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Study of Hydrodynamic Torque of Double Offset Butterfly Valve Disc through Experiment and CFD Analysis

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ABSTRACT:

A butterfly valve is commonly used as control device in applications where the inlet velocity is high and the pressure drop required is relatively low. Hydrodynamic torque is a significant design parameter for engineers dealing with the control valve design. Predicting the hydrodynamic torque for all opening and closing conditions in rotary valves is of utmost importance. This study sought to compare the experimental and simulated computational fluid dynamics (CFD) performance factor and hydrodynamic torque of 150mm double offset butterfly disc for various opening and closing angles in the increments of 10°. In general, as the flow rate increases through the valve, greater force is exerted upon the disc by the fluid. These increased dynamic forces require more torque to rotate the disc. The amount of torque required to rotate the disc during operation varies depending on type of fluid flowing through the valve, velocity, shape and position of the disc. Finally a correlation has been established between the experiment and CFD values and the valve industry can make use of this data for optimum selection of gear box and actuator.

KEYWORDS:

Differential pressure; Hydrodynamic torque; Discharge; Computational fluid dynamics; Butterfly valve

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1. Introduction

A butterfly valve is a type of flow control device, typically used to regulate a fluid flowing through a section of pipe. A flat circular disc (blade) is positioned in the centre of the pipe. The disc has a shaft (rod) through which it connected to an actuator on the outside of the valve. Rotating the actuator turns the disc either parallel or perpendicular to the flow. The valve disc when pivoted at the center and moved with the help of an actuator resembles butterfly wings and therefore they are known as butterfly valves. A butterfly valve, Fig. 1 is from a family of valves called quarter turn valves. The butterfly is a metal disc mounted on a shaft. When the valve is closed the disc is turned so that it completely blocks off the passageway. When the valve is fully open, the disc is rotated a quarter turn so that it allows unrestricted passage. Large butterfly valves are usually equipped with a gearbox (or gear operator). The study of butterfly valves has evolved over the years; most of the earlier studies were based on analytical and experimental approaches because of the notable influence of the butterfly valve on the fluid flowing through it.

Many researchers have done lots of work to study the fluid characteristics of the butterfly valve. One of the earliest and most comprehensive pieces of research on the flow characteristics and performance of butterfly valves was performed by Cohn [1]. Using data provided by previous authors, Cohn attempted to parameterize the torque and flow coefficients based on thickness to diameter ratio for numerous butterfly valve geometries, most of which were symmetrical. Toro [2] investigated a comparison study of 1200mm butterfly valve's experimental performance coefficients using CFD in an incompressible fluid at Reynolds numbers ranging approximately between 10^5 and 10^6. It is found that for mid-open disc angles (α = 30° to 60°), CFD was able to approximately predict common performance coefficients for butterfly valves. For lower valve angles (α = 10° to 20°), CFD simulations failed to predict those same values, while higher valve angles (α = 70° to 90°), gave mixed results. Sarpkaya [3] also studied the torque and cavitation characteristics of idealized 2D and axially symmetrical butterfly valves by considering an idealized case of laminar uniform flow through a symmetrical lamina between two infinite walls. Sarpkaya [3] was able to extend approximate solutions to hydrodynamic torque, cavitation, and flow coefficients for 3D butterfly valves using semi-empirical equations.

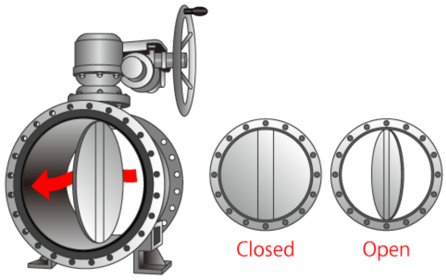

Fig. 1: Butterfly valve, closed and open position

Morris et al [4] experimentally investigated the aerodynamic torque characteristics of butterfly valves using two dimensional planar models and three dimensional prototype valves at chocked and un-chocked operating points, and the results revealed the significance of the flow separation and reattachment phenomena on the aerodynamic torque characteristics of butterfly valves. Cheiworapuek et al [5] investigated incompressible turbulent flow past a butterfly valve at 15°, 30°, 45°, 60° and 90° opening angles. The CFD code FLUENT was used to validate experimental data for butterfly valves having diameters of 150mm and 300 mm. The number of elements used in the simulation ranged from 1.1 million to 1.4 million. The k-ε turbulent model was used. For the experiment, pressure taps were located 1D upstream and 14D downstream. Cheiworapuek observed that vortices were found near the tips of the butterfly valve and became larger as the valve disc was oriented at more closed positions. The loss coefficient was generally unaffected by a change in inlet velocity for a given disc orientation.

Large differences between the experimental data and simulation results were of the order of 50% for loss coefficients and torque. Henderson et al [6] conducted a numerical study of the flow through a safety butterfly valve (Penstock protection valve) in a hydroelectric power scheme to stop water supply to a downstream penstock in order to predict the hydrodynamic torque versus opening angle characteristic. The numerical results showed that a strong vertical flow pattern developed downstream from the valve. Xue et al [7] have done a numerical analysis of butterfly valve and predicted the flow coefficients and hydrodynamic torque coefficients. In this paper, 3D numerical simulations by commercial code CFX were conducted to observe the flow coefficients and hydrodynamic torque coefficient when butterfly valve with various opening degrees and uniform incoming velocity were used in the piping system. Dawy et al [8] used ANSYS FLUENT code and the standard k-ε model to evaluate the flow coefficient for different valve openings.

The results showed good agreement with experimental data. They concluded that CFD provides a means of gaining valuable insight into the flow field of the valve, where complex fluid structure and velocity profile recovery can be observed and studied. Adam [9] stated that as the valve's opening angle is increased from 0° (fully closed) to 90° (fully open), the fluid is able to more readily flow past the valve. Characterizing a valve's performance factors, such as pressure drop, hydrodynamic torque, flow coefficient, loss coefficient, and torque coefficient, is necessary for fluid system to account for system requirements to properly operate the valve and prevent permanent damage from occurring. An optimization procedure of the valve disc is applied in order to reduce the weight of the disc as well as to keep the stress and pressure loss coefficient in the allowable range. Elbakhshawangy et al [10] studied the turbulent flow of water through a butterfly valve of 200 mm diameter. The results showed that the flow is smoother and free of turbulence at small pressure drop across the valve either at large valve opening angle or small inlet velocity. Ibrahim et al [11] implemented a numerical simulation for flow of water past over a butterfly valve using commercial fluid dynamics software FLUENT.

It was found that the flow has a small effect with increasing closing angle till it reaches 55°, where the flow around the valve started to become highly turbulent. An experiment is conducted for a scaled model of 150 mm double offset butterfly valve disc as shown in Fig. 2 and to find out the important parameter in designing of the control valves i.e. hydrodynamic torque (dynamic torque) which is a significant design parameter for engineers dealing with control valve design (main deciding parameter in sizing of the valve actuator) acting on the disc for different velocities at different opening and closing disc angles from 0° to 90° increments of 10° each, and an average opening and closing of hydrodynamic torque is noted. Keeping the input parameters same as that of the experiment, to carry out the computational fluid dynamics (CFD) using the latest simulation software and to find out the average hydrodynamic torque in a similar way as that of the experiment. Finally validation has to be made between the experiment and CFD and a relative difference between the two in percentage has to be studied and established. Based on this outcome, CFD can be used for large size butterfly valves without conducting the experiment.

Fig. 2: Test set up for butterfly valve with double offset disc

2. Butterfly valve torque requirements

Pressure loss across a valve is often attributed to disruptions caused in the flow field such as obstruction, flow separation and mixing. For butterfly valves, pressure losses vary depending on the disk angle configuration, θ and flow rate, Q. The pressure loss is represented by the absolute pressure differential between the measured pressure upstream, $P_{u\theta}$ and the measured pressure downstream, $P_{d\theta}$ using,

$$\Delta P_\theta = P_{u\theta} - P_{d\theta} \quad (1)$$

For a given flow rate, pressure losses will generally decrease as the valve’s opening angle increases due to less interference in the flow. In this study, the upstream and downstream pressures were measured at a point three diameters upstream and six diameters downstream, respectively, as per AWWA guidelines [12]. The sign convention used in this study is for torque around the valve shaft (axis of rotation) to be positive when flow acts to close the valve, such that a positive torque is required to keep the valve open. Measurement of hydrodynamic torque requires measuring the total opening and closing torque, $T_{to\theta}$ and $T_{tc\theta}$ respectively, are defined as follows,

$$T_{to\theta} = T_{d\theta} + T_{b\theta} + T_{cg\theta} + T_p \quad (2)$$

$$T_{tc\theta} = T_{d\theta} - T_{b\theta} - T_{cg\theta} - T_p \quad (3)$$

Where, $T_{d\theta}$is the hydrodynamic torque, $T_{b\theta}$ is the bearing torque, $T_{cg\theta}$ is the centre of gravity torque, and T_p is the packing and hub torque. The various torques will be briefly described below. The bearing torque, $T_{b\theta}$, in a butterfly valve is the frictional resistance to rotation imposed on the valve shaft by the bearings. Its Value is highest at the near-closed position because of the high differential pressure when the valve is nearly closed. Bearing torque reduces to nearly zero as the valve reaches the fully open position and always acts in the opposite direction to the valve's movement. It is defined as follows,

$$T_{b\theta} = \frac{(\pi D_d^2 \Delta P_\theta d_s C_f)}{8} \quad (4)$$

Where, D_d, is the disk diameter, ΔP_θ is the pressure drop while at the disc angle θ, d_s is the shaft diameter, and C_f is the coefficient of friction between the shaft and bushing. Centre of gravity torque, $T_{cg\theta}$, is caused by the offset center of gravity of the disc and occurs when the valve shaft is located in or near the horizontal plane. This torque is often assumed as insignificant, when the stem position is in the horizontal position. Centre of gravity torque is defined as follows,

$$T_{cg\theta} = S_c W_d C_g \cos(\theta + \gamma) \quad (5)$$

Where, S_c is the sign convention variable, W_d is the weight of valve disc, C_g is the valve disc center of gravity distance from the shaft centerline, θ is the valve opening position angle where closed = 0° and fully open = 90°, and γ is the center of gravity offset angle in non-symmetric disc designs. The packing and hub torque is due to friction between the shaft seal and the valve shaft, and the friction between the disc and/or shaft and the body hub seal where the shaft penetrates the pressure boundary. The packing and hub torque always acts in the opposite direction to the valve's movement and is defined as follows,

$$T_p = C_{pck} d_d \quad (6)$$

Where, C_{pck} is a packing coefficient [12] and d_s is the valve shaft diameter. The hydrodynamic flow torque is due to the effects of the internal fluid media (water in this case) or gravity acting on the valve at any given opening angle, θ. Hydrodynamic flow torque is necessary to compute flow charateristics and the torque coefficient for the valve, and in determining motor requirements for operating the butterfly valve. Combining the Eqns. (2) and (3) yields the following hydrodynamic torque,

$$T_{d\theta} = \frac{(T_{to\theta} + T_{tc\theta})}{2} \quad (7)$$

It has a direct effect on the design of the valve disk, valve stem diameter and the actuators used to regulate the valve position. This gives the designer data which can be used to determine the external torque required to hold the valve at a given position. Also, this data helps ensure safe design, as excess torque value over the design limit might result in the rupture of the disk and the valve body causing a hazardous accident. Hence predicting the hydrodynamic torque for all opening conditions in rotary valves is of utmost importance. The $C_{t\theta}$ (Coefficient of dynamic torque) is a dimensionless quantity used by manufacturers and users to determine the torque and power requirements of valves scaled relative one to another. Torque coefficient is defined as follows,

$$C_{t\theta} = \frac{T_{d\theta}}{D_d^3 \Delta P_{d\theta}} \quad (8)$$

Both the $C_{t\theta}$ and ΔP (pressure drop at the valve) strongly depend on the disc shape. Calculating $C_{t\theta}$ for different valves and at different disc opening angles is a very difficult task, and therefore, for using the above equations, experimental data is necessary. The coefficient of dynamic torque comprises the effect of both the pressure drop and diameter scale along with the torque value. However, by the implementation of the numerical methods, the dynamic torque can be calculated before the valve has been actually manufactured.

3. CFD simulation & experimental test

Butterfly valves are widely used in various industries such as water distribution, sewage, oil and gas plants. The hydrodynamic torque applied on the butterfly valve disc is one of the most important factors which should be considered in their design and application. Although several methods have been used to calculate the total torques of these valves, most of them is based on hydrostatic analysis and ignoring the hydrodynamic effect which has a major role to determine the torque of the large-size valves. For finding the dynamic-valve-torque, some empirical formulas and methods have been proposed; for example in AWWA C504 standard, a relationship for calculating the dynamic torque has been given and its variation versus disc angle has been stated. However, the use of these empirical relationships is restricted due to the conditions defined in the standards. In this paper, the dynamic valve torque has been calculated for 150mm butterfly valve under different conditions and also at the different opening angles of the valve disc. For this purpose a CFD method has been used. CFD includes expressions for the conservation of mass, momentum, pressure species and turbulence. Navier-stokes equation given by Claude-Louis Navier and the George Gabriel Stokes. This defines any single-phase fluid flow, is the fundamental basis of all CFD problems. CFD is becoming very useful approach for engineering design and analysis because of improved numerical method and at the same time, it saves time and energy of experimental work.

An experiment is carried out for a model butterfly valve of 150 mm diameter with double offset disc which is manually operated by using hand lever. Schematic diagram of the experimental set up is shown in Fig. 3. Experimental set up for testing butterfly valve of 150 mm comprises of a centrifugal pump of capacity 1250 lpm (liters per min) at 10 m head. The required amount of water is pumped from water storage tank of 6500 liters capacity. The pump with motor is connected to the Motor starter for starting and stopping of the pump. The outlet of the pump is connected by butterfly valve of 150 mm for controlling the flow to the test valve. The outlet of the upstream butterfly valve is connected to electromagnetic flow meter to measure the discharge or flow. In between the upstream butterfly valve and the flow meter a thermometer is connected for measuring the water temperature since density of water changes with change in temperature. The downstream pipe of the flow meter is connected to test section where in at the inlet upstream pressure gauge is provided to measure the pressure $P_{u\theta}$ at the distance of 3D minimum (D is nominal diameter of the Valve) from the test valve Model of 150 mm size butterfly valve.

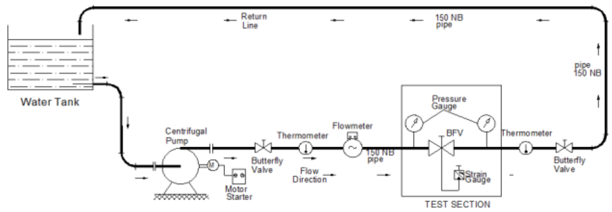

Fig. 3: Schematic diagram of the experimental setup

A torque sensor (based on strain gauge) is mounted in between the test valve shaft (under test section) and the lever from which the torque reading at different valve opening and closing angles can be obtained and readings are taken from the torque sensor display unit. Strain gauges are incredibly accurate if you have the expertise and experience of using and understanding how they work. They have been traditionally associated with inaccurate and unreliable measurements. If used correctly with the right understanding, they are very reliable, stable, robust and a cost-effective method of torque measurement. The downstream end of the test valve is connected with the downstream pressure gauge similar to the upstream arrangement at a distance of 6D (D is nominal diameter of the valve) to measure the pressure, $P_{d\theta}$. After the downstream pressure gauge, a thermometer and butterfly valve is connected to get the reading at the downstream similar to the upstream reading. The other end of the throttle valve is connected with downstream pipe back to the storage tank.

4. Results and discussion

Fig. 4 shows the comparison of the hydrodynamic torque from the experiment and CFD simulation for the variation the butterfly valve opening angle. The maximum valve of the hydrodynamic torque was observed at a valve opening angle of 30° in case of experiment and at a valve opening angle of 20° in case of CFD. The hydrodynamic torque value agrees well with the experimental and CFD values except at 20° and 30° valve opening. The values of the maximum hydrodynamic torque as per experiment is 2.32 N-m and as per CFD, it is 2.42 N-m and the variation in percentage is 5%.

Table 1: Hydrodynamic torque - Experiment vs. CFD

Tdθ,	Valve opening angle from closed to fully open θ, °								
Nm	10	20	30	40	50	60	70	80	90
Test	0.72	2.28	2.32	1.37	0.94	0.61	0.42	0.19	0.11
CFD	0.72	2.42	1.9	1.31	0.91	0.63	0.4	0.24	0.12

5. Conclusion

This work detailed the use of experimental test and CFD simulation to compare the hydrodynamic torque of 150mm double offset butterfly disc for various opening and closing angles. The maximum valve of the hydrodynamic torque was observed at a valve opening angle of 30° and 20° position respectively in case of experiment CFD simulation. As the variation between the CFD and experiment is well within 5%, CFD can be used for larger valve with reduced number of the experiment, which saves time and money.

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