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Original Research Paper

Structural Optimization and Performance Prediction of Digital Valve for Desulfurization and Dedusting

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ABSTRACT

In order to control the dust removal and desulfurization process accurately, it is imperative to obtain the optimal structure parameters of the valve, using CFD to simulate and forecast the flow field numerical design of dust removal and desulfurization of digital valve, designing the $L_{25}(5^6)$ orthogonal test table of valve structure, selecting the arc radius, length, angle, width as the factors. The study determined the flow characteristics, the ideal digital valve of the maximum open flow coefficient and the degree of the digital valve spool inertia as the performance evaluation index of the valve, completed the orthogonal experiment and analysed by range analysis of the results, and obtained the influence of structure parameters on the ranking optimization direction of evaluation index, the simulation forecast data in various opening of digital valve and the flow pressure nephogram and velocity contours of 100% relatively open. A comprehensive quality evaluation index of the valve was made, making the multiobjective optimization problem into a single objective optimization problem of desulfurization dust digital valve optimization through the synthetic weighted mark method. Using box method to optimize the structure of desulfurization and dust removal of digital valve, we obtained the optimal structure parameters: radius of 3.4mm, the angle of 108.05°, length of 14.07mm and width of 37.85mm.

INTRODUCTION

As an important part of desulfurization and dust removal equipment process, the dust removal and desulfurization of digital valve not only have the corrosion and wear resistance, but also can control on-line, adjusting valve at real-time and in order to meet the needs and requirements of the adjustment of the process parameters, the valve should have good adjusting performance.

The purpose of this paper is to design a desulfurization and dust removal digital valve which can meet the technological requirements, online controlling and has a good regulation performance and the flow field numerical simulation, performance prediction of valve and optimization of structure. In recent years, with the industrial and agricultural productions' increasing demand of high performance valves, the researchers have made a lot of research work on the flow field numerical simulation of the valve. Gong Yu (2010) did the numerical simulation of ball valve designed by ourselves and researched the effects of valve opening and fluid velocity on the pressure loss coefficient of the valve. The study found that the pressure loss coefficient is larger when the opening is small; and with the flow velocity increasing, pressure loss coefficient will increase. But when the flow rate increased to a certain degree, the pressure loss coefficient tends to be stable. The characteristics of the valve include flow characteristics, the displacement characteristic and static characteristic. Series Yang Jiwei (1999) let the serial adjusting mode of regulating valve as the object of study, based on the theory of computing in the resistance, derived the equation of flow regulating valve and the deformation equation and intrinsic flow formula of work flow. As the structure of valve has an important effect on the performance of valve, the researchers carried out a lot of work to study the optimization of the valve structure. In order to make the V type ball valve have excellent characteristics of equal percentage regulation, Yao Xiaochun (2009) did the structure optimization of V type ball valve. Let the flow characteristic curve and the standard flow characteristics of the ideal curve of V type open ball valve compared with each other in two different groups based on CFD numerical simulation. Selecting out the V type valve with good regulation characteristics, but this kind of optimization method is not scientific comprehensive optimization and the effects of optimization need to be improved, and it is not practical. This paper uses CFD to simulate the flow field in the valve and extracted the flow forecasting date for characteristic analysis. Based on the analysis of valve flow, with its structure parameters as factor, research of orthogonal experiments were carried out and the valve flow characteristics. Using a complex method algorithm, we optimized the structural parameters of the valve, to obtain the optimum combination of structural parameters.

DIGITAL VALVE FOR DUST REMOVAL AND DESULFURIZATION

Design of Digital Valve for Dust Removal and Desulfurization

Fig. 1 is the valve structure diagram; valve gap main contains five geometry: the arc radius R, arc positioning dimension A, length L, angle and width B. The arc positioning dimension A is constant: A=22mm. The rest of the size is variable, which were chosen as the orthogonal experiment factors.

Drawing the valve 3D part drawings, established the 3D model and assemble into a valve assembly diagram, as shown in Fig. 2. While the valve in the CFD simulation, in order to guarantee the simulation carried out smoothly, we need to add the downstream pipe prolonged in the valve on. The channel geometry model of 100% relative opening degree is shown in Fig. 3. Divided the internal flow channel of the valve, the mesh model of 100% relative opening degree of the valve body flow passage is shown in Fig. 4.

Flow Field Simulation

Making the digital valve grid model of 100% opening flow experiment into Fluent software and numerical simulation of flow field calculation. Fig. 5 is the analysis of convergence of the residual curve interface. Fig. 6 is the pressure contours of flow field when the relative opening degree of the valve is 100%. Fig. 7 is the relative opening degree of the valve in the velocity contours for the flow field of 100%.

The Orthogonal Experiment

The experimental design, implementation and analysis of experimental results are relatively simple while the influence factors are less for experimental problems. But the structure of valve often needs more experimental studies of the influence factors and if we are making comprehensive experiment, the experimental simulation is large in scale and the experiment will have more trouble. Probably it is difficult to carry out the implementation of the one to one, because of experimental conditions and experimental cycle constraints.

Orthogonal experiment is to find out some part of representative combines in all the experimental factor level values. Through the fewer number of experiments and analysis of these experimental results, we obtained the experimental situation comprehensively and found the optimal factor level combination. Predictive optimal valve structure and considering the properties, select the core radius, angle, length and width of four structural dimensions of the valve as experimental factors and each factor set 5 levels. Each factor and each level of value is as given in Table 1.

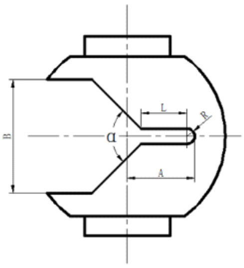

Fig. 1: The overall layout of the digital valve.

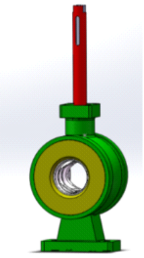

Fig. 2: The 3D assembly of value body.

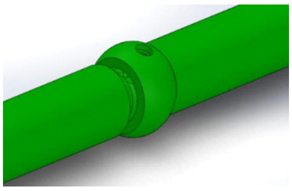

Fig. 3: The channel geometry model of 100% relative opening degree.

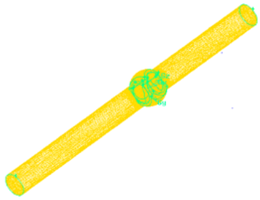

Fig. 4: Grid model of 100% relative opening.

The orthogonal table is a very important tool and its basic characteristic is orthogonality. In the study of orthogonal experiment of valve structure, without considering the interaction between the factors of the experiment, the orthogonal experiment of four factors and five levels can be selected for the orthogonal experiment as given in Table 2.

The Range Analysis

Trend analysis of various factors on the flow characteristics of the ideal flow: According to the orthogonal experimental results of valve structure in Table 2, we calculated the deviation square and an average range of each factor at

Table 1: Table factors and levels of orthogonal test of valve.

Factor Level	The circular arc radius R (mm)	Angle α (°)	Length L (mm)	Width B (mm)
1	1.5	70	13	35
2	2	80	14	36
3	2.5	90	15	37
4	3	100	16	38
5	3.5	110	17	39

Table 2: Results of orthogonal test of valve structure.

Num	The circular arc radius R (mm)	Angle α (°)	Length L (mm)	Width B (mm)	Sum of squares of deviations (1×10-2)	Open degree of flow coefficient (m^3/h)	Moment of inertia (g.mm^2)
1	1	1	1	1	2.96	21.97	227970.76
2	1	2	2	2	3.35	22.27	223011.57
3	1	3	3	3	3.54	23.06	219154.39
4	1	4	4	4	4.14	23.68	216063.86
5	1	5	5	5	4.84	23.85	213547.20
6	2	1	2	3	3.36	20.64	226488.37
7	2	2	3	4	2.80	22.89	221457.96
8	2	3	4	5	3.38	22.05	217671.44
9	2	4	5	1	3.77	22.30	223348.58
10	2	5	1	2	3.58	30.22	203657.22
11	3	1	3	5	3.67	20.01	226250.49
12	3	2	4	1	3.53	20.60	226547.75
13	3	3	5	2	3.55	20.97	223321.77
14	3	4	1	3	3.38	28.25	203277.52
15	3	5	2	4	3.00	28.82	200795.31
16	4	1	4	2	3.49	20.05	228782.81
17	4	2	5	3	3.67	20.27	224606.21
18	4	3	1	4	3.92	26.51	203622.49
19	4	4	2	5	3.84	26.67	200910.09
20	4	5	3	1	4.23	26.54	209395.52
21	5	1	5	4	2.60	21.20	227837.85
22	5	2	1	5	2.32	27.74	205116.10
23	5	3	2	1	1.72	28.18	210659.60
24	5	4	3	2	1.74	28.38	208167.54
25	5	5	4	3	1.29	28.44	206074.88

each level. From Table 3, it can be obviously seen that the effect of size of various factors on the sum of squares of deviations (ideal flow characteristics) are as, radius R> length L> width B> angle.

In Table 3, K1, K2, K3, K4, K5 represent the sum of squares of deviations under five level of the 1, 2, 3, 4, 5 factors; $\overline{K1}$, $\overline{K2}$, $\overline{K3}$, $\overline{K4}$, $\overline{K5}$ represent the average value of the sum of squared differences respectively under five level of the 1, 2, 3, 4, 5 factors. In order to observe the trend directly, we draw the influence and trend map of various factors on the deviation square, as shown in Fig. 8. According to the evaluation index, combined optimal level is $R5\alpha2L2B3$. The radius R is 3.5 mm, the included angle α is 80°, the length L is 14 mm , the width B is 37 mm which can obtain the minimum deviation square and it shows that the parameters of the valve have the best ideal flow characteristics. Valve structure parameters of the optimized flow are not in the existing test, the verification test is carried out with Fluent, to get the set of data with minimum deviation square sum as 1.15×10^{-2}. Compared with 25 groups of test data, it has been found that the deviation square of the test is closed to the minimum in orthogonal test.

Trend analysis of various factors on the flow coefficient: According to the orthogonal experimental results of the valve in Table 2, we calculated the range of flow coefficient of average value under each factor at each level. From Table 4, it can be clearly seen that the size of various factors on the coefficient of flow are angle > length L > the radius of the circular arc R > width B.

In Table 4, K1, K2, K3, K4, K5 represent the sum of the

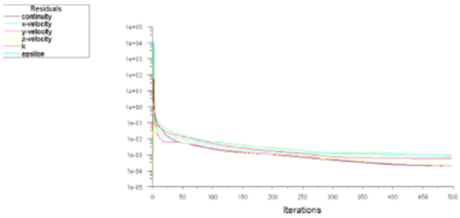

Fig. 5: The residual curve.

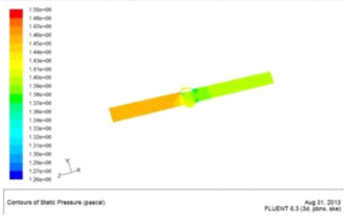

Fig. 6: The flow field pressure nephogram of 100% relative opening.

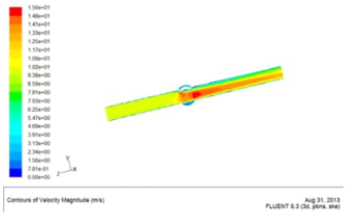

Fig. 7: The flow velocity contours of 100% relative opening.

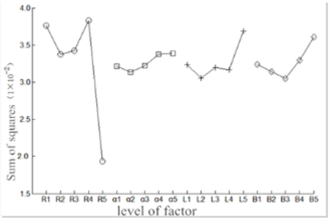

Fig. 8: The influence of factors on the deviation square and trend.

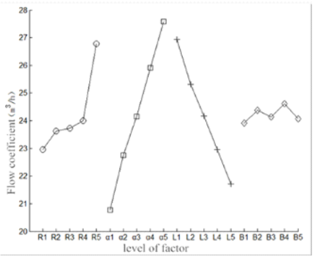

Fig. 9: The trend of various factors on the flow coefficient.

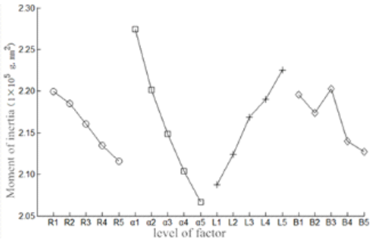

Fig. 10: The trend of the effect of each factor on the moment of inertia.

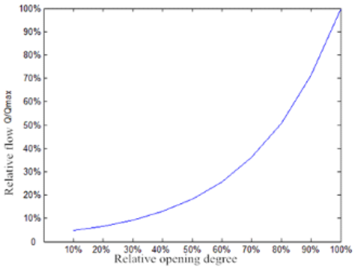

Fig. 11: The equal of 30 percentage flow characteristic curve.

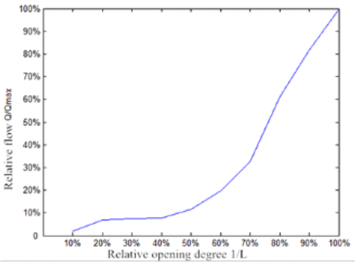

Fig. 12: The valve flow characteristics of the ideal curve.

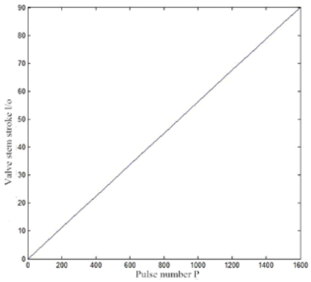

Fig. 13: The value displacement characteristic.

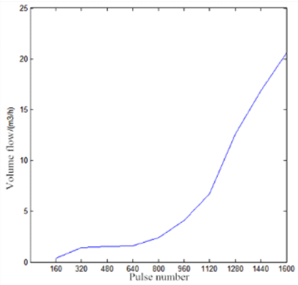

Fig. 14: The static characteristics of the valve curve.

flow coefficient under five level of the 1, 2, 3, 4, 5 factors; $\overline{K1}$, $\overline{K2}$, $\overline{K3}$, $\overline{K4}$, $\overline{K5}$ represent the average value of flow coefficient under five level of the 1, 2, 3, 4, 5 factors. In order to observe the trend directly, we rendered the influence of each factor on the flow coefficient of the trend graph, as shown in Fig. 9. According to the evaluation index, combined optimal level is $R5\alpha5L1B4$. The radius R is 3.5mm and the included angle α is 110°, and the length L is 13mm, the width B is 38mm which can obtain the maximum flow coefficient. Valve structure parameters of the optimized are not in the existing test and the verification test is carried out with Fluent, to get the flow coefficient of the data set as $31m^3/h$. Compared with the 25 groups of experimental data, it was found that the flow coefficient of the test is close to the maximum value in orthogonal test.

Analysis of the factors affecting on the moment of inertia of the trend: According to the orthogonal experimental results of valve in Table 2, we calculated the rotary inertia of the poor average value under each factor at each level. From Table 5, it can be clearly seen that the size of the effect of each factor on the moment of inertia: angle> length L> radius of the circular arc R> width B.

In Table 5, K1, K2, K3, K4, K5 represent the sum of moment of inertia under five level of the 1, 2, 3, 4, 5 factors; $\overline{K1}$, $\overline{K2}$, $\overline{K3}$, $\overline{K4}$, $\overline{K5}$ represent the average value of moment of inertia under five level of the 1, 2, 3, 4, 5 factors. In order to observe the trend directly, we rendered the influence of each factor on the moment of inertia of the trend graph, as shown in Fig. 10. According to the evaluation index, we got the best process combination as $R5\alpha5L1B5$. The radius R is 3.5mm, the included angle α is 110°, the length L is 13mm, and the width B is 39mm which can obtain the minimum moment of inertia. Valve structure parameters of the optimized are not in the existing test and the verification test is carried out with Fluent, to get the Moment of inertia of the data set is 200545.23 $g.mm^2$. Compared with 25 groups of experimental data, we found that the test valve spool inertia close to minimum in orthogonal test.

STRUCTURE OPTIMIZATION

Design the Variables

Selecting the valve flow characteristics of the ideal, the flow coefficient and the moment of inertia as the performance evaluation indexes, which is a single objective function optimization of the valve structure. Considering the setting of valve flow characteristics and flow characteristics of the sum of ideal deviation square and the weight as $w_1 = 0.5$. Setting the weight coefficient of flow as $w_2 = 0.3$. Setting the weight coefficient of flow as $w_3 = 0.2$. Then the evaluation index of the valve is $w = (0.5, 0.3, 0.2)$.

Comprehensive Target Function

Comparing the scores of the numerical performance indexes of the 25 groups' experiments and using $Y(i,j)$, represented the j trials of each index score. For the two evaluation indexes of the deviation square and moment of inertia, according to percentile calculation, we set the maximum performance index value of $A_{j\max}$ is 52 points and the minimum value of $A_{j\min}$ is 100 points. Arranged according to the various numerical order of size, the difference between the numerical is 2 adjacent. For the flow coefficient evaluation, according to percentile calculation, we set the minimum performance index value of $A_{j\min}$ as 52 points and the maximum value of 100 points. Arranged according to the various numerical order of size, the difference between the numerical is 2 adjacent. Let the weighted score of each performance index of the comprehensive weighted value added as each test score which can use Y_i^* to represent for. The higher value indicates a better comprehensive performance by the group test. According to this train of thought, the formula of the comprehensive target function can be established:

$$Y_j^* = \sum_{i=1}^{3}\left[Y(i,j)\times Wi\right] \qquad ...(1)$$

Optimization Method

Selecting the compound shape method as the optimization method, let the 25 groups of experimental results in Table 2 evaluated by using comprehensive evaluation method and the results are given in Table 6. Select the highest score of 9 groups of value as the initial complex valve structure of complex optimization. Using the box method to optimize the valve structure, when the optimization test is carried out to the 21 step, the termination condition is reached at the end of the experiment, and the optimization is over. Table 7 is the results of optimization of the complex method. Table 7

Table 3: The influence of factors to the data deviation square sum.

	R	α	L	B
K1	18.83	16.08	16.16	16.21
K2	16.89	15.67	15.27	15.71
K3	17.13	16.11	15.98	15.24
K4	19.15	16.87	15.83	16.46
K5	9.67	16.94	18.43	18.05
$\overline{K1}$	3.766	3.216	3.232	3.242
$\overline{K2}$	3.378	3.134	3.054	3.142
$\overline{K3}$	3.426	3.222	3.196	3.048
$\overline{K4}$	3.83	3.374	3.166	3.292
$\overline{K5}$	1.934	3.388	3.686	3.61
Range	1.896	0.254	0.632	0.562
Number	1	4	2	3

Table 4: Analysis of the data of various factors on the flow coefficient.

	R	α	L	B
K1	114.83	103.87	134.69	119.59
K2	118.1	113.77	126.58	121.89
K3	118.65	120.77	120.88	120.66
K4	120.04	129.53	114.82	123.1
K5	133.94	137.87	108.59	120.32
$\overline{K1}$	22.966	20.774	26.938	23.918
$\overline{K2}$	23.62	22.754	25.316	24.378
$\overline{K3}$	23.73	24.154	24.176	24.132
$\overline{K4}$	24.008	25.906	22.964	24.62
$\overline{K5}$	26.788	27.574	21.718	24.064
Range	3.822	6.8	5.22	0.702
Number	3	1	2	4

Table 5: Analysis of the effect of each factor on data of moment of inertia.

	R	α	L	B
K1	1099747.78	1137330.28	1043644.09	1097922.21
K2	1092623.57	1100739.59	1061864.94	1086940.91
K3	1080192.84	1074429.69	1084425.90	1101364.34
K4	1067317.12	1051767.59	1095140.74	1069777.47
K5	1057855.97	1033470.13	1112661.61	1063495.32
$\overline{K1}$	219949.556	227466.056	208728.818	219584.442
$\overline{K2}$	218524.714	220147.918	212372.988	217388.182
$\overline{K3}$	216038.568	214885.938	216885.180	220272.868
$\overline{K4}$	213463.424	210353.518	219028.148	213955.494
$\overline{K5}$	211571.194	206694.026	222532.322	212699.064
Range	8378.362	20772.03	13803.504	7573.804
Number	3	1	2	4

Table 6: The results of orthogonal test of comprehensive weighted score.

Num	Sum of squares of deviations (1×10^{-2})		Open degree of flow coefficient (m^3/h)		Moment of inertia ($g.mm^2$)		Comprehensive weighted score Y^*
	Numerical	The evaluation value	Numerical	The evaluation value	Numerical	The evaluation value	
1	2.96	88	21.97	66	227970.76	54	74.6
2	3.35	84	22.27	70	223011.57	70	77.0
3	3.54	74	23.06	76	219154.39	74	74.6
4	4.14	60	23.68	78	216063.86	78	69.0
5	4.84	56	23.85	80	213547.20	80	68.0
6	3.36	82	20.64	60	226488.37	60	71.0
7	2.80	90	22.89	74	221457.96	72	81.6
8	3.38	80	22.05	68	217671.44	76	75.6
9	3.77	66	22.30	72	223348.58	66	67.8
10	3.58	70	30.22	100	203657.22	92	83.4
11	3.67	68	20.01	52	226250.49	62	62.0
12	3.53	76	20.60	58	226547.75	58	67.0
13	3.55	72	20.97	62	223321.77	68	68.2
14	3.38	80	28.25	92	203277.52	96	86.8
15	3.00	86	28.82	98	200795.31	100	92.4
16	3.49	78	20.05	54	228782.81	52	65.6
17	3.67	68	20.27	56	224606.21	64	63.6
18	3.92	62	26.51	82	203622.49	94	74.4
19	3.84	64	26.67	86	200910.09	98	77.4
20	4.23	58	26.54	84	209395.52	84	71.0
21	2.60	92	21.20	64	227837.85	56	76.4
22	2.32	94	27.74	88	205116.10	90	91.4
23	1.72	98	28.18	90	210659.60	82	92.4
24	1.74	96	28.38	94	208167.54	86	93.4
25	1.29	100	28.44	96	206074.88	88	96.4

shows that the seventeenth group of synthetic weighted mark is the highest value. That is the best combination of structural parameters is the seventeenth group. Weighted score is 94.5 points. That is the radius = 3.4mm, the angle = 108.05°, length =14.07mm and width = 37.85mm were the best structural parameters.

RESEARCH ON THE FLOW CHARACTERISTICS OF DESULFURIZATION DUST REMOVAL VALVE

Let the grid model 100% valve imported into CFD software Fluent and carried on 10 times of flow field numerical simulation. Table 8 is the volume flow data which were obtained

Table 7: Complex optimization results.

Num	Name	The circular arc radius R (mm)	Angle α (o)	Length L(mm)	Width B (mm)	Dispersion flat and evaluation value	Full flow coefficient of evaluation value	The evaluation value of moment of inertia	Comprehensive weighted score Y*
1	note	2	80	15	38	80	60	60	70.0
2	note	2	110	13	36	65	100	85	79.5
3	note	2.5	100	13	37	70	80	90	77.0
4	note	2.5	110	14	38	75	95	100	86.0
5	note	3	100	14	39	60	65	95	68.5
6	note	3.5	80	13	39	85	70	80	79.5
7	note	3.5	90	14	35	95	75	65	83.0
8	note	3.5	100	15	36	90	85	70	84.5
9	note	3.5	110	16	37	100	90	75	92.0
10	shrink	2.92	98.45	14.08	37.75	85	85	90	86
11	shrink	2.70	94.09	14.3	37.26	80	90	95	86
12	shrink	2.91	99.25	13.94	37	85	95	90	89
13	shrink	2.9	100.18	14.04	36.9	90	85	85	87.5
14	shrink	3.22	92.6	13.88	37.67	95	90	90	92.5
15	shrink	3.16	97.52	14.29	36.56	85	90	95	88.5
16	shrink	3.1	100.21	14.45	37.02	80	95	100	88.5
17	shrink	3.4	108.05	14.07	37.85	100	95	80	94.5
18	shrink	3.07	99.89	14.31	37.27	95	85	90	91
19	shrink	3.03	98.98	14.35	37.19	90	85	85	87.5
20	reflect	3.4	103.26	14.73	37.45	95	85	90	91
21	reflect	3.39	103.48	14.56	37.25	95	85	90	91

Table 8: The relative opening degree of simulation forecast data.

Relative opening degree/%	Volume flow/(m^3/h)	flow coefficient/%	relative flow/%	relative coefficient of flow/%
10	0.39	0.39	1.89	1.89
20	1.44	1.44	6.99	6.99
30	1.52	1.52	7.38	7.38
40	1.62	1.62	7.86	7.86
50	2.39	2.39	11.60	11.60
60	4.07	4.07	19.76	19.76
70	6.70	6.70	32.52	32.52
80	12.62	12.62	61.26	61.26
90	16.83	16.83	81.70	81.70
100	20.60	20.60	100	100

from the valve under each opening degree in the numerical simulation.

For the control system of desulfurization and dust removal system, we hope that the regulating function is inhibited when load is small and the regulating action became strengthened while the load is heavy. This compensation depends on the valve flow characteristics and the equal percentage flow characteristic just has this effect. The equal percentage flow characteristics may also be referred to the number of flow characteristics. Setting boundary condition: $Q=Q_{min}$ while $l=0$; $Q=Q_{min}$ while $l=l_{max}$. The mathematical expression is:

$$\frac{d\frac{Q}{Q_{\max}}}{d\frac{l}{l_{\max}}}=k\frac{Q}{Q_{\max}} \qquad ...(2)$$

For the type (2), integral transform into the boundary conditions can be:

$$\ln\frac{Q}{Q_{\max}}=\left(\frac{l}{l_{\max}}-1\right)\ln\frac{Q_{\max}}{Q_{\min}} \qquad ...(3)$$

Making $\frac{Q_{\max}}{Q_{\min}} = R$, it can obtain:

$$\frac{Q}{Q_{\max}} = R^{\left(\frac{l}{l_{\max}}-1\right)} \qquad ...(4)$$

The valve body part is V type ball valve and in order to study the pros and cons of the flow characteristics of the valve, we plotted a tunable parameter as the ratio of R=30 equal percentage flow characteristic curve, as shown in Fig. 11. By using the forecast data of numerical simulation of valve CFD, we draw the flow characteristics of the ideal curve, as shown in Fig. 12. Relationship between pulse signal and valve stem stroke called displacement characteristics. Fig. 13 is the valve displacement characteristic curve. The relationship between the control signal and the flow is the static characteristics of the valve. Fig. 14 is the static characteristic of the valve curve. By comparing Figs. 11 and 12, we found that the trend of equal percentage flow characteristic curve and the valve flow characteristics of the ideal curve is consistent and the design of the valve has good equal percentage flow characteristic. As can be seen from Fig. 13 that there is a linear relationship between the number of pulses and valve displacement and it has good control performance. It can be seen from Fig. 14 that the relationship between the pulse number and volume flow meet with the valve flow characteristics of the ideal curve and it has good equal percentage flow characteristic.

CONCLUSIONS

(1) For the numerical simulation of flow field, the results show that the pressure on the front end of the valve is huge and the pressure on valve back is small. The outlet velocity of valve is larger.

(2) Design the L_{25} (5^6) orthogonal test table, selected the ideal valve of flow characteristics, the flow coefficient under maximum opening degree and spool inertia as its performance evaluation index. The influence factors on the valve flow characteristics of ideal size of the order is: radius R> length L> width B> angle α; the factors to influence the flow coefficient of valve in the fully open in size of the order is: angle > length L> radius R> width B; the influence of various factors on the valve core of the moment of inertia in the size of the order is: angle > length L> radius R> width B.

(3) To optimize the complex valve structure, we get the optimum combination of structural parameters: radius of 3.4mm, the angle of 108.05°, length of 14.07mm and width of 37.85mm.

(4) The author designed the valve which has good equal percentage flow characteristics and good control performance.

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