Numerical Analysis for the Effect of Upstream Orifice Hole Diameter on the Flow Characteristics around the Butterfly Valve

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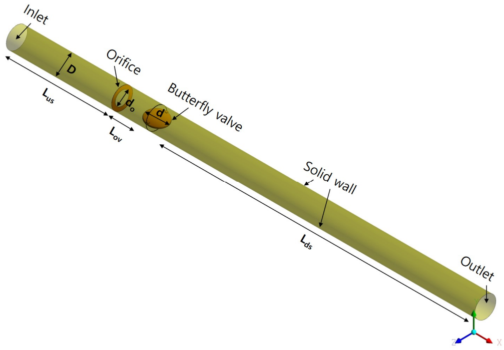
1. Introduction

Domestic nuclear power plant operators have conducted in-service testing (IST) to assess the operational readiness of safety-related valves after the first electrical generation by the nuclear heat. One of the representative IST-related valve types, a butterfly valve, is most commonly used in the primary component cooling water system and containment purge & venting systems for various purposes, such as opening/closing the pipeline and flow rate control [1]. For high flow rate (or fluid velocity), the effect of an upstream flow disturbance may cause the fatigue failure of torque train components in the butterfly valve [2] due to the insufficient length of straight pipe between the primary devices (e.g., orifice, elbow, venturi) and a butterfly valve [1]. Previous experimental and numerical studies [3,4] to examine the effect of an upstream flow disturbance on the butterfly valve's performance mainly focused on an elbow [1]. On the other hand, regardless of the extensive literature survey, the references to deal with the flow characteristics of a butterfly valve downstream of an orifice were hardly seen [1]. Orifice flow is characterized by primary and secondary recirculation region, core region, axisymmetric shear-layer region, shear-layer reattachment region, and so on. These complex flow patterns may change depending on the orifice hole diameter [5].

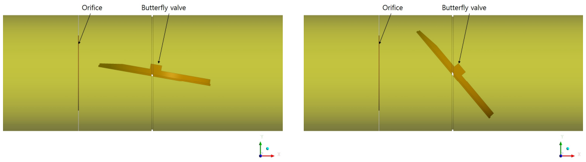
In this study, the numerical simulation was performed to find the effect of an upstream flow disturbance (caused by an orifice with the different hole diameter) on the flow characteristics around the butterfly valve by changing the length of the straight pipe between an orifice and a butterfly valve. For reference, the effect of the different flow disturbance devices (e.g., elbow, reducer) can be found in the author's separate papers [6,7].

2. Analysis Model

Fig. 1 shows a schematic diagram of the present analysis model. The corresponding butterfly valve was used in the Tennessee Valley Authority's Great Falls Hydro Plant [8]. Geometrical specification of an analysis model was explained in Table I. As shown in Fig. 1(b) and 1(c), the larger magnitude of a valve disc angle, the more a valve closes. The water properties at 25 °C were applied [1]. Among the various primary devices, an orifice of diameter ratio (β)=0.35, 0.50, and 0.65 was chosen as an upstream flow disturbance device.



(a) Isometric view



(b) α=10° (c) α=50°

Fig. 1. Schematic diagram of an analysis model.

Table I: Geometrical specification of an analysis model.

Parameters	Unit	Magnitudes
Valve disc diameter (d)	m	3.53
Orifice hole diameter (d_o)	m	1.281, 1.83, 2.379
Pipe diameter at inlet & outlet (D)	m	3.66
Diameter ratio (β=d_o/D)	-	**0.35, 0.5, 0.65**
Upstream pipe length (L_{us})	m	17.65 (5d)
Downstream pipe length (L_{ds})	m	52.95 (15d)
Length between an orifice and valve (L_{ov})	m	0.353, 3.883, 7.413, 10.943 (0.1d, 1.1d, 2.1d, 3.1d)
Valve disc angle (α)	Deg.	10, 30, 50, 70

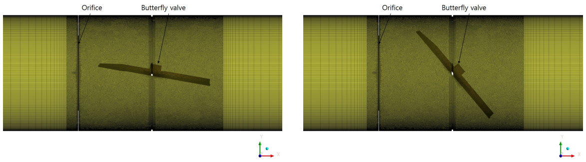
3. Numerical Modeling

The complex flow around an orifice and a butterfly valve was solved by ANSYS CFX R19.1 under the steady, incompressible, turbulent, and single-phase flow conditions. The applied numerical methods were summarized in Table II.

Table II: Summary of the numerical methods.

Items		Notes
Discretization accuracy (for convection term)	Momentum eqn.	High resolution
	Turbulence eqn.	High resolution
Turbulence model		SST k-ω
Near-wall region		Automatic wall treatment
Convergence criteria		Residuals (rms) < 10^{-3}

As shown in Fig. 2, an unstructured hybrid (consisting of hexahedral, tetrahedral, and wedges type) grid system made by ANSYS Advance Meshing was used [1]. The full geometry of a butterfly valve was considered in case the flow could not maintain the symmetrical pattern while passing through the valve disc [1]. Based on the grid sensitivity study [9], the total nodes number between about 8.5×10^6 and 1.29×10^7, depending on L_{ov}, was finally used in the calculation [1]. To properly predict the complex flow around an orifice & the valve disc and its effect on the hydrodynamic force, dense grid distribution near the valve disc, orifice, and pipe wall were used [1].



(a) α=10° (b) α=50°

Fig. 2. Grid system.

Inlet condition was the specified constant volumetric flow rate between Q_{in} = 1.4 (α=70°) and 42.5 m^3/s (α=10°); depending on the valve disc angles, turbulence intensity of 5%, and eddy viscosity ratio of 10 [1]. The average static pressure of 0 Pa was used as the outlet condition [1]. The solid walls were assumed to be smooth with zero surface roughness, and a no-slip condition was applied there [1].

The code validation result for the above-mentioned numerical modeling can be found in the author's separate paper [1].

4. Results and Discussion

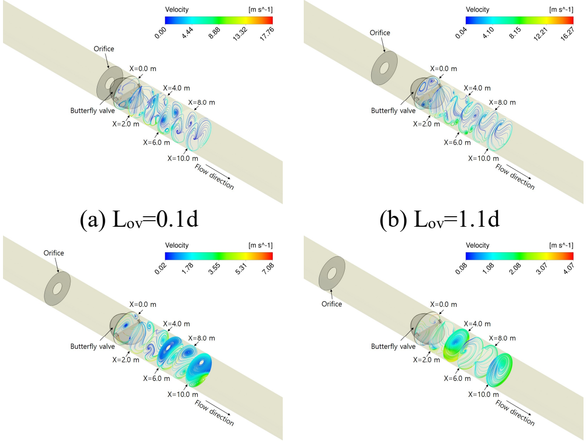
4.1 General Flow Pattern

Fig. 3~5 show the streamline at the selected planes (X=0.0 m ~ 10.0 m) downstream of a butterfly valve depending on the magnitude of β and L_{ov}.

For β=0.35, the streamline showed the asymmetric vortex pattern for all L_{ov} (see Fig. 3). The reason may be that both high velocity core flow passing through the orifice hole and the primary recirculation flow behind an orifice strongly interact with the valve disc and consequently, the symmetrical vortex pattern breaks down. Also, significant fluctuations (unsteady features) for the flow velocity, the hydrodynamic force, and torque were found (not shown for brevity).

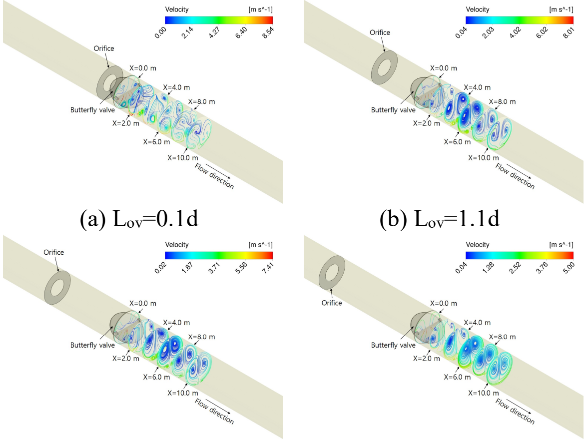
In the case of β=0.50, the streamline showed the symmetric vortex pattern except for L_{ov}=0.1d (see Fig. 4). For β=0.65, the symmetric vortex pattern was found for all L_{ov} (see Fig. 5). In summary, the vortex pattern changed depending on the magnitude of β and L_{ov}.

For reference, the reverse flow and axial velocity distribution for β=0.5 can be found in the author's separate paper [1].



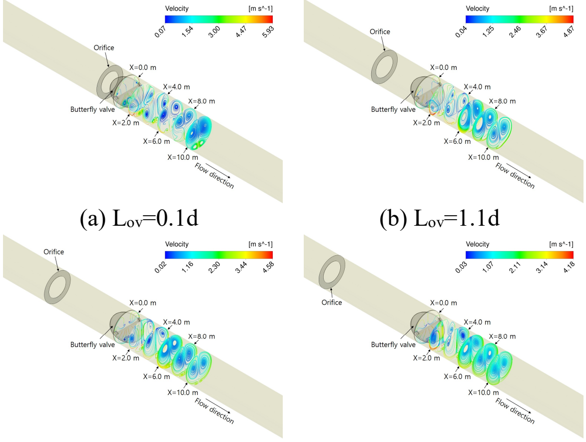
(a) L_{ov}=0.1d (b) L_{ov}=1.1d
(c) L_{ov}=2.1d (d) L_{ov}=3.1d

Fig. 3. Streamline at the selected planes downstream of a butterfly valve (α=30°, β=0.35).



(a) L_{ov}=0.1d (b) L_{ov}=1.1d
(c) L_{ov}=2.1d (d) L_{ov}=3.1d

Fig. 4. Streamline at the selected planes downstream of a butterfly valve (α=30°, β=0.50).



(a) L_{ov}=0.1d (b) L_{ov}=1.1d
(c) L_{ov}=2.1d (d) L_{ov}=3.1d

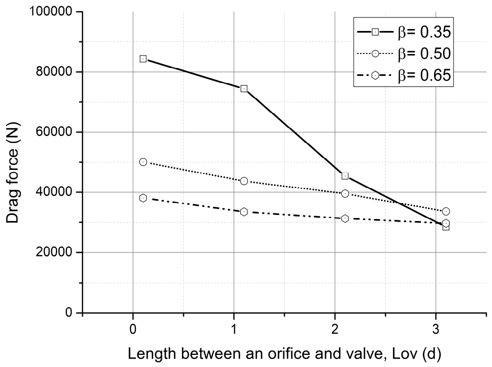
Fig. 5. Streamline at the selected planes downstream of a butterfly valve (α=30°, β=0.65).

4.2 Hydrodynamic Force and Torque

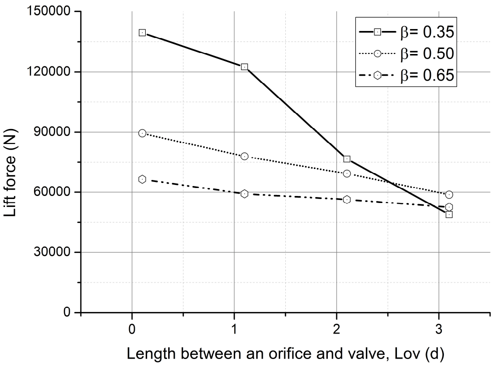
Fig. 6 shows the valve disc's hydrodynamic (drag and lift) force depending on the orifice diameter ratio (β).

Except for L_{ov}=3.1d, the hydrodynamic force had the larger magnitude with the smaller β. One of reason may be the flow acceleration due to the reduction of the flow area passing through an orifice.

As L_{ov} increased, the hydrodynamic force gradually decreased. It means that the effect of an upstream flow disturbance (caused by an orifice) on the butterfly valve's hydrodynamic force diminishes. A similar trend for hydrodynamic force was found at the other valve disc angle (α). For β=0.35, the magnitude of the hydrodynamic force showed the largest reduction at the length from L_{ov}=1.1d to 2.1d.



(a) Drag force



(b) Lift force

Fig. 6. Valve disc's hydrodynamic force depending on the orifice diameter ratio (α=30°).

Fig. 7 shows the valve disc's torque depending on the orifice diameter ratio (β). For L_{ov}=0.1d, the torque had the larger magnitude with the smaller β, similar to the hydrodynamic force. For reference, the negative (-) sign indicates the clockwise direction.

5. Conclusions

In this study, the effect of an upstream flow disturbance (caused by an orifice with the different hole diameter) on the flow characteristics around the butterfly valve was numerically examined using ANSYS CFX R19.1. The main conclusions are as follows:

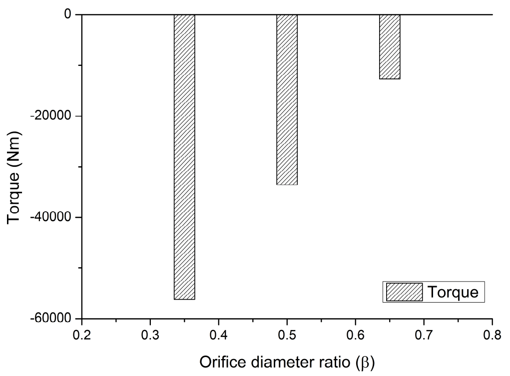


Fig. 7. Valve disc's torque depending on the orifice diameter ratio (α=30°, L_{ov}=0.1d).

(1) For the specific magnitude of α, the vortex pattern (symmetric or asymmetric) downstream of the valve disc changed depending on the magnitude of β and L_{ov}.
(2) For α=30°, the hydrodynamic force gradually decreased as L_{ov} increased. A similar trend for the hydrodynamic force was found at the other valve disc angle (α).

For the specific magnitude of α, β, and L_{ov}, the significant fluctuations (unsteady features) for the flow velocity, the hydrodynamic force, and torque were found. Therefore, additional unsteady simulation is in progress, and the supplementary results will be shown in a separate paper.

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.

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