한국기계가공학회지, 제20권, 제8호, pp. 107～114(2021.08) ISSN 1598-6721(Print)
Journal of the Korean Society of Manufacturing Process Engineers, Vol. 20, No. 8, pp. 107~114(2021.08) ISSN 2288-0771(Online)

https://doi.org/10.14775/ksmpe.2021.20.08.0107

A Study on the Orifice Shape of High-Differential Pressure Control Butterfly Valve

Ik-Sang Yun[*], Jeong-In Jin[**], Sung-Ki Lyu[*,#]
[*]School of Mechanical & Aerospace Engineering, Gyeongsang National University
[**]Korea Testing Laboratory

고차압 제어 버터플라이 밸브의 오리피스 형상에 관한 연구

윤익상[*,**], 진정인[**], 류성기[*,#]
[*]경상국립대학교 대학원 기계항공공학부, [**]한국산업기술시험원

(Received 10 June 2021; received in revised form 12 July 2021; accepted 31 July 2021)

ABSTRACT

Butterfly valves are used in various industries to control the flow rate, flow direction, pressure, and temperature. These are gaining popularity in the field of plant industry to enable high-differential pressure because of their low maintenance costs and ease of installation. This study presents a numerical analysis method to analyze changes in the flow characteristics of a high-differential pressure control butterfly valve based on the location and shape of the orifice. The numerical analysis was conducted using a commercial CFD program. The analysis results show a correlation between the orifice shape and cavitation phenomenon.

Key Words : Butterfly Valve(버터플라이밸브), High-Differential Pressure(고차압), Orifice Shape(오리피스 형상), Numerical Analysis(수치해석), Cavitation Phenomenon(캐비테이션 형상)

1. Introduction

A butterfly valve for controlling high-differential pressure is widely used across various industries owing to its advantages, such as economic feasibility, easy installation, and convenient maintenance. However, cavitation frequently occurs from a sudden pressure drop in the vena contracta and high pressure recovery due to the nature of a butterfly valve; thus, research is required to investigate measures for reducing the occurrence of the cavitation phenomenon to satisfy the high-differential pressure control demand of a plant system.

Most studies on butterfly valves have been conducted as a numerical analysis of flow characteristics and loss factor according to flow control. Park et al. applied the design of experiments to perform computational fluid dynamics (CFD) analyses for evaluating the properties considering the pressure loss coefficient and stress of a butterfly valve.[1] Song et al. used a numerical analysis method to analyze the valve

---

Corresponding Author : sklyu@gnu.ac.kr
Tel: +82-55-772-1632, Fax: +82-55-772-1578

structure and perform a flow analysis to deduce the optimal design of a butterfly valve, and the accuracy of the optimal design was verified through an experiment.[2] Huang et al. used a flow analysis program to analyze the three-dimensional noncompressible flow characteristics within a valve according to the disk angle of a butterfly valve using a numerical analysis method.[3] William et al. detected cavitation and noise limit according to the cavitation stage based on the experimental data of noise generated in a butterfly valve.[4] Extensive research has been conducted on the monitoring of cavitation occurring in a butterfly valve, complex disk surface shape, and the association between the flow characteristics and the occurrence of cavitation.[5-9] It is advisable to reduce the occurrence of cavitation fundamentally by improving the design of a butterfly valve. However, flow characteristics may vary when applied to an actual pipe system depending on various factors, such as the length and shape of a pipe conduit and turbulent flow, and an unexpected cavitation phenomenon may occur. Adjusting valve design or replacing the valve requires extensive amounts of cost and time.

Therefore, this study aimed to reduce the occurrence of cavitation by gradually lowering the abrupt pressure drop in the control part of a butterfly valve by installing an orifice at the front and rear ends of the butterfly valve for controlling high-differential pressure. The flow coefficient, the degree of cavitation occurrence, and correlation are analyzed according to the shape of the orifice using a numerical analysis program, and the design plan of the orifice with favorable conditions for reducing the cavitation phenomenon is deduced.

2. Numerical analysis method

2.1 Governing equations

ANSYS Workbench 19.2, which is a commercial CFD program, was used in this study for analyzing the characteristics of a butterfly valve for controlling high-differential pressure and an orifice. 3D governing equations are required to identify the characteristics of a flow field in the three dimensions of a valve, orifice, and the inside of pipes. The Reynolds-averaged Navier–Stokes equations were used as the governing equations, whereas energy equations were excluded, as heat transfer through the pipes and valve is insignificant. The continuity and momentum equations used in this study can be expressed as shown in Equation (1) and (2) below.

$$\frac{\partial}{\partial x_j}(\rho U_i) = 0 \tag{1}$$

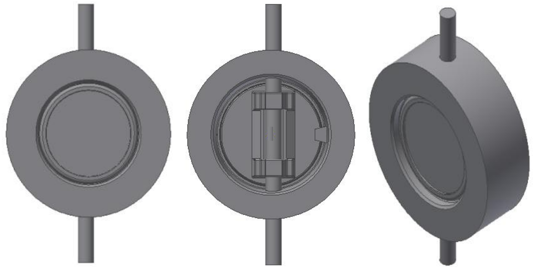
$$\frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial P}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial}{\partial x_j}(\rho \overline{u_i u_j}) \tag{2}$$

2.2 Analysis model

Fig. 1 shows the shape of a butterfly valve for controlling high-differential pressure, which is used in this study as a 3D model of an offset butterfly valve of Class 300 and size 100A. Fig. 2 shows the shape of an orifice for reducing the cavitation phenomenon occurring in the butterfly valve. The study was conducted using five orifice types with different numbers of orifice bores, bore diameters, and total areas of the bores. The basic specifications of the orifice are listed in Table 1. The area ratio is defined as the relative ratio of the cross-sectional area of the flow inside the pipe of size 100A used in this study to the total cross-sectional area of the bores.

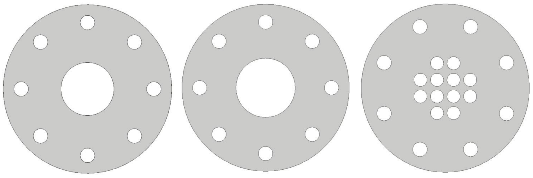
2.3 Boundary conditions

The standard k–ε turbulence model was used in this study, whereas the walls of the pipes and valve were set with nonslip viscous flow. Water at the temperature of 25℃ was used as the applied fluid. To ensure that the developed flow was sufficiently generated, the analysis domain was created as follows: the pipe length ranged from the nominal diameter of 11D from the front end of the valve to 21D from the rear end of the valve, whereas the pipe diameter was set to 100A, which is identical to the valve diameter. Two boundary conditions were given for analyzing the cavitation index under valve usage conditions and for measuring the flow coefficient, which is a major indicator of valve performance. Accordingly, a numerical analysis was performed. First, for measuring the flow coefficient, the flow conditions were set as follows: the pressure at the 2D location from the front end was set to 3 bar, whereas the pressure at the 6D location from the rear end was set to 2.5 bar with respect to the nominal diameter of the valve.

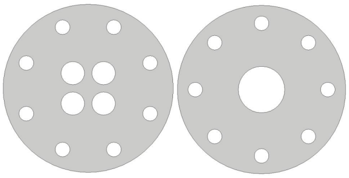


a) Front view b) Rear view c) ISO view

Fig. 1 3D modeling of the butterfly valve



a) Orifice Type 1 b) Orifice Type 2 c) Orifice Type 3



d) Orifice Type 4 e) Orifice Type 5

Fig. 2 Type of orifices by shape

Table 1 Specifications of orifice shape

	Type 1	Type 2	Type 3	Type 4	Type 5
Number of Bore	1	1	12	4	1
Bore diameter (mm)	80	90	20	35	70
Bore total cross-section area(mm^2)	5027	6362	3770	3848	3848
Area ratio	0.65	0.8	0.5	0.5	0.5
Orifice thickness (mm)	10				

Second, for measuring the cavitation index and the degree of cavitation phenomenon, the flow speed was set to 7 m/s, which is a valve usage condition, and the outlet was set to the atmospheric pressure condition.

Fig. 3 shows the grid system used in this study where polyhedral elements are used to constitute the grids of the pipe, valve, and orifice. The grid sizes of the valve and orifice were set to 3 mm, whereas that of the peripheral part was set to 10 mm. The number of generated nodes was approximately 120,000, whereas the number of generated elements was approximately 650,000.

2.4 Numerical analysis verification

The flow coefficient of the valve and the cavitation index were measured through experiments for verifying the analysis program and numerical analysis conditions used in this study. The numerical analysis results obtained from the CFD program and the experimental values were compared to verify the accuracy of the numerical analysis approach.

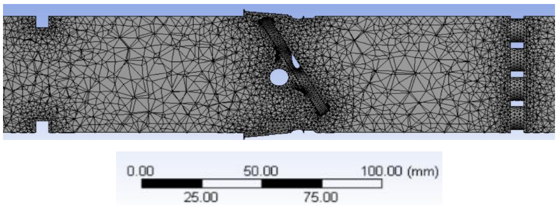


Fig. 3 3D mesh model including pipe system, orifice and butterfly valve

The test equipment components and test procedures specified in the KS Standards (KS B 2101) were complied with to conduct the test for determining the flow coefficient of the valve. The cavitation index σ was calculated using Equation (3) based on P_v, which is the vapor pressure of the liquid, after measuring P_1, which is the pressure at a point 1D away from the front end with respect to the nominal diameter of the valve, and P_2, which is the pressure at a point 5D away from the rear end.

$$\sigma = \frac{P_2 - P_v}{P_1 - P_2} \qquad (3)$$

Fig. 4 and Fig. 5 show the graphs of the flow coefficient of the butterfly valve and the cavitation index, respectively, based on the comparison between the numerical analysis result and the experimental values. A difference within 5% was observed when the flow coefficient and cavitation index were compared at the opening angles of the valve of 30° and 70°. This signifies that the validity of the settings and interpretation of the numerical analysis conditions is sufficiently ensured. Accordingly, the above numerical analysis conditions were applied to analyze the flow characteristics and cavitation reduction effect according to the orifice shape and location using a numerical analysis program.

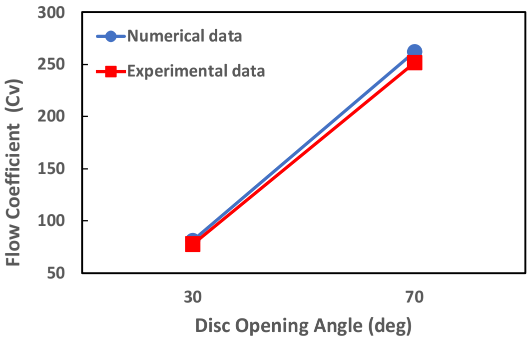


Fig. 4 Flow coefficient of butterfly valve at 30 deg and 70 deg

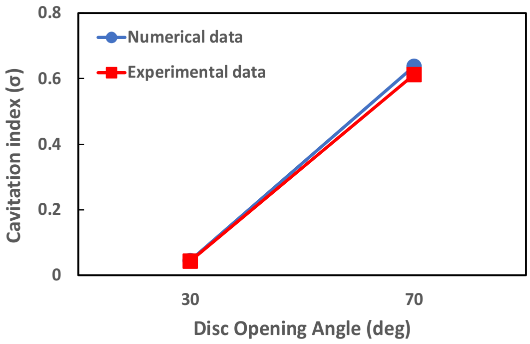


Fig. 5 Cavitation index of butterfly valve at 30 deg and 70 deg

3. Result and discussion

3.1 CFD results according to the changes in orifice shape

An orifice was installed in a pipe system for reducing cavitation in a butterfly valve for controlling high-differential pressure. Subsequently, the cavitation reduction effect and the changes in flow characteristics were analyzed using a CFD program. The five orifice types in Fig. 2 were combined at the front and rear ends of the valve. Type 1 and Type 2 were installed at a nominal diameter 1D away from the front end of the valve; Type 3–Type 5 were installed at a nominal diameter 1D away from the rear end of the valve.

The flows of a total of 12 cases, including the cases where there was no orifice at the front and rear ends, three cases of an orifice installed at the front end, and four cases of an orifice installed at the rear end, were analyzed. The 12 cases of orifice combinations are presented in Table 2. Fig. 6 shows the graph of analyzing the flow coefficient of the 12 cases. When the valve disk opening angle was 30°, the flow coefficient of each case was reduced by approximately 10% compared with when there was no orifice and the values were fairly even. It can be inferred that the presence or shape of the

Table 2 Specifications of orifice shape

Division	Inlet orifice	Outlet orifice
No orifice	-	-
CASE 1	Type 1	-
CASE 2	Type 2	-
CASE 3	-	Type 3
CASE 4	-	Type 4
CASE 5	-	Type 5
CASE 6	Type 1	Type 3
CASE 7	Type 1	Type 4
CASE 8	Type 1	Type 5
CASE 9	Type 2	Type 3
CASE 10	Type 2	Type 4
CASE 11	Type 2	Type 5

orifice did not have a significant effect, as the opening of the valve disk did not sufficiently secure a flow path. When the valve disk opening angle was 70°, the flow coefficient of case 8 was approximately 65% that of the case where there was no orifice, which confirmed that the orifice significantly hinders the flow. The results of case 3–case 5 were similar for both small and large valve opening angles, whereas the results of case 6–case 8 and those of case 9–case 11 were similar as well. Therefore, it can be concluded that the size and number of bores have a minor influence on the flow coefficient if the total bore cross-sectional area of the orifice is identical.

Fig. 7 and Fig. 8 show the graphs of the cavitation index and cavitation volume for the 12 cases of orifice combinations. Fig. 9 shows the distribution of the flow velocity within the pipe at a small opening angle, whereas Fig. 10 shows the distribution of the cavitation volume.

The CFD results showed that the lowest cavitation volume occurred in case 6 when the valve disk opening angle was 30°, which is approximately 26% of the cavitation volume when there was no orifice. Thus, it was confirmed that installing an orifice reduces the occurrence of cavitation. Furthermore, the distributions of the cavitation volume and flow velocity showed that a large eddy was generated at the rear end of the valve when there was no orifice. Thus, it can be inferred that implosion occurs due to cavitation, which leads to the generation of an eddy. When an orifice was installed, a relatively smaller eddy was generated between the valve and the rear orifice, whereas both eddy and cavitation occurred at the rear end of the orifice. In the velocity distribution of case 6 and case 9, an eddy was not generated at the rear end of the orifice and a stable flow was generated. A greater number of orifice bores further reduces the occurrence of cavitation and stabilizes the flow in the pipe at the rear end.

When the valve disk opening angle was 70°, a greater degree of cavitation occurred in all the cases where an orifice was installed compared with the case where no orifice was installed. Owing to the nature of a butterfly valve, the flow is less hindered by the disk at a large opening angle, whereas cavitation occurs significantly at a small opening angle, such as 30°. Hence, the cavitation reduction effect of installing an orifice is maximized at a small opening angle.

The total cross-sectional area of the orifice bores and the number of bores are major parameters to be considered when designing an orifice for reducing the cavitation in a butterfly valve. As the flow coefficient can be adjusted by the total cross-sectional area of the bores, and the cavitation phenomenon can be reduced with the number of bores, an optimal design of the orifice can be implemented to improve the flow characteristics while reducing cavitation without having to change the valve.

3.2 Empirical experiment

The CFD analysis results showed that cavitation was reduced by approximately 75% in case 6 where an orifice was installed at the front and rear ends of the valve. The occurrence of cavitation can be observed through an empirical experiment, but precisely measuring the degree of cavitation still entails difficulties.

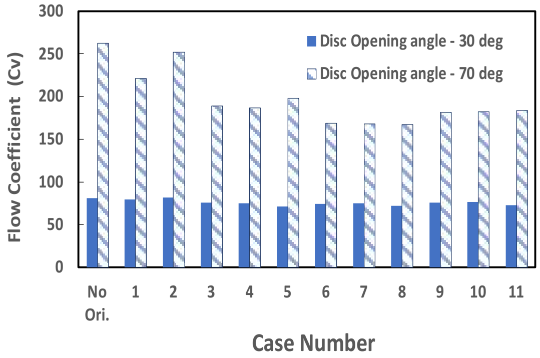


Fig. 6 Graph of flow coefficient

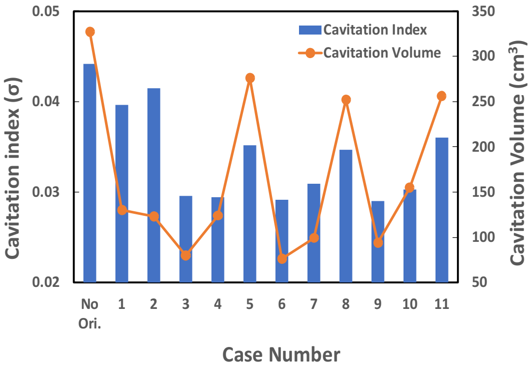


Fig. 7 Graph of cavitation characteristic at 30 deg

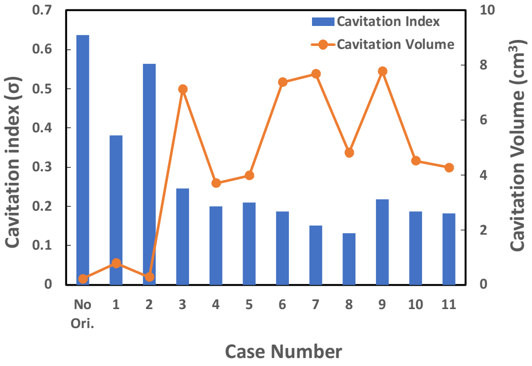


Fig. 8 Graph of cavitation characteristic at 70 deg

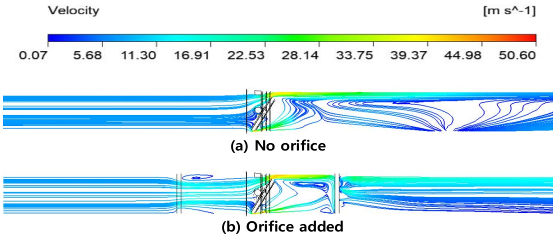


Fig. 9 Velocity and streamline distribution at 30 deg

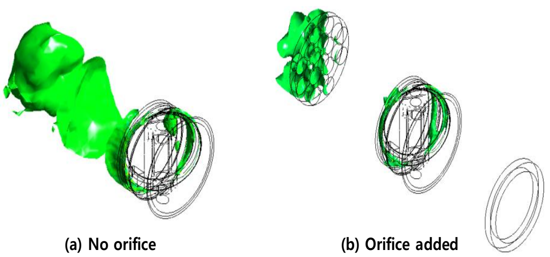


Fig. 10 Cavitation volume distribution at 30 deg

Therefore, the reliability of the performance of an orifice was indirectly secured by comparing the results of an empirical experiment on the flow coefficient and cavitation index with those of the CFD analysis.

Fig. 11 and Fig. 12 show the results of the flow coefficient of a butterfly valve and cavitation index measured through empirical experiment equipment where the data of the numerical analysis results and experimental results are compared. The difference between the empirical experiment results of the flow coefficient and cavitation index and the numerical analysis results obtained through the CFD analysis was within 8%.

The error value was higher than the experimental results of the valve obtained for verifying the numerical analysis. The degree of precision when processing the orifice and the surface roughness of the orifice may have caused an error in the measurement of the flow characteristics, which possibly increased the error. When manufacturing a specimen, a higher level of reliability must be secured through precision processing.

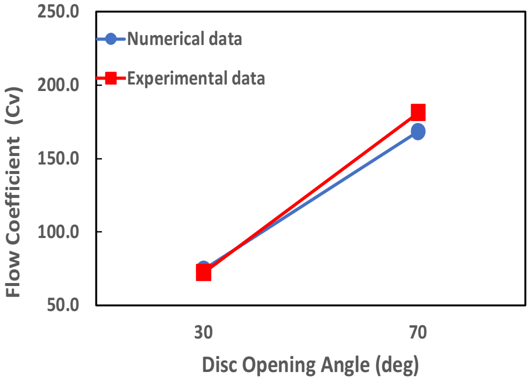


Fig. 11 Flow coefficient of butterfly valve & orifice at 30 deg and 70 deg

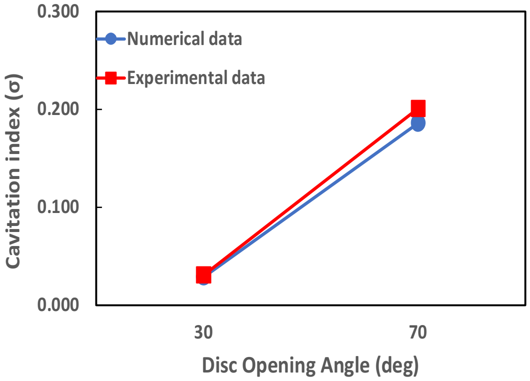


Fig. 12 Cavitation index of butterfly valve & orifice at 30 deg and 70 deg

3.3 Correlation analysis

The Pearson correlation coefficient was applied to analyze the correlation between the orifice shape and the cavitation reduction effect. The Pearson correlation coefficient represents the linear correlation between two variables. It has a value between -1 and +1 according to the Cauchy–Schwarz inequality, where +1 indicates a perfectly positive linear correlation, 0 indicates no linear correlation, and -1 indicates a perfectly negative linear correlation.

The Pearson correlation coefficient, which is obtained by dividing the covariance of two variables in the interval scale or ratio scale data by the square of standard deviation, can be calculated as shown in Equation (4).

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \tag{4}$$

For Type 3–Type 5 where the orifice was installed at the rear end of the valve, the total cross-sectional area of the bores was designed to be identical while adjusting the diameter and number of the bores. When the bore diameter was small, the number of bores was increased to ensure that the total cross-sectional area of the bores was identical. The Pearson correlation coefficient was calculated by setting the orifice diameter and cavitation volume as two variables to analyze the correlation between the cavitation reduction effect and the orifice diameter under the assumption that the total cross-sectional area of the orifice was identical. The correlation coefficient showed a contrasting trend when the opening angles of the valve were small and large: a positive correlation was observed at a small opening angle, whereas a negative correlation was observed at a large opening angle. In other words, as the bore diameter increases, cavitation increases at a small opening angle but decreases at a large opening angle.

4. Conclusion

In this study, an orifice was installed at the front and rear ends of a butterfly valve for controlling high-differential pressure and the flow coefficient and cavitation volume were analyzed with respect to the changes in the orifice shape.

1. A difference of 8% was observed between the empirical experiment results and the CFD analysis results, and thus, the reliability of the boundary condition settings for the CFD analysis and interpretation results was secured.

2. At a small opening angle, the change in the flow coefficient was approximately 10% depending on the presence or shape of an orifice, which is insignificant. At a large opening angle, the flow coefficient decreased as the area ratio of the orifice decreased, as the orifice interfered with the flow.
3. The occurrence of cavitation could be reduced by 75% by installing an orifice at the front and rear ends of the butterfly valve.
4. When the total area ratio of the orifice was identical, the Pearson correlation coefficient showed that a multi-bore orifice with a small opening angle and a single-bore orifice with a large opening angle are effective in reducing the occurrence of cavitation.

REFERENCES

1. Park, Y. C., Choi, J. S., and Kang, J., "A Optimization of Butterfly Valve using the Characteristic Function," Journal of the Korea Society of Ocean Engineers, Vol. 19, No. 3, pp. 59-65, 2005.
2. Song, X. G., Wang, L., Baek, S. H., and Park, Y. C., "Multidisciplinary optimization of a butterfly valve," ISA Transactions, Vol. 48, No. 3, pp. 370-377, 2009.
3. Huang, C., and Kim, R. H., "Three-Dimensional Analysis of Partially Open Butterfly Valve Flows". Journal of Fluids Engineering, Vol. 118, No. 3, pp. 562-568, 1996.
4. Rahmeyer, W. J., "Cavitation noise from butterfly valves", Nuclear Engineering and Design, Vol. 72, No. 3, pp. 297-301, 1982.
5. Hwang, W. W., Goh, M. H., and Yang, B. S., "Cavitation Condition Monitoring of Butterfly Valve Using Support Vector Machine," Transactions of the Korean Society for Noise and Vibration Engineering, Vol. 14, No. 2, pp. 119-127, 2004.
6. Yoon, J. Y., "Numerical Analysis of Flows in Butterfly Valves to Prevent Cavitation", Journal of Fluid Machinery, Vol. 7, No. 1, pp. 9-16, 2004.
7. Kim, J. Y., "Numerical Study on Cavitation Growth Rdeuction in Butterfly Valve", Master's thesis, Changwon national university, 2010.
8. International Electrotechnical Commission(IEC), "IEC 60534-2-1 Industrial-process control valves - Part 2-1: Flow capacity - Sizing equations for fluid flow under installed conditions", 2011.
9. Lee, D. M., "Optimization of Butterfly Flow Control Valve for Topside of Offshore Plant", Doctoral thesis, Pusan national university, 2014.