem



(c) disc (d) body

Fig. 9 Stress distribution of valve

Table 3. Stress results of seismic analysis for valve

Loading condition	Disc.	Max. Stress [MPa]	SF(Safety factor)
Normal pressure	Body	68.12	3.0
	Disc	81.52	2.5
	Stem	29.89	10.4
	Seat	57.22	9.6
	Retainer	22.32	9.2
Reverse pressure	Body	38.62	5.3
	Disc	162.50	1.3
	Stem	32.38	9.6
	Seat	51.12	10.8
	Retainer	28.69	7.1

Figure 9 shows the result of the seismic analysis (stress) of the valve when normal pressure load is applied. The maximum stress of the valve occurs in the disc part, and its size is about 81.5MPa, which is about 9% higher than the general structural analysis result. Compared to the yield strength of the disc, the safety factor is about 3.0, which means that the valve is stable.

Table 3 represents the maximum stress and stability obtained by seismic analysis when reverse and normal pressures are applied to the butterfly valve.

The maximum stress calculated in the analysis is divided by the yield strength of the material. If this value is greater than 1, the valve can be evaluated as stable. As a result of the seismic analysis, the valve is stable and shows a tendency similar to general structural analysis. Compared with general structural analysis, the overall stress value is about 9% to 11%. In particular, when the reverse pressure is applied, the safety factor of the disc is about 1.3.

5. Conclusions

In this study, the flow stability and flow-structure analysis of a 400A butterfly valve were performed to evaluate the stability of the valve. The flow velocity and pressure distribution according to the disc open angle were derived from the flow analysis, and the stability was examined by performing the fluid-structural interaction analysis.

As the open angle of the valve disc decreased, the pressure distribution tended to be uniform. As the open angle of the disc increased, the flow velocity decreased and the velocity distribution changed more strongly. The fluid-structural interaction analysis showed that the larger the disk open angle, the lower the stress and the greater the stresses in the seat and body. In the case of a valve body, the safety ratio was about 2.2 when the open angle was 40°, whereas result of the fluid-structural interaction analysis for the main parts of the valve showed that the valve system was safe. In seismic analysis, compared to the general structural analysis, the maximum value of the stress value of the valve was about 9% to 11% when the seismic load was applied.

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