A CFD Study of the Flow Field and Aerodynamic Torque on a Triple-offset Butterfly Valve Used in Nuclear Power Plant

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1. PURPOSE

Triple-offset butterfly valve is one advanced kind of butterfly valve. It is potential in nuclear power plants because of its advantages in high temperature and high pressure occasions. There are few papers on performance of triple-offset butterfly valve. This paper is intended to predict the performance of a triple-offset butterfly valve used in a nuclear power plant using computational fluid dynamics, providing useful conclusions to help engineers using triple-offset butterfly valve in nuclear power plants.

2. METHOD

1) Valve geometry

The simulated geometrical model of a triple-offset butterfly valve is plotted in Fig. 1.

![Fig. 1 The simulated geometrical model of a triple-offset butterfly valve.](image)

2) Simulation model

a) Grid generation

In this paper, valve section was modeled with tetrahedral elements without prismatic layer. Near the disk faces and hub faces, the grids were denser than other regions of the valve section to resolve the boundary layer. Upstream section and downstream section were modeled with hexahedral elements.

b) Grid elements number

By studying the relation between simulation results and five different grid elements number for 90 deg disk position, the grid size about 2.8 million elements was selected for all simulated conditions.

c) Numerical method

The numerical results were obtained using the high-resolution formulation of the Navier-Stokes equation. The incompressible, steady-state solver was used. The κ-ε renormalization group theory (RNG) was selected as the turbulence model based on the practice of Zachary (2008).

d) Boundary conditions

Inlet boundary: The mass flow rate of helium with pressure of 7MPa, temperature of 250°C was set to 96kg/s.

Outlet boundary: The static pressure at the outlet boundary was set to 7MPa.

Wall boundary: The valve surfaces and channel walls were treated as smooth walls.

3) Simulation

The flows across the triple-offset butterfly valve at six different valve disk positions were computed. These six valve disk positions were 90 deg, 70 deg, 60 deg, 45 deg, 30 deg and 20 deg, which could compose of a stroke in general. The computational results were obtained through CFX 12 which has been applied in various fields.

3. Conclusions

First, with the disk-opening angle decreases, the total torque exerted by helium gas is always helpful to self-closing for disk and the magnitude of the total torque increases. Due to the self-closing torque, some self-lock function should be added to prevent self-closing in normal conditions.

Secondly, with the disk-opening angle decreases, the vortex and recirculation regions become greater. This caused more pressure drop across the valve disk.

Finally, with the disk-opening angle decreases, the predicted dimensionless resistance coefficient increases, and the torque coefficient decreases.

REFERENCES

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ABSTRACT

Triple-offset butterfly valve is one advanced kind of butterfly valve. It is potential in nuclear power plants because of its advantages in high temperature and high pressure occasions. There are few papers on performance of triple-offset butterfly valve. This paper is intended to predict the performance of a triple-offset butterfly valve used in a nuclear power plant using computational fluid dynamics. The flow field and aerodynamic torque on the triple-offset butterfly valve were studied at six different disk positions from 90 deg to 20 deg (where 90 deg is in the full open position). The selected six different disk positions indicated a stroke. The flow fields were predicted using the k-epsilon renormalization group theory (RNG) turbulence model. The computational results were obtained using CFX 12. The flow field is illustrated using velocity contours and disk pressure profiles, illustrating the effects of the disk position. Some results of flow field are compared to those of symmetric disk butterfly valve which have been validated by test results. Based on the flow field, valve resistance coefficient and aerodynamic torque coefficient with the disk positions are obtained, providing a better understanding of the performance of the triple-offset butterfly valve throughout a stroke.

1. INTRODUCTION

Triple-offset butterfly valve is one advanced kind of butterfly valve. Because of its different structural characteristics from other types of butterfly valve, triple-offset butterfly valve has much more advantages in high temperature and high pressure occasions. Therefore, it is potential in nuclear power plants, especially in high temperature gas cooled reactor plants. It has begun to be used in nuclear power plants reported by Kalsi (2004).

Now one nuclear plant is ready to utilize triple-offset butterfly valve as piping component to perform safety function of isolating the helium gas flow of the process under accidental conditions. In normal condition, the triple-offset butterfly valve is in full open position. However, in accidental conditions, it is required to be closed in a time as short as possible to alleviate the accidental consequence. Then the pressure drop across the valve in normal condition and the torque exerted to the valve disk by gas, including both the magnitude and direction of torque, are two key parameters that engineers in nuclear power plant want to know. The former influences the required pressure rise supplied to the flow loop. The latter influences the design of the valve actuator. However, these two parameters are closely related with butterfly valve performance information.

Accurate butterfly valve performance information is necessary to ensure the safe operation of nuclear power plant. Generally, butterfly valve performance information are obtained through an experimental testing of prototype or scaled valves but can also be obtained through an adequate computational fluid dynamics (CFD) code. Experiments have disadvantages of expensive cost and limited test objects. Comparatively, CFD is an economical and efficient method to calculate the valve performance.

There have been some papers on studying butterfly valve performance by CFD and their CFD results have been in good agreement with experimental results by Zachary and Charles (2006, 2008). But they are all about the symmetric disk butterfly valve. There is no paper on studying triple-offset butterfly valve by CFD or by experiment. Triple-offset butterfly valve has different structure from that of symmetric disk butterfly valve. Even though there are reports on triple-offset butterfly valves having been applied in various occasions, no result on their performance can be obtained because of manufactures and users’ privacy.

The objective of this study is to predict the triple-offset butterfly valve performance through CFD, including the prediction of pressure drop across the valve and the torque magnitude and direction exerted to valve disk, showing the dependence of different pressure profiles and velocity.
profiles on different disk positions, and provide insight into the incompressible flow field in a triple-offset butterfly valve.

This paper will first introduce the structure of triple-offset butterfly valve, secondly develop simulation model based on methods of symmetric disk butterfly valve, then predict the performance of triple-offset butterfly valve at six different disk positions of a stroke through developed simulation model, and finally analyze the simulation results, providing useful conclusions to help engineers using triple-offset butterfly valve in nuclear power plants.

2. STRUCTURE OF TRIPLE-OFFSET BUTTERFLY VALVE

The structure of the triple-offset butterfly valve studied in this paper is shown in Fig. 1. It consists of valve body, valve seating, valve disk, valve shaft, sealing surface. In Fig. 1, the intersect point of two red lines indicates the valve shaft, the green line indicates the centerline of the valve body; the yellow line indicates the cross section of the sealing surface, and the blue line indicates the rotational centerline of the valve seating. Triple offsets are displayed by three characters $a$, $b$, $\beta$ individually. Here:

- $a$ indicates the axial offset between valve shaft centerline and sealing cross section;
- $b$ indicates the radial offset between valve shaft centerline and centerline of the valve body;
- $\beta$ indicates the angular offset between centerline of the valve body and rotational centerline of the valve seating.

Because of the angular offset, the sealing surfaces between the valve seating and the valve disk are oblique frustum of a cone. This feature can eliminate the extrusion between valve seating and valve disk thoroughly and makes the triple-offset butterfly valve have many advantages over other types of butterfly valve.

[Image of the triple-offset butterfly valve]

Fig. 1 The sketch of the triple-offset butterfly valve studied in this paper.

Generally, according to the number of offset, butterfly valves are classified into four types: symmetric, single-offset, double-offset and triple-offset. The detailed comparisons between triple-offset butterfly valve and other types of butterfly valve are as follows.

1) Symmetric and single-offset butterfly valves can not work in high temperature or in high pressure occasions. Because the valve disk is symmetrical about the valve shaft, the valve is called symmetric butterfly valve. It is of zero offset. For symmetric and single-offset butterfly valves, there is strong extrusion between valve disk and valve seating while the valve disk is in full close position. Therefore, symmetric and single-offset butterfly valves can not work in high temperature or in high pressure occasions.

2) Double-offset butterfly valve can work in high temperature occasions and can not work in high pressure occasions. For double-offset butterfly valve, it is of improved structures and the extrusion between valve disk and valve seating is attenuated greatly. Its sealing performance is implemented through the line contact between valve disk and valve seating, which would fail in high pressure. Its seal can be made of metal materials which can work in high temperature. Therefore, double-offset butterfly valve can work in high temperature occasions and can not work in high pressure occasions.

3) Triple-offset butterfly valve can work in both high temperature and high pressure occasions. For triple-offset butterfly valve, because of the angular offset, the extrusion between valve disk and valve seating is eliminated thoroughly and the sealing performance is implemented through the interface pressure between valve disk and valve seating. The higher the working pressure, the better the sealing performance. The sealing principle makes the seal of triple-offset butterfly valve can be made of metal materials. Therefore, triple-offset butterfly valve can work in both high temperature and high pressure.

In addition, because there is no extrusion between valve disk and valve seating, there is no friction and wear for valve seating of triple-offset butterfly valve. Compared to other types of butterfly valves, this can extend the valve seating life.

Finally, there is less resistance for valve disk when it is being closed for triple-offset butterfly valve. This will shorten the close time of valve disk.

The butterfly valve is quarter-turn valve. In this study, the valve needs to be rotated 90 deg in a time as short as possible when nuclear accidents occur, changing from in full open position to in full closed position. And nuclear accidents generally are of high temperature and high pressure. Based on above comparisons, triple-offset butterfly valve is the most suitable to satisfy our demands.

3. COMPUTATIONAL MODEL

3.1 Geometrical Model

Fig. 2 illustrates the simulated geometrical model of a
triple-offset butterfly valve with a 0.07 aspect ratio. The aspect ratio is the ratio of maximum disk thickness to disk diameter. The downstream disk face is a smooth plate. The upstream disk face is joint with a cylindrical hub to allow for the shaft.

The geometrical model consists of three sections: the upstream section, valve section and downstream section. Based on papers of Zachary and Charles (2006, 2008), five disk lengths of upstream pipe and ten disk lengths of downstream pipe are sufficient to achieve reliable results for straight pipe.

3.2 Grid Generation
In this study, valve section was modeled with tetrahedral elements without prismatic layer. Near the disk faces and hub faces, the grids were denser than other regions of the valve section to resolve the boundary layer. Upstream section and downstream section were modeled with hexahedral elements.

Fig. 2 The simulated geometrical model of a triple-offset butterfly valve with a 0.07 aspect ratio.

The surface model grid for the triple-offset butterfly valve is shown in Fig. 3. The sketch of the grid for 90 deg disk position is shown in Fig. 4.

Five grid systems were developed for 90 deg disk position. The grids increased in node count and in refinement of the disk geometry. The relation between calculated pressure drop ratio and grid elements number is plotted in Fig. 5. Here, the pressure drop ratio is defined as the ratio of pressure drop of every grid elements number to the obtained maximum pressure drop for 90 deg disk position. From Fig. 5, the pressure drop ratio with grid size about 2.8 million elements is located in the convergence region. So the grid size about 2.8 million elements was selected for all simulated disk positions.

Fig. 3 The surface model grid for the triple-offset butterfly valve.

Fig. 4 The sketch of the grid for 90 deg disk position.

The surface model grid for the triple-offset butterfly valve

Fig. 5 The relation between calculated pressure drop ratio and grid elements number. The pressure ratio is defined as the ratio of pressure drop of every grid elements number to the obtained maximum pressure drop for 90 deg disk position.

3.3 Numerical Method
The numerical results were obtained using the high-resolution formulation of the Navier-Stokes equation. The steady-state solver was used.

In this study, the triple-offset butterfly valve worked in helium atmosphere with pressure of 7MPa, temperature of 250℃. For 90 deg disk position, the Mach number is 0.01. So the helium in given conditions could be treated as incompressible gas. In this paper, incompressible simulation was done as a preliminary simulation. Compressible simulation will be done to compare with incompressible simulation in later study.

The κ-ε renormalization group theory (RNG) was selected as the turbulence model in this paper. This selection was based on the comparisons of four turbulence models supplied Zachary and Charles (2006) and on the application of κ-ε RNG by Zachary and Charles (2008). Zachary and Charles (2008) obtained good results in agreement with the experiment data.

3.4 Boundary Conditions
According to the actual work condition of the triple-offset butterfly valve, the following boundary conditions were set.

1) Inlet boundary
The mass flow rate of helium with pressure of 7MPa,
temperature of 250°C was set to 96 kg/s.

2) Outlet boundary
The static pressure at the outlet boundary was set to 7 MPa.

3) Wall boundary
The valve surfaces and channel walls were treated as smooth walls.

4. FLOW FIELD

The flows across the triple-offset butterfly valve at six different valve disk positions were computed. These six valve disk positions were 90 deg, 70 deg, 60 deg, 45 deg, 30 deg and 20 deg, which could compose of a stroke in general. Because of the difficulties on grid generation and great computational inaccuracies at valve disk positions less than 20 deg, the flows for valve disk positions less than 20 deg were not considered in this study. The computational results were obtained through CFX 12 which has been applied in various fields. Zachary and Charles (2008) used CFX 10 to calculate the three dimensional flow field of symmetric disk and obtained results in good agreement with the experimental data, which validated the validity of CFX 10 in valve flow field more or less.

In this paper, the flow field was illustrated using velocity contours and disk pressure profiles. All velocity contours’ unit is m/s. All pressure profiles’ unit is MPa. Pressure values in all figures are relative to 7 MPa.

For display simplicity, the flow fields of 90 deg, 70 deg, 45 deg, and 20 deg disk positions were selected to display. These four disk positions were chosen because (1) 90 deg position indicated the full open position, 20 deg indicated the position close to be fully closed, 70 deg and 45 deg indicated the middle positions of a stoke, (2) the results of 70 deg and 45 deg could be compared to related results obtained by Zachary and Charles (2008) to validate the results in this paper, (3) these angles provided a valuable insight into the tendencies of pressure drop and aerodynamic torque magnitude and direction throughout the stroke.

4.1 90 deg Disk Position

Fig. 6 indicates the velocity contours for 90 deg disk position. At this position, the valve is opened fully, and the flow area is affected slightly. Compared to the symmetric flow across a symmetric disk butterfly valve at 90 deg disk position plotted in Fig. 7, the flow across the triple-offset butterfly valve is very different because of the asymmetric shape of valve disk. For disk at 90 deg, there are two small vortex regions formed around the hub and upstream face. And there is a wake region at the trailing edge because of the disk thickness.

The flow is from left to right.

Fig. 7 The velocity contours are shown for a symmetric disk butterfly valve at 90 deg disk position. The flow is from left to right.

Fig. 8 indicates the pressure contours on both disk faces. These two disk faces in Fig. 8 are oriented with the trailing edge up and the leading edge down. Similar to the flow field characteristics around airfoils, the upstream face is pressure face. High pressure region is on the upstream face near the leading edge. The pressure across the downstream face is fairly smooth except the small region of lower pressure near the leading edge. This might be caused by the separation of small portion of flow from the leading edge.

Fig. 8 The pressure contours are shown for the (a) upstream face and (b) downstream face of the disk at 90 deg. The disk is oriented so that the trailing edge is up and
the leading edge is down.

4.2 70 deg Disk Position

Fig. 9 The velocity contours are shown for disk at 70 deg. The flow is from left to right.

This figure shows the velocity contours for a disk at 70 deg. The flow direction is from left to right.

Fig. 10 indicates the pressure contours on both disk faces. These two disk faces in Fig. 10 are oriented with the trailing edge up and the leading edge down. Because of the change in disk position, the pressure profile on the upstream face is different from that of 90 deg disk. Compared to the pressure of disk faces, the pressure on the upstream face grows bigger, while the pressure on the downstream face becomes smaller.

4.3 45 deg Disk Position

Fig. 11 The velocity contours are shown for disk at 45 deg. The flow is from left to right.

Fig. 12 The pressure contours are shown for the (a) upstream face and (b) downstream face of the disk at 45 deg. The disk is oriented so that the trailing edge is up and the leading edge is down.

Fig. 9 indicates the velocity contours for 70 deg disk position. At this position, the flow separates from the leading edge and forms a small recirculation region. The flow remains partially unattached from the downstream face. This flow behavior and flow structure is similar to that of 70 deg disk position at a valve pressure ratio of 0.96 given by Zachary and Charles (2008). In Fig. 9, the flow separates from the hub surface due to the shape of valve disk.

Fig. 10 indicates the pressure contours on both disk faces. These two disk faces in Fig. 10 are oriented with the trailing edge up and the leading edge down. Because of the change in disk position, the pressure profile on the upstream face is different from that of 90 deg disk. Compared to the pressure of disk faces, the pressure on the upstream face grows bigger, while the pressure on the downstream face becomes smaller.
Fig. 11 indicates the velocity contours for 45 deg disk position. At this position, the flow separates from the leading edge and the trailing edge. The pressure drop across the valve disk makes the gas expand. Compared to the results of 70 deg disk position, because the disk throat near the leading edge and the disk throat near the trailing edge become smaller, the flow vortex region downwards the downstream face becomes much bigger. The flow behavior and flow structure in Fig. 11 is much similar to that of 45 deg disk position at a valve pressure ratio of 0.75 given by Zachary and Charles (2008), which verifies the correctness of the simulation in this paper to some extent.

Fig. 12 indicates the pressure contours on both disk faces. These two disk faces in Fig. 12 are oriented with the trailing edge up and the leading edge down. At this position, the pressure on the upstream face continues to increase, while the pressure on the downstream face continues to decrease. The pressure profile on the upstream face changes due to the different angle of attack.

4.4 20 deg Disk Position

Fig. 13 indicates the velocity contours for 20 deg disk position. At this position, the disk is close to be fully closed. The flow area across disk throats is so small that the jet flow is formed. The maximum velocity is 416m/s, wherever it is 93m/s at 90 deg disk position. Correspondingly, a large region of vortex and recirculation downwards the downstream face is formed, which causes big pressure drop across the valve.

Fig. 14 indicates the pressure contours on the disk faces. The disk faces in Fig. 14 are oriented with the trailing edge up and the leading edge down. At this position, the pressure on the upstream face continues to increase, while the pressure on the downstream face continues to decrease. The pressure profiles on both disk faces are close to uniform.

4.5 Conclusions of Fluid Field

From the above results analysis, the following two conclusions can be obtained:

1) With the disk position changing from 90 deg to 20 deg, the flow area across the valve becomes smaller, and the maximum velocity grows bigger. The region of vortex and recirculation tends to become bigger. So there is more pressure drop while flowing across the valve.

2) With the disk position changing from 90 deg to 20 deg, the high pressure region always occurs on the upstream face towards the leading edge and continues to increase, while the pressure on the downstream face is always lower than that on the upstream face and continues to decrease. So the pressure difference between upstream face and downstream face towards the leading edge is greater than that towards the trailing edge. On the other hand, because of the offset structure of triple-offset butterfly valve, the distance from the leading edge to valve shaft is longer than that from the trailing edge to valve shaft. Therefore, the total torque exerted by gas would tend to rotate the valve disk from upstream face to downstream face, which is consistent with the valve disk close direction, and the magnitude of the total torque will increase with the valve disk position towards the full closed position.

5. Aerodynamic Torque Analysis

A new set of coordinates was developed, which defined the valve shaft centerline as $z$ axis and defined the origin as the intersect point of the axial offset and the radial offset of the triple-offset butterfly valve. The new set of coordinates is shown in Fig. 15.

The torque exerted to the disk by gas at every disk position was calculated in this new set of coordinates through CFX 12. The values obtained were negative. According to the right-hand rule, it was referred that the direction of the torque was clockwise, which was consistent with the closing
direction of valve disk. This is in accordance with the second conclusion in section 4.5. The direction of torque is helpful in closing the valve, which can shorten the closing time of valve disk and is what we want in accidental conditions. On the other hand, it can cause the disk to be closed unexpectedly when operating in normal condition. So it is necessary to add self-lock function to prevent the self-closing of valve disk in normal condition.

As to the magnitude of torque, it is plotted in Fig. 16. Here, the torque ratio is defined as the ratio of torque at every disk position to the obtained maximum torque in this study. From Fig. 16, it is seen that the torque ratio increases with the disk position changing from 90 deg to 20 deg. It increases sharply from 40 deg position to 20 deg position.

Fig. 15 The new set of coordinates was developed. Its z axis was defined as the valve shaft centerline.

Fig. 16 The torque ratio plot at every disk position. The torque ratio is defined as the ratio of torque at every disk position to the obtained maximum torque in this study.

6. PRESSURE DROP ANALYSIS

Pressure drop is an important parameter for engineers. For the butterfly valve studied in this paper, the pressure drop at every disk position under given boundary conditions was calculated and plotted in Fig. 17. Here, the pressure drop ratio is defined as the ratio of pressure drop at every disk position to the obtained maximum pressure drop in this simulation. From Fig. 17, it is seen that the pressure drop ratio increases with the disk position changing from 90 deg to 20 deg. That is to say, among the calculated disk positions, the pressure drop at 20 deg disk position is the biggest and at 90 deg is the smallest. This tendency is in accordance with the first conclusion in section 4.5.

Fig. 17 The pressure ratio plot at every disk position. The pressure ratio is defined as the ratio of pressure drop at every disk position to the obtained maximum pressure drop in this simulation.

7. PERFORMANCE COEFFICIENTS ANALYSIS

Above torque ratio and pressure drop analysis are useful for specific application. For valve performance analysis and comparison, it is best to study the flow field and aerodynamic torque using dimensionless parameters [2]. In this study, the dimensionless resistance coefficient and torque coefficient at every disk position are predicted.

7.1 Resistance Coefficient

Resistance coefficient is used to judge the resistance acting on the gas flow produced by valve. It is defined by

$$\xi = \frac{\Delta P_v}{\left(\frac{\rho U^2}{2}\right)}$$

(1)

Where,

- $\xi$ = resistance coefficient
- $\Delta P_v$ = valve differential pressure, Pa
- $\rho$ = gas density, $\text{kg/m}^3$
- $U$ = average velocity of gas in pipe, $\text{m/s}$

Based on the simulated results, the resistance coefficients for all simulated disk positions are shown in Fig. 18. The resistance coefficient increases with the disk position changing from 90 deg to 20 deg. At 90 deg, the resistance coefficient is close to zero, which indicates the resistance of valve acting on gas flow is very small in disk fully opened condition. The accuracy of plot of Fig. 18 needs to be verified by experimental data in future.

7.2 Torque Coefficient

Torque coefficient is a function of aerodynamic torque and valve differential pressure. It is defined by

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\[ C_i = \frac{T_{aero}}{D_d \Delta P_v} \]  

(2)

Where,

\[ tC_i = \text{Torque coefficient} \]
\[ T_{aero} = \text{Aerodynamic torque, } N \cdot m \]
\[ D_d = \text{Disk diameter, } m \]
\[ \Delta P_v = \text{Valve differential pressure, Pa} \]

Based on the simulated results, the torque coefficients for all simulated disk positions are shown in Fig. 19. The torque coefficient decreases with the disk position changing from 90 deg to 20 deg. At 90 deg, the torque coefficient is the biggest. All the torque coefficient values fall into the scope \([0, 0.2]\) of experimental data given by Zachary and Charles (2008). But the actual accuracy of this plot also needs to be verified by experimental data in future.

8. CONCLUSIONS

Valuable insight into the flow field, pressure drop and aerodynamic torque acting on a triple-offset butterfly valve disk is provided by CFD. Based on different valve disk positions, the tendency of the pressure drop and aerodynamic torque is studied. From this study, the following conclusions can be obtained under given boundary conditions:

First, with the disk-opening angle decreases, because of the pressure on valve disk surfaces and the valve offset structure, the total torque exerted by gas is always helpful to self-closing for disk and the magnitude of the total torque increases. Due to the self-closing torque, some self-lock function should be added to prevent self-closing in normal conditions.

Secondly, with the disk-opening angle decreases, the region of vortex and recirculation becomes greater. This caused more pressure drop across the valve disk.

Finally, with the disk-opening angle decreases, the predicted dimensionless resistance coefficient increases, and the torque coefficient decreases.

Because a proper example containing both specific valve geometrical dimensions and related experimental data can not be found, the simulation model can not be verified. Furthermore, the simulation results obtained in this paper can not be validated. They will be validated by experimental data in the near future.

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