Design Optimization of V-sector Ball Valve Core

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Abstract: In order to solve the problem that the percentage characteristic of V-sector ball valve is poor at the relatively small opening degree, a design optimization flow of valve core is proposed for the first time. The process uses numerical simulation, sample mean evaluation and area average equivalence to calculate the equal percentage characteristics coefficient $R_Q$ of DN65 V-sector ball valve core, and uses experiments to verify the rationality of the process, and further extends it to other models of ball valves. The results show that the original DN65 V-sector Ball valve core does not meet the equal percentage characteristics in the opening area of 28.6% to 7.1%. After the optimized design, the equal percentage characteristics coefficient $R_Q$ of the ball valve core has been effectively improved, and the level of increase has more than doubled. And the equal percentage characteristics coefficient obtained by test exceeds the optimized design results. Further extended in the DN100 V-sector ball valve core, it is known that this optimization design method has universal applicability; V-sector ball valve core design optimization method is an efficient and reliable valve core design method, can improve the level of Valve core flow control, improve the valve core design ability.

1. Introduction
From the invention of valves to today, people have been searching for a kind of valve, which can combine the advantages of good regulation performance, simple structure, small fluid resistance, tight and reliable sealing, convenient switching and so on. V-sector ball valve is one of the results of the search. Although the existing V-sector ball valves are close to equal percentage flow characteristics in most cases, the equal 100-bit characteristics of these V-sector ball valves can be guaranteed only when the relative opening is large, otherwise, they can not be guaranteed. Therefore, optimizing the shape of the valve core in order to achieve the goal of optimizing 100-bit characteristics, has increasingly become the most desirable and most difficult barrier to break in the field of valve research [1-5].

In order to get better V-sector ball valves with equivalent 100-bit characteristics, domestic and foreign research teams have done a lot of research on them. Zhang Xiheng[6-7] of Lanzhou University of Technology used CFD software as a tool to explore the flow characteristics at different openings, carried out simulation analysis, and obtained relevant data. At the same time, Zhang introduced the equipment for testing the flow characteristics of V-sector ball valve. FLUENT software was used to simulate the three-dimensional flow field inside the ball valve in E Jiaqiang[8] of Changsha University of Technology. Ming-Jyh Chern[9] of National Taiwan University of Science and Technology carries
out flow characteristics and flow pattern tests of ball valves under different structural parameters, and studies and discusses the data to explore the causes of cavitation phenomenon. P Merati[10] of West Kentucky University used LDC and FLUENT software to simulate the flow characteristics of V-sector ball valves. In all the above related studies, the flow characteristics of the valve core are tested by numerical simulation or experiment, and the data are analyzed comprehensively. There are relatively few studies on the design optimization of V-sector ball valves.

In this paper, a method of optimum design for V-sector ball valve core is presented, and the DN50 V-sector ball valve core is used for optimum design verification and analysis. First, the original design flow, the original equivalent flow rate characteristics and the theoretical flow rate of V-sector ball valve are calculated by numerical simulation analysis method. Then, the improved flow rate and the improved 100-bit flow rate are calculated by optimum analysis technology. Finally, the rationality of the optimization design process of the valve core is verified by combining the experimental data, and it is further extended to other caliber valves. Through theoretical and experimental verification and analysis, a reliable design method is provided for the design of the same type of V-sector valve.

2. Valve core design optimization process

Design optimization is a method to design complex systems and subsystems by making full use of and exploring the cooperative mechanism of interaction in systems. In order to obtain the shape of DN65 V-sector ball valve core with equal 100-bit characteristics, first, the flow rate of original ball valve at each opening should be calculated by numerical method, and the equivalent 100-bit characteristic coefficient should be calculated according to the flow rate; the difference of equivalent 100-bit characteristic coefficient under different opening should be compared, and the mean of sample distribution can be obtained by mathematical statistical method to calculate rationality. Discussing flow rate; Comparing the difference between theoretical flow rate and calculated flow rate, modifying the shape of valve core according to the equivalent area method, calculating the equivalent 100-bit characteristic coefficient of the corrected valve core, retrieving the sample mean and standard deviation, calculating the theoretical flow rate and correcting the shape of the valve core; finally, the design and optimization of the valve core can be completed at a more balanced level with equivalent 100-bit characteristics. The design flow of the core is shown in Figure 1. The specific steps of the design optimization process of the valve core are as follows:

![Figure 1 Optimization of the valve core framework](image-url)
Step1: Choose the original core shape
The model DN65 V-sector ball valve is selected to optimize the design of the core. The inner diameter of the core is 50mm, and the original design opening angle is 22.5 degrees, as shown in Figure 2. CFD numerical simulation analysis software is used for mathematical modeling and mesh generation. Opening angle and boundary size are selected as optimization design parameters, and appropriate optimization size range is selected to realize automatic mesh generation when changing geometry in the design process.

Step2: Calculate actual flow $Q_1$
The key point of V-sector ball valve core design is to investigate the flow characteristics, which indicate the flow through the core at different openings. In most cases, the flow characteristic curve, the relative opening and the relative flow of the valve are obtained under the corresponding fixed pressure drop of the control valve. The mathematical expression of equivalent percentage flow is as follows:

$$\frac{Q}{Q_{\text{max}}} = R_Q \left(\frac{l}{L}\right)^{-1}$$

In the formula, $R_Q$ denotes equivalent 100-bit characteristic coefficient, $l$ expressing the travel of a certain opening, $L$ expressing the travel of a full opening, Relative opening $l/L$ represents the quotient between the travel of a certain opening and a full opening. $Q$ expressing the flow of a certain opening, $Q_{\text{max}}$ expressing the flow of a full opening, Relative flow $Q/Q_{\text{max}}$ represents the quotient of flow at a certain opening $Q$ and at full opening $Q_{\text{max}}$.

Based on the original physical model and CFD numerical analysis, a total of 13 design points with relative opening from 0% to 100% were selected, and the flow values at different opening were calculated by numerical optimization algorithm. The data are shown in Table 1.

Step3: Calculate equivalent 100-bit characteristic coefficient $R_Q$
Equivalent 100-bit characteristic coefficient $R_Q$ reflects the merits and demerits of valve regulation ability. The basic characteristic of a valve with equal equivalent 100-bit characteristic should be that the size of $R_Q$ is similar.

Equivalent 100-bit characteristic coefficients $R_Q$ at different openings are calculated by using the mathematical expression of equivalent percentage flow. The data are shown in Table 1. Relative opening from 92.9% to 50% is more uniform. Opening from 21.4% to 7.1% increases very quickly. The geometric shape of this interval is the region that needs to be adjusted.

| Relative opening | Actual flow $Q_1$ | Relative circulation | Theoretical flow | Equivalent 100-bit characteristic |
|------------------|-------------------|---------------------|-----------------|-----------------------------------|
| 92.9%            |                   |                     |                 |                                   |
| 50%              |                   |                     |                 |                                   |
| 21.4%            |                   |                     |                 |                                   |
| 7.1%             |                   |                     |                 |                                   |
The \( R_Q \) value of each opening is set as the sampling sample \((x_1, x_2, ..., x_n)\), and 92.9% of the opening is taken as the benchmark. The 100-bit characteristic coefficient is equal to 32.19, 42.47, 62.41 and 119.9 points after removal. Select other \( n = 9 \) sample points, do sample mean \( \overline{R_Q} = \frac{1}{n} \sum x_i \), use sample mean to solve all \( n = 13 \) sample standard deviation \( S = \sqrt{\frac{1}{(n-1)} \sum (x_i - \overline{R_Q})^2} \), use sample standard deviation as the judgment basis of valve core calculation.

**Step5:** Calculated sample mean \( \overline{R_Q} \)

Sample mean in Step4 step is selected as the next equivalent 100-bit characteristic coefficient \( \overline{R_Q} \), and the theoretical flow based \( Q_2 \) on sample mean \( \overline{R_Q} \) under corresponding opening condition is calculated by using the mathematical expression of equivalent percentage flow, as shown in Table 1.

**Step6:** Theoretical flow calculation \( Q_2 \)

The main purpose of calculating the theoretical flow rate \( Q_2 \) based on the sample mean \( \overline{R_Q} \) is to adjust the valve core structure, and adjust the cross-section area under the corresponding opening condition by \( Q_2/Q_1 = A_{x_1}/A_{x_2} \). The ratio of the theoretical flow rate \( Q_2 \) to the actual flow rate \( Q_1 \) is the cross-section area ratio under the corresponding opening condition.

**Step7:** Comparing actual flow \( Q_1 \) with theoretical flow \( Q_2 \)

The area of rectangular sector is calculated by \( A = \alpha \pi (r_2^2 - r_1^2)/360 \), which is the distance between sector and central point. The radian area is calculated by \( A = \alpha \pi r^2/360 \), and the shape of valve core is adjusted by flow ratio and area ratio.

**Step8:** Improved core shape

According to the improved shape of the valve core, the grid is re-divided, the flow rate and the equivalent 100-bit characteristic coefficient are calculated, and whether the equivalent 100-bit characteristic coefficient is approximately the same is compared. Sample mean and standard deviation are taken to determine whether further modification is needed. If modification is needed, the theoretical flow rate is continued to be revised, and the actual flow rate and the theoretical flow rate are compared to obtain a new fan. Section area to modify the shape of the core. Through repeated iterations until the characteristic coefficients of 100 bits are approximately the same, Table 2 is the...
final result of numerical optimization. From the table, it can be found that when the opening is 92.9%, the flow rate of the improved core increases to 5.10 kg/s and the equivalent 100-bit characteristic coefficient decreases to 8.32. In the region of 28.6% to 14.3% relative opening, the equivalent 100-bit characteristic coefficient is improved compared with the prototype.

According to the above processes, the improved V-sector ball valve model as shown in Fig. 3 can be obtained, and the improved flow value in Table 2 can be obtained. Comparing the $R_{Q_i}$ values of Equivalent 100-bit characteristic coefficients in Table 1 and Table 2, it can be seen that the $R_{Q_i}$ values of Equivalent 100-bit characteristic coefficients of improved V-type ball valves are more balanced and more stable in a relatively small range of opening.

| Relative opening/l/L | Actual flow $Q_1$ kg/s | Relative circulation volume $Q/Q_{max}$ % | Equivalent 100-bit characteristic coefficient $R_{Q_i}$ |
|----------------------|------------------------|------------------------------------------|------------------------------------------------------|
| 92.9                 | 5.10                   | 85.95                                    | 8.32                                                 |
| 85.7                 | 4.32                   | 72.83                                    | 9.20                                                 |
| 78.6                 | 3.66                   | 61.69                                    | 9.53                                                 |
| 71.4                 | 3.06                   | 51.60                                    | 10.13                                                |
| 64.3                 | 2.52                   | 42.49                                    | 10.99                                                |
| 57.1                 | 2.06                   | 34.77                                    | 11.76                                                |
| 50.0                 | 1.68                   | 28.33                                    | 12.46                                                |
| 42.9                 | 1.39                   | 23.43                                    | 12.67                                                |
| 35.7                 | 1.14                   | 19.23                                    | 12.99                                                |
| 28.6                 | 0.63                   | 10.65                                    | 23.01                                                |
| 21.4                 | 0.40                   | 6.77                                     | 30.79                                                |
| 14.3                 | 0.21                   | 3.54                                     | 49.35                                                |

Figure.3 Optimized DN65 V-sector ball valve figure

3. Test verification
The improved DN65 V-type ball valve was tested by using the flow test device of the ball valve. The flow characteristics of the V-sector ball valve core at different opening degrees were measured. The relative opening and $R_{Q_i}$ of the V-sector ball valve core were calculated by using the expression of equivalent 100-bit flow rate.

Fig. 4 is the physical diagram of the flow characteristic test device for V-sector ball valve spool. The medium in the water tank is pressurized to 392 280 Pa in the pump, then flows into the water pipe, passes through the throttle valve, reaches the ball valve, and then returns to the water tank through the outlet pipe to form a closed loop. The function of throttle valve is to control the pressure in the pipeline. The pressure gauges at the inlet and outlet are used to monitor the pressure of the medium in
the tube at both ends of the ball valve, and are transmitted to the computer together with the flow data measured by the flow meter. During the test, by adjusting the opening of the ball valve to ensure the pressure at both ends of the valve, the required flow data can be obtained, as shown in Table 3.

Table 3. Flow characteristic test data for DN65 V-sector ball valve core

| Relative Opening l/L | Relative circulation volume Q/Qmax | Equivalent 100-bit characteristic coefficient RQS |
|----------------------|-----------------------------------|-----------------------------------------------|
| 93.1                 | 85.6                              | 9.17                                          |
| 87.3                 | 72.9                              | 8.58                                          |
| 81.6                 | 64.1                              | 8.46                                          |
| 74.2                 | 58.3                              | 8.18                                          |
| 68.5                 | 48.4                              | 9.56                                          |
| 61.3                 | 39.3                              | 11.26                                         |
| 55.9                 | 32.6                              | 12.04                                         |
| 49.1                 | 27.0                              | 12.74                                         |
| 42.6                 | 22.1                              | 13.58                                         |
| 36.3                 | 16.8                              | 15.97                                         |
| 29.8                 | 14.0                              | 16.07                                         |
| 23.3                 | 9.82                              | 20.24                                         |
| 16.4                 | 8.42                              | 19.31                                         |
| 10.5                 | 4.73                              | 29.62                                         |
| 4.7                  | 2.97                              | 38.42                                         |

By sorting out $RQS$, relative opening $l/L$ and equivalent throughput $Q/Q_{max}$ in tables 1, 2 and 3, the column and curve as shown in Figure 6 are obtained. The column diagram reflects the average of $RQS$ of the original core, the numerically optimized core and the test core. It can be found that the uniformity of the test data is the best, which fully proves the rationality of the optimization design of DN65 V-sector ball valve. Using relative opening $l/L$ and relative traffic flow $Q/Q_{max}$ to draw the equivalent 100-bit characteristic curves of the three models, we can find that the original model has a lower position of equivalent 100-bit characteristic line, a slightly higher numerical model, the relative position of the test model is the highest, and its stability is the best. The numerical and experimental models validate that the flow characteristic curve of DN50 V-sector ball valve core after optimization is more in line with the exponential function curve, reflecting the more excellent 100-bit characteristic after optimization.
4. Promotion and application of design optimization

In order to popularize this optimization method, the design optimization analysis of DN100 V-sector ball valve core is carried out. The results are shown in Table 4. The data of relative opening $l/L$, equivalent throughput $Q/Q_{\text{max}}$, theoretical throughput and equivalent 100-bit characteristic coefficients are calculated in turn. Comparing the original model with the optimized model under different opening conditions, it is easy to observe that the design optimization model has been improved obviously in the area with the opening less than 28.6, and the optimized equivalent 100-bit characteristic coefficients have been obtained. Characteristic coefficient $R_Q$ value is more balanced.

Table 4. Original and Optimization data for DN100 V-sector ball valve

| Relative opening $l/L$% | Actual flow $Q_1$ kg/s | Relative circulation volume $Q/Q_{\text{max}}$% | Theoretical flow $Q_2$ kg/s | Equivalent 100-bit characteristic coefficient $R_Q$ | Improved flow $Q_i$ kg/s | Relative circulation volume $Q/Q_{\text{max}}$% | Equivalent 100-bit characteristic coefficient $R_{Qi}$ |
|-------------------------|------------------------|---------------------------------------------|----------------------------|-----------------------------------------|------------------------|---------------------------------------------|----------------------------------------|
| 92.9                    | 11.02                  | 83.94                                       | 10.82                      | 11.59                                   | 12.32                  | 83.88                                       | 11.71                                   |
| 85.7                    | 9.20                   | 70.10                                       | 8.91                       | 12.02                                   | 10.39                  | 70.78                                       | 11.24                                   |
| 71.4                    | 6.51                   | 49.63                                       | 6.05                       | 11.61                                   | 7.50                   | 51.04                                       | 10.52                                   |
| 64.3                    | 5.17                   | 39.40                                       | 4.99                       | 13.57                                   | 6.10                   | 41.56                                       | 11.69                                   |
| 57.1                    | 4.10                   | 31.24                                       | 4.11                       | 15.10                                   | 4.88                   | 33.24                                       | 13.06                                   |
| 50.0                    | 3.18                   | 24.22                                       | 3.39                       | 17.04                                   | 3.91                   | 26.62                                       | 14.11                                   |
| 42.9                    | 2.44                   | 18.56                                       | 2.79                       | 19.05                                   | 3.06                   | 20.86                                       | 15.53                                   |
| 35.7                    | 1.77                   | 13.39                                       | 2.30                       | 22.81                                   | 2.31                   | 15.71                                       | 17.80                                   |
| 28.6                    | 1.23                   | 9.37                                        | 1.90                       | 27.50                                   | 1.69                   | 11.52                                       | 20.61                                   |
| 21.4                    | 0.80                   | 6.10                                        | 1.56                       | 35.12                                   | 1.12                   | 8.15                                        | 24.32                                   |
| 14.3                    | 0.46                   | 3.50                                        | 1.29                       | 49.89                                   | 0.78                   | 5.32                                        | 30.63                                   |
| 7.1                     | 0.21                   | 1.63                                        | 1.06                       | 84.00                                   | 0.46                   | 3.11                                        | 41.95                                   |

5. Conclusion

This paper mainly elaborates an optimization design method of V-sector ball valve core. Through the design optimization of DN50 V-sector ball valve core, the improvement of 100-bit characteristics of the spool before and after optimization is verified by data, and the rationality of the optimization design is further verified by experiments. The application of this optimization method in other V-sector ball valve cores shows that this method is not only applicable to DN65 type ball valves,
but also to most V-sector ball valves. In view of this design optimization method, this paper summarizes the following conclusions:

1) By means of numerical simulation, sample mean evaluation and area average equivalence method, the flow characteristics of V-sector core with 100-bit can be effectively improved, and the numerical distribution can be more uniform under different opening conditions.

2) The optimization method of V-sector ball valve core design is an efficient and reliable method of core design, which can improve the ability of core design.

3) The optimization method of V-sector ball valve core design can improve the flow control level of the core and provide effective data support for the design of electric and manual control valves.

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