International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:8, No:12, 2014

Numerical Study of a Butterfly Valve for Vibration Analysis and Reduction

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***Abstract*—**This work presents a Computational Fluid Dynamics (CFD) simulation of a butterfly valve used to control the flow of combustible gas mixture in an industrial process setting.The work uses CFD simulation to analyze the flow characteristics in the vicinity of the valve, including the pressure distributions and Frequency spectrum of the pressure pulsations downstream the valves and the vortex shedding allow predicting the torque fluctuations acting on the valve shaft and the possibility of generating mechanical vibration and resonance.These fluctuations are due to aerodynamic torque resulting from fluid turbulence and vortex shedding in the valve vicinity.

The valve analyzed is located in a pipeline between two opposing 90^o elbows, which exposes the valve and the surrounding structure to the turbulence generated upstream and downstream the elbows at either end of the pipe.CFD simulations show that the best location for the valve from a vibration point of view is in the middle of the pipe joining the elbows.

***Keywords*—**Butterfly Valve Vibration Analysis, Computational Fluid Dynamics, Fluid Flow Circuit Design, Fluid Mechanics.

I. INTRODUCTION

BUTTERFLY valves are popularly used in service in the process industry pipeline systems for flow control or as safety equipment.A butterfly valve consists of three basic components: the valve seat, the valve disk and the supporting shaft.The disc element is suspended inside a tubular housing to form the desired obstruction in the fluid flow. Flow control is achieved by adjusting the orientation of the disc in the valve housing relative to the axis of discharge by a rotary motion.Compared to other devices of the same size, butterfly valves have the advantage of simple mechanical assembly and small flow resistance at the fully open position, additionally, they are lightweight, their simple rotational action allows easy manipulation of the valve using an external actuator. The flexibility offered by such valves has ensured their acceptance in a variety of applications covering a wide range of industries including petrochemical, oil and gas, aerospace, etc.

For economical, space and access reasons, the piping system may be very compact, and consequently the valve may need to be placed in critical spots near an elbow or a bifurcation. Such a placement could influence the aerodynamic torque resulting from the fluid forces on the valve, and could lead to undesired vibrations and load fluctuations.An accurate knowledge of the fluid dynamics forces acting on the valve disk, including the time average and the fluctuating aerodynamic torque is required in order to design a piping circuit which avoids the torque fluctuations and the resulting undesired vibration of the valve and its support structure.

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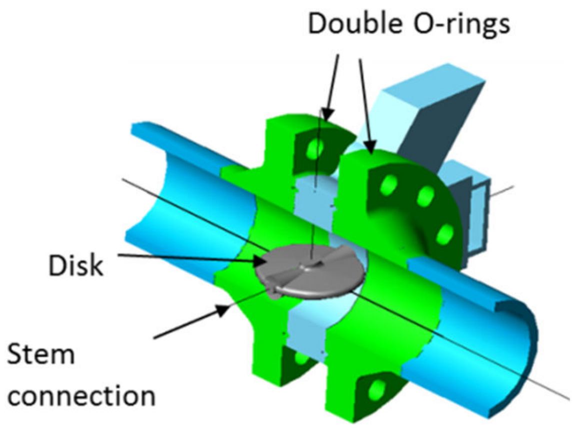
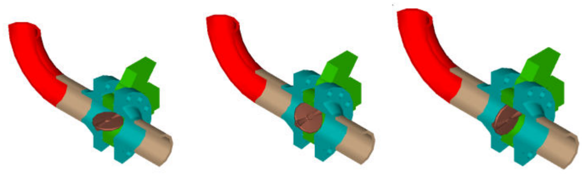


(a) Butterfly valve



(b) Fully open (c) 45 degrees (d) closed

Fig. 1 (a) Butterfly valve and its components (b)-(d) Shaft axis and rotation in relation to elbow

The pressure drops throw the butterfly valves are relatively low, these pressure losses theoretically was studied for a practical butterfly valves done by Kimura and Tanaka [1]. Jeon et al. studied the performance comparison of butterfly valves shapes [2]. For case large buttery valves, the structural analysis and the pressure drops studied by Song et al. [10]. As a source of the butterfly valve desk vibration is the fluid flow vortices, Cheiworapuek et al. [5] observed that these vortices were found near the tips of the buttery valve and became larger as the valve disk was oriented at more closed positions. Feng et al. [6] studied double eccentric buttery valve. They found that a double eccentric structure had improved dynamic response of this valve. The transonic flow around a symmetric disk butterfly valve is associated with the appearance of shock waves, these shock waves studied, for example by Hasan et al. [8]. TLeutwyler and Dalton [7],[9] conducted a CFD study using hybrid grids for symmetrical buttery valves in compressible turbulent fluids at various angles and over a range of pressure ratios.

In this work, a CFD simulation of the butterfly valve shown in Fig. 1 was performed. The valve is placed in the fluid circuit shown schematically in Fig. 2, which shows the design parameters varied.In particular, CFD analyses were used to obtain flow characteristics around the Butterfly valve.Frequency spectrum of the pressure pulsations downstream the valve and the vortex shedding wavelengths provide a prediction of the torque fluctuations acting on the valve and the possibility of generating mechanical vibration and resonance.

II. CFD Model

A. Model Description

Four different cases were studies, with the values of the design parameter indicated for each case in Table I. For each case 3D CFD simulations were performed. The flow characteristics for the valves considered are conveyed by studying the flow behavior in the pipe and in the vicinity of the valve.

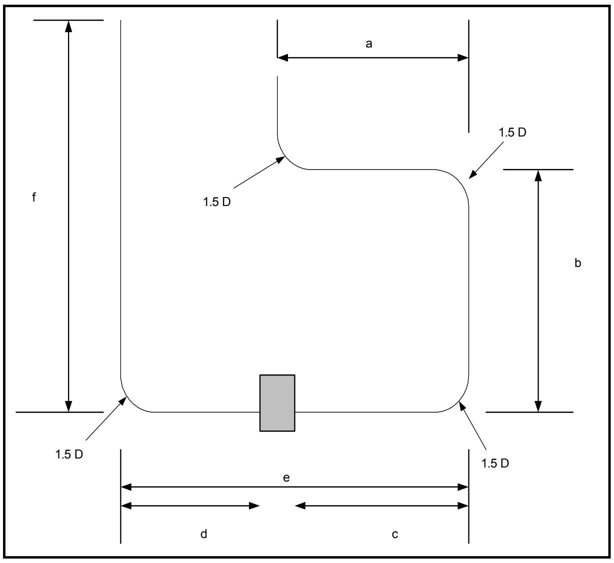


Fig. 2 Fluid circuit studies illustrating valve placement and the different design parameters

CFD simulations have shown that for the two cases of Pipe 1 and Pipe 3, ($d/c = 0.82$), the velocity distribution and the vorticity spectrum indicate that the flow has reached its fully developed nature, and the effect of the elbow on the flow is not very strong. This is due to the positioning of the valve near the middle point between the two elbow, i.e. at a point where d/c=1. In the case of Pipe 2 ($d/c = 2$) and Pipe 4$d/c = 2.1$, the location of the valve is away from the middle point of the pipe in a region where the turbulence generated by the elbow is high. When this turbulence is combined with the vortex shedding from the leading or trailing edge of the valve, serious instantaneous torque fluctuations on the disk of the valve takes place.These torques will be transmitted to the valve's support structure and will produce significant random mechanical vibrations on the valve's components, and its support structure, which may be at one of its resonant frequencies.Those two cases present the worst cases and lead to vibrations that could result in the failure of the valve shaft or body due to the high resulting mechanical stresses.

TABLE I
Design Parameters for the Circuit in Fig. 2

Pipe	ID*	OD	a	B	C	d	e	f
1	17.9	21.6	190	240	150	123	283	2219
2	17.9	21.6	190	240	90	182	283	1680
3	17.9	21.6	190	240	150	123	283	1290
4	22.4	26.7	186	240	88	183	283	861

*All Dimensions in cm, ID=Inner diameter, OD=Outer Diameter.

B. Theoretical Background and Model Validation

The fluid torque acting on a butterfly valve in general is due to the hydrostatic torque and the aerodynamic torque. The hydrostatic is attributable to the hydrostatic pressure forces in terms of the height of a fluid and induced by the difference in head vertically across a horizontal line. This static torque occurs at intermediate positions of disk only when its axis is horizontal.The aero or hydrodynamic torque is the result of forces produced by the fluid. As soon as the valve is sufficiently opened, the aerodynamic torque becomes the major torque acting on the valve's disk, and if the axis of the valve is vertical, the hydrostatic torque is null. The aerodynamic torque may be calculated by integrating the instantaneous pressure forces acting on the two faces of the disk.

$$T(t) = \oint P(t).l\, dA \tag{1}$$

where $P(t)$ is the instantaneous pressure acting on an infinitismal area dA, and l is the elementary lever arm (perpendicular distance between the center of dA and the shaft axis). The integration in (1) is carried out over the area of the disk from both sides.

The nondimensional torque coefficient C_T may be defined as [3]:

$$C_T = \frac{T(\alpha, t)}{0.5\rho V^2 D^3} \tag{2}$$

where α is the valve's angle from the horizontal

To validate the ability of the used CFD software fluent ANSYS [4] to predict torque coefficients on a butterfly valve placed between two elbows, numerical simulations were performed to predict the torque coefficient on a 300 mm diameter disk of a butterfly valve placed at an angle of 30 degrees to flow direction and a at distance of 1500 mm downstream a 90 degree elbow with a flow with velocity of 39 m/s , see Fig. 3. An experimental investigation on this setting was conducted by Danbon and Solliec [3] and estimates the torque coefficient to be 0.25. Seven simulations were performed on such a model to investigate accuracy of the numerical predictions and the sensitivity of the obtained results to different turbulence models, discretization schemes, and grid refinement levels. Table II compares the results of these simulations to each other and compares the predicted drag coefficients to the experimentally determined value of 0.25 [3]. The comparisons in Table II show that the best prediction of 0.26 was achieved using the k-ω shear stress transport (SST) turbulence model, the 2nd order upwind discretization scheme, and 92,000 or more mesh elements. Use of the other turbulence models led to predictions that were significantly higher (standard k-ε model with two types of wall functions) or lower (standard low Reynolds number k-ω model) than those from the k-ω SST turbulence model. Use of the 1st order upwind discretization scheme led to predictions that were significantly higher than those from the 2nd order upwind scheme. The results were less sensitive to grid size, for the range of sizes simulated, than to choice of turbulence model and discretization scheme. The middle level tested (92,000 mesh elements) was sufficient to produce grid-independent results.

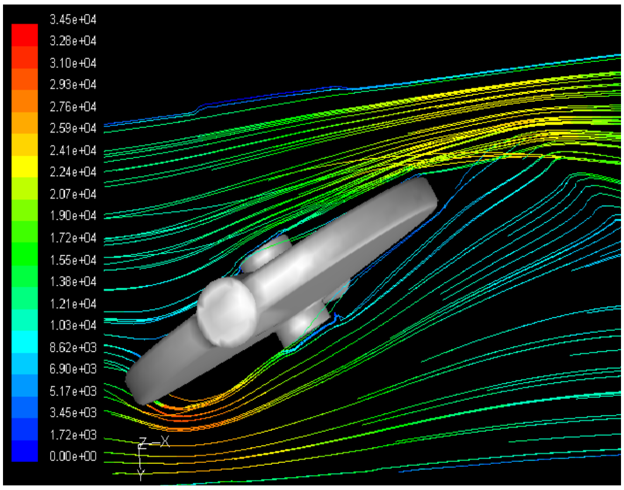


Fig.3 Predicted flow patterns around a 30 degree disk placed downstream an elbow

The ability of the CFD model to predict the torque coefficient of the disc placed downstream an elbow within 4 percent of the experimental value provided confidence that a similar CFD model, using the k-ω SST turbulence model and 2nd order upwind discretization scheme, would provide satisfactory predictions of the torque coefficients for a partially open, disc-shaped butterfly valve placed between two elbows.

TABLE II
COMPARISON OF CFD-PREDICTED TORQUE COEFFICIENTS

Case	Turbulence Model	Discretization Scheme	Grid Size	Predicted C_T	Error %
1	Standard k-ε with wall function	2nd order upwind	53,000	0.29	16
2	Standard k-ε with non-equilibrium wall function	2nd order upwind	53,000	0.29	16
3	Standard k-ω	2nd order upwind	53,000	0.22	-12
4	k-ω SST model	2nd order upwind	53,000	0.28	12
5	k-ω SST model	1st order upwind	53,000	0.30	20
6	k-ω SST model	2nd order upwind	92,000	0.26	4
7	k-ω SST model	2nd order upwind	155,000	0.26	4

III. CFD SIMULATION RESULTS OF THE FLOW FIELD IN THE PRESENCE OF THE BUTTERFLY VALVE

Figs. 4 and 5 show the simulation results for the valve configuration in the flow circuit denoted as Pipe1 and Pipe 3 in Table I when the valve is in the fully open state with less pressure variation around the butterfly valve. Fig.5 shows the vortices magnitude inside the numerical cells which demonstrate that the flow in the valve's vicinity is relatively steady. Figs. 6 and 7 show the simulation results for the valves in the same pipes with the valve at a 45^o angle. The results also show relatively steady flow patterns.Figs.8 and9 show the flow pattern for the valve configuration in Pipe 2 at the 45^o angle. These figures demonstrate an extremely more complex flow pattern than that of the configurations in Pipe 1 and Pipe 2, where the valve is present in near middle position. The presence of the vortices and eddies is clear and the vorticity spectrum in Fig. 9 indicate the presence of vorticities with much higher frequencies. The results of Pipe 4 also show the same general pattern of Pipe 2.

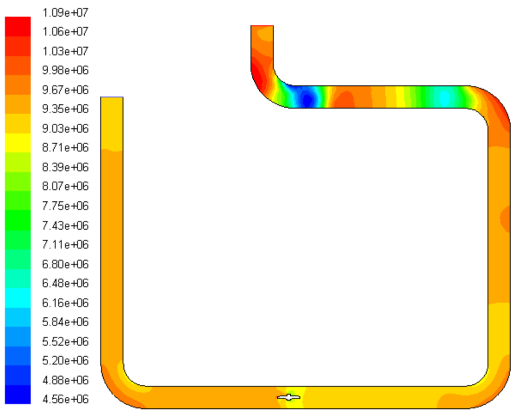


Fig. 4 Static pressure contours, (Pipe 1 and Pipe 3), fully open valve

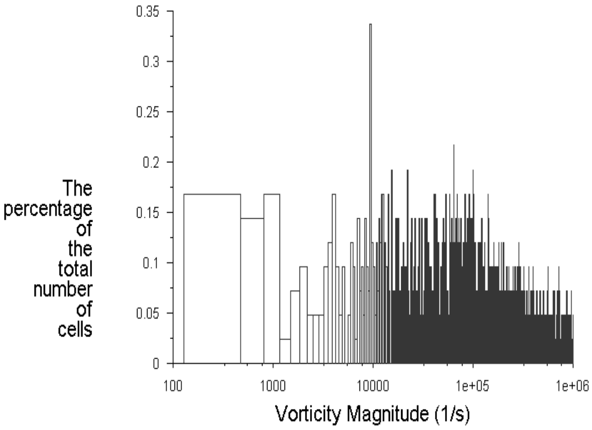


Fig. 5 Voricity spectrum, (Pipe 1 and Pipe 3), fully open valve

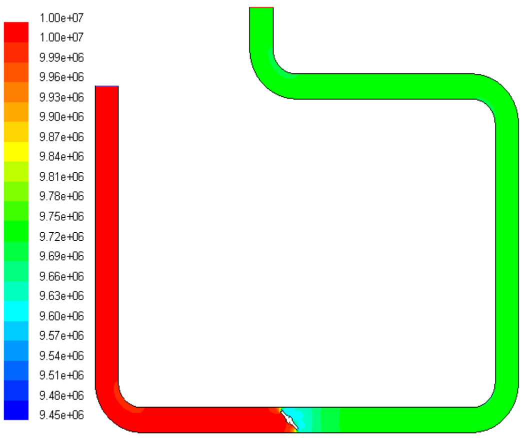


Fig. 6 Static pressure contrours (Pipe 1 and Pipe 3) , valve at 45°

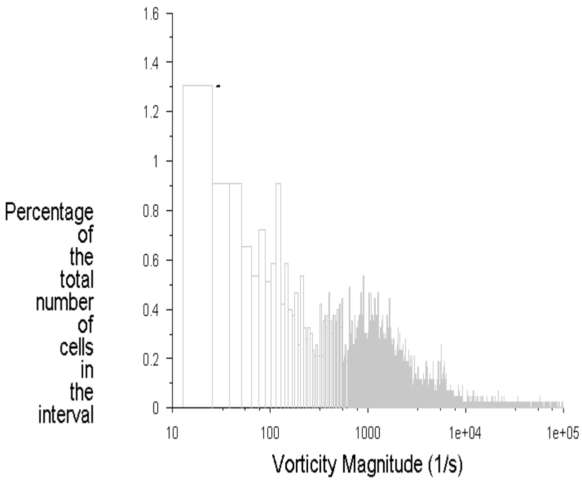


Fig. 7 Voricity spectrum, (Pipe 1 and Pipe 3), valve at 45o

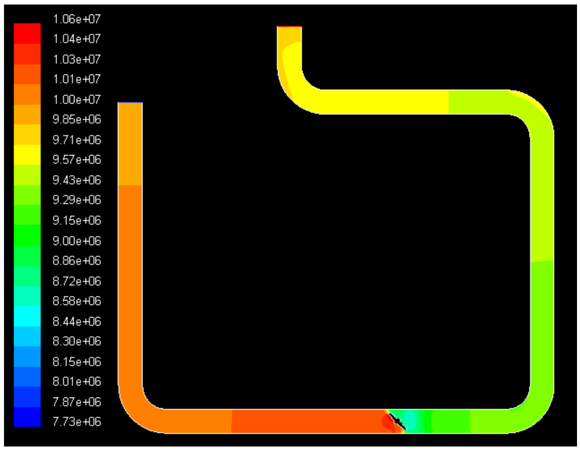


Fig. 8 Static pressure contours (Pipe 2, valve at 45o)

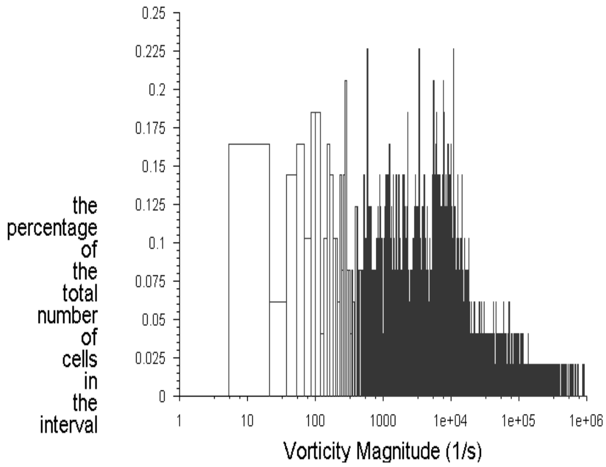


Fig. 9 Vorticity spectrum, (Pipe 2), valve at 45o

IV. Conclusions and Recommendations

A 3D Computational Fluid Dynamics (CFD) simulation for a butterfly valve located between two opposing 90° elbows was performed in this work. The objective of the study is to analyze the torque fluctuations on the valve's shaft due to fluid turbulence and aerodynamic forces of the flow field.CFD simulations show that the disturbance induced by the elbow seems to disappear near the middle of the pipe joining the elbows. Thus installing the valve in this location minimizes the torque fluctuations on the valve's disk.If, on the other hand, the valve is installed at a location close to one of the elbows, then the combined turbulence generated by the elbow and the vortex shedding from the leading or trailing edge of the valve become high and lead to serious instantaneous torque fluctuations on the disk of the valve.These torques will be transmitted to the valve's support structure and will produce significant random mechanical vibrations on the valve's components, which may be at one of its resonant frequencies.These vibrations could result in the failure of the valve shaft or body due to the high mechanical stresses.

In order to avoid the vibrations that my result in the described system, it is recommended to (a) place the valve at a distance near the middle of the pipe joining the two elbows, (b) the length of the pipe joining the two elbows should be at least 16*D*, and (c) to align the axis of rotation of the valve's shaft with the plane of the elbow.

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