Hydraulic Performance of the Control Butterfly Valves of the Bottom Outlet of Kassa Chai Dam

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ABSTRACT

The bottom outlet of Kassa Chai Dam, Kirkuk, Iraq was designed and constructed to control the storage outflow by using two 1.4m diameter butterfly valves at its end two branches. During the dam commissioning, a series of operation tests were conducted on the bottom outlet under different openings of its valves. Intense noise and vibration were noticed and reported at these valves. To specify the causes of these intense noise and vibration and to propose solutions to eliminate them, the velocity profiles and pressure variations along the bottom outlet of Kassa Chai Dam and at its valves were investigated. A full-scale 3D mathematical model for the bottom outlet was analyzed by using the commercial CFD code Fluent. CF D Fluent based on solving Navier-Stock equations by finite volume method. The standard k-ε turbulence model was selected to deal with turbulence. Simulations were carried out under different operation conditions, including different water levels of the dam reservoir and different angles of the valves opening as well. Outline from study showed that negative pressures developed at the downstream side of the valve especially at small angles of valve openings. To overcome the problem of negative pressure, a suitable solution is suggested to improve the outlet performance by installing a cone valve at the downstream end of the bottom outlet. Results of investigation when using the cone valve showed that no negative pressure developed at the end of the bottom outlet.

INTRODUCTION

Butterfly valves are used to control the outflow of the bottom outlet of Khassa Chai Dam, which is located north-east of Kirkuk City, Iraq. During the dam commissioning, intensive noise and vibrations at these valves were noticed and reported that can affect the safety of the dam. This problem may be due to high flow velocities and negative pressures developed at valves causing cavitation (FEMA, 2010).

Generally, this work aimed at studying the reported problem of the noise and the vibrations at the control valves of bottom outlet of Kassa Chai Dam. The hydraulic performance of the bottom outlet of was investigated. The investigation includes analyzing the profile of the velocities of the flow and the variation of the pressure along the bottom outlet of the dam and at its control valves. This investigation was carried out under different reservoir levels and different valve openings by using Computational Fluid Dynamics, CFD, code Fluent. The investigation helped in understanding and specifying the cause of the noise and vibrations, and suggesting a solution to get rid of the problem.
There exist many studies that were conducted to study the velocities and pressure variations of the flow at butterfly valves by the aid of ANSYS Fluent Computational Fluid Dynamics software, such as Brett et al., 2011, Nazary et al., 2011, Toro, 2012, Dawy et al., 2013, and Elbakhshawangy et al., 2015. These studies indicated that CFD was able to model the general behavior of flow around a butterfly valve for different angles of valve opening.

THE BOTTOM OUTLET OF KHASSA CHAI DAM

The bottom outlet of Khassa Chai Dam consists of an intake with a 13m vertical shaft and a 304.5m steel pipe of 2m in diameter coated with reinforced concrete. The steel pipe is then divided into two identical branches at its end. Figure 1. Each branch is a steel pipe of 1.4m diameter provided with two butterfly valves mounted in series. The first butterfly valve is used for emergency and maintenance purposes that is kept fully opened during normal operation. The second valve is used to control the outflow discharges.

Operating one branch of the bottom outlet of Khassa Chai Dam will develop high velocities compared to that when operating two branches. Therefore, the case of operating one branch represents the worst case of the problem of noise and vibration at the butterfly valve and is the case considered in this paper.

THE GOVERNING EQUATIONS

ANSYS Fluent solves numerically the governing equations of steady, incompressible three-dimensional flow. These equations are the continuity and Navier-Stokes equations, which are based on principles of physics mass conservation and Newton’s Second Law within a moving fluid. Continuity and Navier-Stokes equations are described by Eq. (1) and (2) respectively:

\[ \rho \frac{D}{D} \left( U \right) = 0 \quad (1) \]

\[ \rho \frac{D}{D} \left( \frac{U^2}{2} + \phi \right) + \nabla \cdot (\tau) = \rho f \quad (2) \]

In turbulent flow condition, FLUENT provides several turbulent models to solve such as Spalart-Allmaras, k-\( \varepsilon \), k-\( \omega \), large eddy simulation (LES), and Reynolds stress model (RSM). This study will focus on using the k-\( \varepsilon \) model which is a semi-empirical two equation model. The simplicity of this model, its robust and reasonable accuracy explains its popularity (Versteeg and Malalasekera, 1995). It relates the turbulent kinetic energy \( k \) and its turbulent dissipation rate \( \varepsilon \) with the turbulent viscosity \( \mu_t \). The transport equations for the standard k-\( \varepsilon \) model are described by the following equations:

\[ \frac{D}{D} \left( \rho k \right) = \nabla \cdot \left( \frac{\tau}{\mu} \right) + \rho \varepsilon \quad (3) \]

\[ \frac{D}{D} \left( \rho \varepsilon \right) = \nabla \cdot \left( \frac{\tau}{\mu} \right) - \rho \varepsilon + \rho \varepsilon \beta \phi \quad (4) \]

Where is the turbulent viscosity modeled as:

\[ \mu_t = \rho \varepsilon \quad (5) \]

\( \beta = \frac{2}{1 + \rho_{	ext{c}}} \)

\( \rho_{	ext{c}}, \beta \) and are empirical constants having the following default values and their values are (\( \beta = 0.09 \))

And
μ = Liquid dynamic viscosity, kg/ms.

k = turbulent kinetic energy, m$^2$/s$^2$.

ε = turbulent dissipation rate,
m$^2$/s$^3$.

ρ = Liquid density, kg/m$^3$.

P = Pressure, N/m$^2$.

CFD ANALYSIS PROCESS APPLIED TO KHASSA CHAI DAM

The process to perform a CFD analysis generally includes a pre-processing, solver, and post processing. Pre-processing involves the definition of the geometry of the flow domain, mesh generation and definition of the materials and setting appropriate boundary conditions. In the solver process the governing flow equations are solves for flow system. The post processor includes results visualization for appropriate graphical representations, such as vector plots, contour plots, streamlines, or data curves etc.

Operating one branch as the worst case that may cause the vibration. Therefore, one branch was taken into consideration. The flow domain of Khassa Chai Dam was modeled using CAD package, Solidworks. Depending on the angle of the opening of the butterfly valve, seven full scale 3D models were generated. Each of these models have a different opening of the butterfly valve.

The commercial package, GAMBIT 2.4.6, was used to create a high quality unstructured tetrahedral mesh. Tetrahedral mesh can be used with adaptive mesh refinement especially at the complex geometry of the butterfly valve. By using the GAMBIT, the bottom outlet was divided into several segments having different mesh sizes. The smaller mesh size was used at the end of the bottom outlet and at the valves where the flow conditions are highly changed and to increasing the mesh quality. Figure 2 shows a close-up view of the generated model and the generated mesh at the location of the butterfly valve. The model meshes consist of about 3 to 4 million cells with gradual elements sizes.

The angles of the butterfly valve opening that were taken into consideration are 5, 15, 30, 45, 60, 75 and 90 degrees. Different values of inlet pressure head were applied for each of the seven models. The applied values of the pressures cover the range of water levels between the minimum to the maximum. Five elevations of reservoir water were considered including the maximum of 495 m.a.m.s.l, the minimum of 466 m.a.m.s.l, and three other levels of reservoir levels of 472, 479, and 486 m.a.m.s.l. The elevation of the inlet of the bottom outlet is 461 m.a.m.s.l. So that the pressure heads at the entrance of the bottom outlet as an upstream boundary condition are 5, 11, 18, 25, and 34 m. Descriptions of the simulations under the different valve openings and reservoir levels are summarized by Fig. 3.

The pressure at the end of the bottom outlet was set to be at 1 atmosphere. The valve body and the pipe wall were set as wall boundary condition. The water density $\rho$ is set to 998.2 kg/m$^3$ and its dynamic viscosity $\mu$ is 0.001kg/ms.

Once all the parameters of system of the bottom outlet of Khassa Chai Dam are identified, the system is set to be solved by using CFD code Fluent. A high-performance computer was used for this purpose to handle the large number of the mesh elements. A minimum residual target of $10^{-4}$ was set as solution convergence criteria.

Appropriate graphical representation of gained results of simulations was used. Vector field plots and shaded contour plots were used for the representation of the profiles velocities and the variation of pressures, respectively.

![Fig.2. The model and mesh of the Butterfly valve.](image-url)
RESULTS AND ANALYSIS

Figures 4 to 8 show the profiles of the flow velocities at the butterfly valve for different angles of valve opening (θ) and different values of pressure at the bottom outlet entrance. The profiles of the flow velocity are affected by changing the valve opening angle much more than changing the pressure at inlet of the bottom outlet. At small opening angles, a flow jet was created because of the small flow area between the pipe and the valve disk edges. As the valve opening is increase, the streamlines at the downstream side of the valve is becoming uniform. This is an indication that the disturbance is greatly reduced when increasing the angle of valve opening. The maximum obtained velocity is 39.23 m/s. This value was obtained with the angle of opening of 75 degree and the pressure at the inlet of 34 m. The maximum velocity value at the valve obtained at this angle of opening at the top edge of disc of the valve, Figure 9.

Figures 10 to 14 show the pressure variation at the butterfly valve for different angles of the valve opening and different values of pressure at the inlet of the bottom outlet. It is clear that the angle of opening affects the pressure variation at the valve much more than the pressure at the inlet of the bottom outlet. The highest values of pressure always occur at the upstream side of the valve disc and the pressure values significantly decreased at the valve edges, these results were agreed with the results of (Elbakhshawangy et al., 2015). Low negative pressure values existed in the downstream region immediately behind the valve and then the pressure increased again by getting far from the valve in the downstream region. By increasing the valve opening angel, the pressure difference at both sides of the valve decreases. The minimum negative pressure values at the butterfly valve is about -99 m that was obtained with the angle of opening of 75° and the pressure at the inlet of 34 m.
Fig. 6. The velocity profiles at the butterfly valve, pressure head at inlet is 18m.

Fig. 8. The velocity profiles at the butterfly valve, pressure head at inlet is 34m.

Fig. 7. The velocity profiles at the butterfly valve, pressure head at inlet is 25m.

Fig. 9. Close up side view, showing the flow velocity at the valve at angle of opening of 75°.

Fig. 10. The pressure variation at the butterfly valve, pressure head at inlet is 5m.

Fig. 11. The pressure variation at the butterfly valve, pressure head at inlet is 11m.
Due to the high flow velocities and the development of low negative pressure at the control valves of Khassa Chai Dam, it seems that it was not desirable to use the butterfly valves to control the outflow of the bottom outlet of the dam. “Normally butterfly valves are used as on-off valves and are usually installed in a valve chamber on the water side of bottom outlet lines in dams or in gravity lines leading to water treatment plants or hydro power plants. In dam applications, control valves such as needle valves or fixed cone valves are installed after the butterfly valves on the air side. These valves always work as flow regulating or control valves. Unlike butterfly valves or gate valves assuming only shut-off functions in pipeline systems, needle valves and fixed cone valves can meet the requirements of regulating operations” (Oppinger, 2007).

It was suggested to install a fixed cone valve to control outflow of the bottom outlet and to disperse the outflow of water into the atmosphere. This solution minimizes the costs and structural work required to modify the constructed bottom outlet of Khassa Chai Dam. The cone valve consists of a cylindrical shell and a system of equally spaced vanes, and the cone. The vanes are attached radially to the shell and cone. The cylindrical sleeve is opened and closed by means of a pair of hydraulic pistons (Fagerburg, 1983). ROSS VALVE MFG. CO. fixed cone valve model, Figure 15, was adopted as the suggested solution to reduce the flow velocities and eliminate negative pressures developed at the end of the bottom outlet. This valve has radially four vanes where there are no horizontal position vanes.

Fig.12. The pressure variation at the butterfly valve, pressure at inlet is 18m.

Fig.13. The pressure variation at the butterfly valve, pressure head at inlet is 25m.

Fig.14. The pressure variation at the butterfly valve, pressure head at inlet is 34m.

Fig.15. Ross cone valve
The flow of the bottom outlet was reanalyzed when using the suggested cone valve installed at the end of the bottom outlet. The analysis was carried out with different water levels of the reservoir and different cone valve openings, while the butterfly valves were set at fully open position. Descriptions of the simulations under the different valve openings and under different operation condition of pressure head at the entrance of the bottom outlet are summarized by Figure 16.

Fig.16. Design of simulation models with the suggested cone valve.

Figures 17 to 21 show the velocity profiles at cone valve region at different cone openings. The velocity profile is uniform. The maximum velocity of the flow is about 31.6 m/s was obtained with the valve of opening of 25% and 50% and the pressure at the inlet of 34 m.

Figures 22 to 26 show the pressure variations at the cone valve at different cone openings. It is clear that the negative pressure is eliminated at end of the bottom outlet except at some points at the edges of the butterfly valve under the condition of large cone openings, Figure 27.

Fig.17. The velocity profiles at the butterfly and cone valves, pressure head at inlet is 5m.

Fig.18. The velocity profiles at the butterfly and cone valves, pressure head at inlet is 11m.

Fig.19. The velocity profiles at the butterfly and cone valves, pressure head at inlet is 18m.

Fig.20. The velocity profiles at the butterfly and cone valves, pressure head at inlet is 25m.
Fig. 21. The velocity profiles at the butterfly and cone valves, pressure head at inlet is 34 m.

Fig. 22. The pressure variation at the butterfly and cone valves, pressure head at inlet is 5 m.

Fig. 23. The pressure variation at the butterfly and cone valves, pressure head at inlet is 11 m.

Fig. 24. The pressure variation at the butterfly and cone valves, pressure head at inlet is 18 m.

Fig. 25. The pressure variation at the butterfly and cone valves, pressure head at inlet is 25 m.

Fig. 26. The pressure variation at the butterfly and cone valves, pressure head at inlet is 34 m.
It must be noted that at the inside curve of the bottom outlet branching region, the flow velocity is very high and the pressure is always negative. Figure 28, during all analysis under all the examined operation conditions especially during large opening of both butterfly and cone valves. This negative pressure may cause local cavitation at this region and needs frequent maintenance.

CONCLUSIONS

The investigation of the water flow through the bottom outlet of Khassa Chai Dam was conducted. The results of this investigation indicated the following conclusions.

1. Jet is developed at small angles of the butterfly opening.

2. Increasing the angle of the valve opening make the flow smoother and velocity profile more uniform.

3. There is high pressure drop upstream and downstream the butterfly valve especially at the small opening angles. This drop is decreased by increasing the valve opening angle.

4. Low negative pressure values existed in the downstream region immediately behind the valve.

5. It is not desirable to use the butterfly valves to control the outflow of bottom outlets of dams due to high flow velocities and development of negative pressure at the valve.

6. A sound solution of low cost that requires minimum structural modification is to use a cone valve at the end of the existing bottom outlet of Khassa Chai Dam.

7. When using the cone valve, no negative pressures were developed at the valve location, So that the problem of noise and vibration can be solved.

REFERENCES

Brett, G., Riveland, M., Jensen, T. C., and Heindel, T. J. 2011. Cavitation from a Butterfly Valve: Comparing 3D Simulations to 3D X-Ray Computed Tomography Flow Visualization, Mechanical Engineering Conference Presentations, Papers, and Proceedings, paper 125.

Dawy A., Sharara A., and Hassan A. 2013. A numerical investigation of the incompressible flow through a butterfly valve using CFD, International Journal of Emerging Technology and Advanced Engineering, Volume 3, Issue 11.

Elbakhshawangy, H. F., Abd El-Kawi, O. S., and Sarhan, H. H. 2015. Numerical Study Of Incompressible Flow Characteristics Through Butterfly Valve, Journal of Multidisciplinary Engineering Science and Technology (JMEST), Vol. 2 Issue 7.

Fagerburg, T. L., 1983, Fixed Cone Valve Prototype Tests New Melons Dam, California, Technical report.

Nazary H., Aalipour N., and Alizadeh M. 2011. Investigation of the Flow and Cavitation in a Butterfly Valve, Journal of Mechanical Research and Application, Vol. 3, No. 1.

Neilson, F. M., 1971, Howell-Bunger Valve Vibration Summersville Dam Prototype Tests, Technical report.

Oppinger, P. 2007, Control valves for bottom outlets in dams and in hydro-power plants, International edition of Industriearmaturen, Gremany.

Toro, A. D. 2012, Computational Fluid Dynamics Analysis of Butterfly Valve Performance Factors, M. Sc. thesis, College of Engineering, Utah State University, Logan, Utah.

Versteeg, H.K., and Malalasekera, W. 2007, An Introduction to Computational Fluid Dynamics: The Finite Volume Method.
Federal Emergency Management Agency, 2010,”
Technical Manual: Outlet Works Energy Dissipators: Best Practices for Design, Construction, Problem Identification and Evaluation, Inspection, Maintenance, Renovation, and Repair”, FEMA P-679.