CFD Analysis for the Effect of Upstream Elbow Flow Disturbance on the Hydraulic Characteristics of the Butterfly Valve; Depending on the Configuration of the Valve Disc Arrangement

Gong Hee Lee*, Seon Ho Choi
Reactor System Department, Korea Institute of Nuclear Safety, Daejeon, 34142, Korea

**Corresponding author: ghlee@kins.re.kr*

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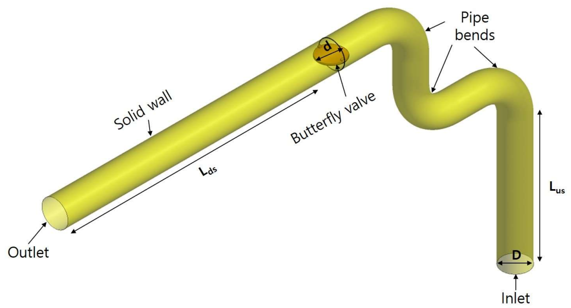
1. Introduction

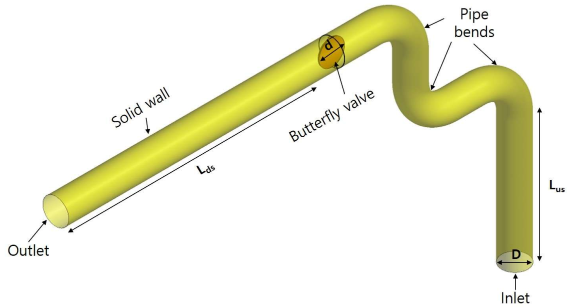
As the operational period of the domestic nuclear power plants increases, various issues have arisen in the field of in-service testing (IST), which checks the current performance of safety-related components and monitors their performance changes [1]. For instance, there was a case in which a butterfly valve was damaged due to the very short straight length between the multi-hole orifice installed at the pump discharge of the essential service water system (a representative IST-related system) and the valve itself [1]. Thus, especially at high flow rates (or fluid velocities), the effect of upstream flow disturbances on the butterfly valve's performance such as head loss, torque, etc. and integrity can be substantial due to the insufficient straight pipe length between primary devices (e.g., orifice, elbow) and the butterfly valve [2]. According to the EPRI technical report [3], the configuration in which the valve shaft and the elbow lie in the same plane is generally recommended, because it has the least effect on valve performance in both the closing and opening directions. Therefore, in this study, the effect of upstream elbow flow disturbances on the hydraulic characteristics of a butterfly valve; depending on the configuration of the valve disc arrangement was examined using ANSYS CFX R19.1.

2. Analysis Model

Fig. 1 shows a schematic diagram of the analysis model used in this study. The model consists of multiple 90° bends arranged in the same plane and a butterfly valve. A valve disc angle of zero ($\alpha = 0°$) indicates that the valve is fully open [2]. The geometrical specifications of the analysis model are provided in Table I. Water properties at 25 °C were applied in the simulation [2].



(a) Horizontal arrangement



(b) Vertical arrangement
Fig. 1. Analysis model.

Table I: Geometrical specification of an analysis model

Parameters	Unit	Magnitudes
Pipe diameter (D)	m	3.66
Valve disc diameter (d)	m	3.53
Valve disc angle (α)	Deg.	0, 10, 20, 30, 40, 50, 70
Radius of curvature	m	1.5D
Upstream straight length (L_{us})	m	5D
Downstream straight length (L_{ds})	m	10D

3. Numerical Modeling

The flow around the butterfly valve was assumed to be steady, incompressible, turbulent, and single-phase [1]. For reference, the numerical methods and boundary conditions used in this study are summarized in Table II.

An unstructured hybrid grid system consisting of tetrahedral, hexahedral, prism, and pyramid elements was generated using ANSYS Advanced Meshing. The full geometry of the butterfly valve was considered for the possibility of asymmetric flow behavior [1]. Based on the grid sensitivity study, a total number of elements ranging from approximately 7.4×10^6 to 8.5×10^6, depending on the valve disc angle (α), was finally used in the calculations. To accurately predict the complex flow phenomena such as flow separation and recirculation around the valve disc, a dense grid distribution near the valve disc and pipe wall was used [2]. This grid pattern is generally recommended for flow simulations around a butterfly valve [2]. The validation results of the numerical model, as described above, can be found in the author's separate publication [2].

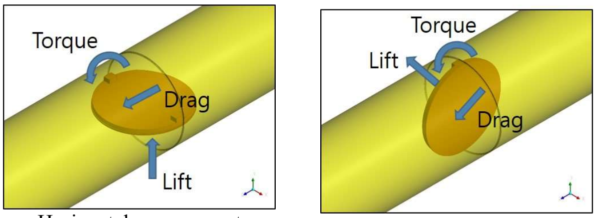
Table II: Numerical methods and boundary conditions for flow analysis

Numerical methods		**Note**
Discretization accuracy for convection term	Momentum eqn.	High resolution
	Turbulence eqn.	High resolution
Turbulence model		SST k-ω
Velocity-pressure coupling		Rhie Chow (4th order)
Near wall treatment		Automatic wall treatment
Convergence criteria		$< 3\times10^{-4}$
Boundary conditions		**Note**
Inlet	Flow rate	1.4~56.6 m^3/s
	Turbulence	medium intensity (5%)
Outlet		static pressure
Wall		no-slip & smooth wall

4. Results and Discussion

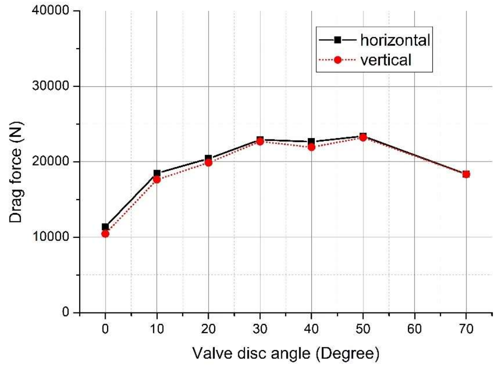
Fig. 2 presents a comparison of hydraulic forces and torque magnitudes depending on the configuration of the valve disc arrangement. For the drag force acting on the valve disc, the horizontally arranged disc exhibited relatively higher magnitudes at most disc angles. Similarly, the lift force and torque reached their maximum values at a valve disc angle of α = 10°, and, like the drag force, were also higher for the horizontally arranged disc. According to the EPRI technical report [3], when the valve disc is horizontally arranged, the effect of gravity induces a difference in the static head of the working fluid between the upper and lower sides of the disc, resulting in a hydrostatic torque component. Depending on its direction relative to the valve's opening and closing motion, hydrostatic torque can either assist or oppose the actuator. In general, hydrostatic torque is negligible except in large valves with diameters of 30 inches (DN 750) or greater. Furthermore, when the valve disc is vertically arranged, the hydrostatic torque is considered to be approximately zero. For these reasons, the vertical arrangement of the valve disc is typically preferred.

Fig. 3 illustrates the streamlines in vertical cross-sections along the main flow direction, depending on the configuration of the valve disc arrangement. The cross-sectional positions are referenced from the center of the butterfly valve disc. Differences in streamline patterns were observed starting from the X = -2.1m cross-section, depending on the configuration of the valve disc arrangement. At X = 2.0 m, when the disc was horizontally arranged, the streamlines exhibited a quasi-symmetric pattern relative to the vertical centerline.

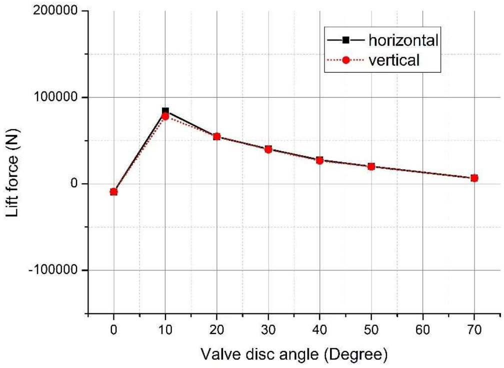


Horizontal arrangement Vertical arrangement

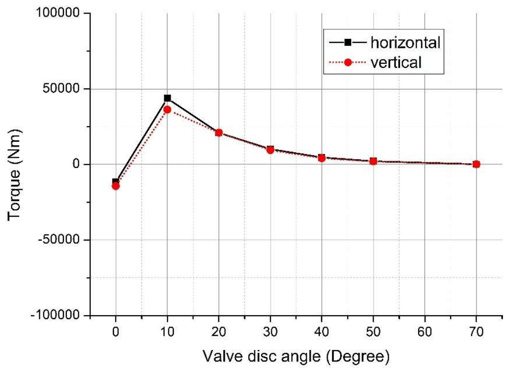
(a) The acting direction of the hydraulic force and torque



(b) Drag force



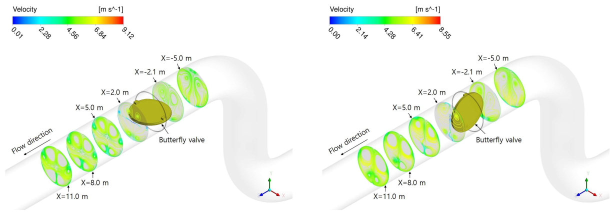
(c) Lift force



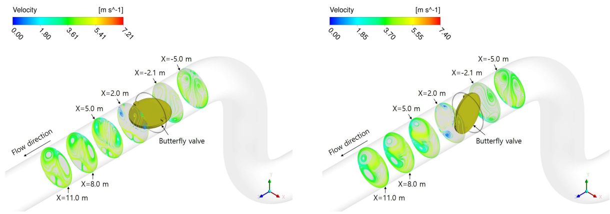
(d) Torque

Fig. 2. Comparison of hydraulic forces and torque depending on the configuration of the valve disc arrangement.

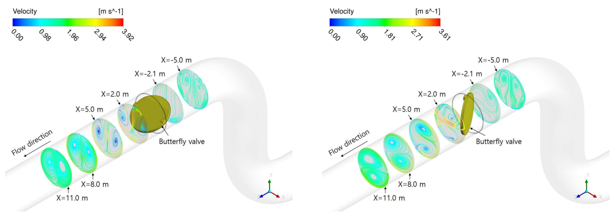
This quasi-symmetric streamline pattern was observed at all valve disc angles except at α = 70°. At this angle, where the flow velocity was relatively low, asymmetric streamline patterns were observed in the vertical cross-sections downstream of the valve disc.



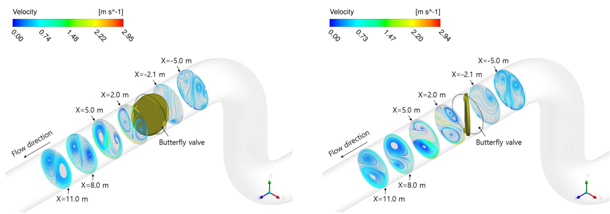
(a) α = 0°



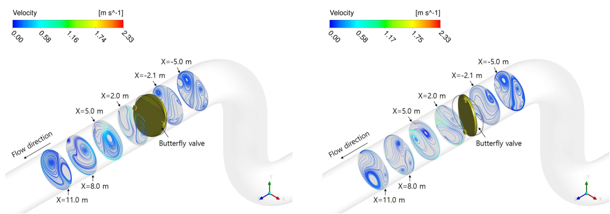
(b) α = 10°



(c) α = 30°



(d) α = 50°



(e) α = 70°

Fig. 3. Streamlines in the vertical cross-sections along the main flow direction (left: horizontal arrangement, right: vertical arrangement)

When the disc was vertically arranged, the streamlines exhibited a quasi-symmetric pattern with reference to the horizontal centerline for valve disc angles between α = 10° and 50°. However, the degree of symmetry was less pronounced compared to the case of horizontal disc arrangement. At α = 0°, the streamline pattern was similar to that of the horizontally arranged disc, indicating that the configuration of the valve disc arrangement does not significantly affect the flow pattern passing through the disc. Similar to the case of the horizontally arranged valve disc, at α = 70°, where the flow velocity was relatively low, asymmetric streamline patterns were observed in the vertical cross-sections behind the valve disc.

5. Conclusions

From CFD analysis for the effect of upstream elbow flow disturbance on the hydraulic characteristics of the butterfly valve; depending on the configuration of the valve disc arrangement, the following main conclusions can be drawn:

(1) It was found that both the lift force and torque reached their highest magnitudes at a valve disc angle of α = 10°. Similar to the drag force, they were relatively higher for the horizontally arranged disc.

(2) When the valve disc was vertically arranged, the streamlines exhibited a quasi-symmetric pattern with respect to the horizontal centerline for valve disc angles between α = 10° and 50°. However, the degree of symmetry was less pronounced compared to the case of horizontal disc arrangement.

DISCLAIMER

The opinions expressed in this paper are those of the author and not necessarily those of the Korea Institute of Nuclear Safety (KINS). Any information presented here should not be interpreted as official KINS policy or guidance.

ACKNOWLEGEMENT

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