Characteristic Analysis and Experiment of a Dynamic Flow Balance Valve

Li Bin¹, Guo Song¹, Mao Xuyao¹, Wu Chao¹, Zhang Deman¹, Shang Jin¹ and Liu Yinshui²

¹Wuhan Second Ship Design and Research Institute, Wuhan, China
²Huazhong University of Science and Technology, Wuhan, China
libinizju@sina.com, guosongjie555@163.com, dreamforty@126.com, wuchaowhu@163.com, lin1985101@sina.com, shangkk0221@me.com, liuwater@tom.com

Abstract. Comprehensive characteristics of a dynamic flow balance valve of water system were analysed. The flow balance valve can change the drag efficient automatically according to the condition of system, and the effective control flowrate is constant in the range of job pressure. The structure of the flow balance valve was introduced, and the theoretical calculation formula for the variable opening of the valve core was derived. A rated pressure of 20kPa to 200kPa and a rated flowrate of 10m³/h were offered in the numerical work. Static and fluent CFX analyses show good behaviours: through the valve core structure optimization and improve design of the compressive spring, the dynamic flow balance valve can stabilize the flowrate of system evidently. And experiments show that the flow control accuracy is within 5%.

1. Introduction

The flow balance valve can change the drag efficient automatically according to the condition of system. Constant flowrate valve is one kind of these valves, and the effective control flowrate is constant in the range of job pressure. When the pressure difference between the valve inlet and outlet is changed, the valve is automatically closed or reduced to keep the flowrate constant [1-4]. The flow balance valve is widely used in pipe network system, which can solve the problem of hydraulic imbalance in the system.

Valve module, compressible spring, spool valve, check ring, valve body, valve bonnet were main component of the valve. Figure 1 illustrates the structural details of the valve. Water is corrosive. Corrosion was taken into consideration on component material selections. Major component materials are shown in Table 1.

Flowrate stability and vibration are admittedly issues for valve component and system development. The stability and precision of the traditional flow balance valve cannot meet the requirement of high precision flowrate control, and the valve core vibration problem is serious. The spool valve was the main factor affecting valve performance.

Numerical decompositions based on the physical structure of the valve were executed, mathematic model was established, and then simulation work was carried out. The results were pretty suggestive on optimal design and improvement of the dynamic flow balance valve.
2. Mathematic models

The following assumptions were made to simplify the mathematic model [5-8]. Figure 2 shows the lateral face flow area of the valve. Figure 3 shows the lateral face flow area was divided along the axis, $X_0=0$, $X_i=L_i/N$, $X_N=L$. $Y_0$, $Y_i$, $Y_N$ were the corresponding projection height.

Most of the variables and corresponding physical significances were also displayed.

- Flow medium was regarded as incompressible.
- The viscous friction and windage force of spool valve were ignored.
- Flow state was regarded as laminar.
- Outlet port pressure was negligibly small and set zero.
- Cavitation did not occur at the valve.
- Gravity was ignored.

1. Flowrate equation of concentric ring

$$q = \frac{u \Delta p}{8 \mu} \left[ (r_3^4 - r_1^4) + \frac{(r_3^2 - r_1^2)^2}{\ln r_3 / r_1} \right]$$

2. Force equation of spool valve
3. When the pressure difference between the two sides of the spool valve was increased by the minimum working pressure $p_1$ to the maximum working pressure $p_2$, the length of the compressible spring went from $X_0$ to $L+X_0$. Initial length equation of compressible spring

$$X_0 = \frac{\Delta p_1}{\Delta p_2 - \Delta p_1} \times L$$

(3)

4. Length equation of the lateral face

$$a = \frac{A}{i \times n}$$

(4)

5. Flowrate equation of the valve

$$Q = A \sqrt{\frac{2 \Delta p_1}{\rho} + \left(1 - \frac{n \times y_i}{2 \pi \times r_i} \right) \frac{B \times \Delta p_1}{x_i}}$$

(5)

6. Coefficient equation of $A$

$$A = C_1 \times \frac{\pi d^2}{4} + n \times C_2 \cdot A_i + n \times C_3 \cdot A_i$$

(6)

7. Coefficient equation of $B$

$$B = \frac{\pi}{8 \mu} \left[ \frac{(r_2^4 - r_1^4)}{\ln r_2 / r_1} \right]$$

(7)

8. Circulation area equation of spool valve

$$A_i = \frac{[Q \left(1 - \frac{n \times y_i}{2 \pi \times r_i} \right) \frac{B \times \Delta p_1}{x_i}] \sqrt{\frac{2 \Delta p_1}{\rho} - C_1 \times \frac{\pi d^2}{4} - n \times C_2 \cdot A_i}}{n \times C_2}$$

(8)

9. Pressure equation of spool valve

$$\Delta p = \frac{x_0 + x_i}{x_0} \times \Delta p_1$$

(9)

Where $C_1$ and $C_2$ were the flowrate coefficients of spool valve, $n$ was the number of the lateral face flow area, $D$ was the valve core dimensions, $d$ was the lateral face hole dimensions, $L$ was the stroke of the spool valve.

Eliminate the derivation items in the equations above, and then the corresponding projection height is able to be estimated as:

$$Y_i = \frac{(A_{i+1} - A_{i+1}) \times N}{2L}$$

(10)

3. Analysis

Simulation analysis was divided into two parts. One was the basic flowrate characteristics, and the other was flow field characteristics [9-10]. AMESim was adopted for the flowrate characteristics simulation (as seen in Figure 4).
3.1. Flowrate characteristic analysis

Flowrate stability was selected as representations of primary static and dynamic characteristics of the valve. A various pressure difference between the two sides of the spool valve from 20kPa to 200kPa was given as the original input, Figure 5–Figure 7 were different performances of flowrate when simulation conditions changed.

3.1.1. Influences by different stroke of spool valve

The rated different pressure $(\rho)$ was from 20kPa to 200kPa and the rated flowrate $(Q)$ was 10m$^3$/h. For better differential pressure flowrate characteristics, 18mm, 20mm, 22mm and 24mm were considered as the proper parameter of $X_n$.

The trends of flowrate $Q$ curves are almost consistent under different stroke of spool valve, but the maximum flowrate changes as the relative stroke of spool valve changes. That is, the larger the stroke of spool valve, the smaller the maximum flowrate value, the higher the valve stability. The maximum flowrate value is 10.73m$^3$/h when the stroke of spool valve is 18mm. The stroke 22mm and stroke 24mm curves are almost overlapping under different pressure $(\rho)$. As seen in Figure 5.

Consider the stability of valve and the influence on valve rigidity by different stroke of spool valve, on account of structural constraint and actual applications, 22mm is recommended to be set among 18mm–24mm. The maximum flowrate value is 10.35m$^3$/h when the stroke of spool valve is 22mm.

3.1.2. Influences by different area of spool valve

Figure 6 shows flowrate $(Q)$ under different lateral face flow area. For better differential pressure flowrate characteristics, 220mm$^2$, 250mm$^2$, 280mm$^2$ and 310mm$^2$ were considered as the proper parameter of the lateral face flow area $(A_0)$. The trends of all curves are similar. The maximum flowrate value is 10.55m$^3$/h and the minimum flowrate value is 9.61m$^3$/h when the lateral face flow area is 310mm$^2$. The valve stability is the worst. As seen, curve at 250mm$^2$ and 280mm$^2$ have good performance in flowrate stability.

On account of structural constraint and processing difficulty, 250mm$^2$ is recommended to be set among 220mm$^2$–310mm$^2$. The maximum flowrate value is 10.32m$^3$/h and the minimum flowrate value is 9.86m$^3$/h.

3.1.3. Influences by different stiffness coefficient of spring

Stiffness is the most important parameter of compressing spring. Figure 7 shows flowrate $(Q)$ under different stiffness coefficient of spring. Figure 7 indicates that the smaller the stiffness coefficient of spring, the higher the valve stability. As seen, stiffness coefficient of spring has little effect on flowrate stability. When stiffness coefficient of spring various from 5.5N/mm to 7N/mm, the three
curves are basically coincident. 6N/mm is recommended to be set among 5.5N/mm~7N/mm considering the size of valve module.

3.1.4. Design of spool valve curve
According to the above design, $X_n$ and $Y_n$ were identified. $X_i$ and $Y_i$ could be predicted from equation (10). Then the value of $X_i$ and $Y_i$ are obtained in Table 2.

| Parameters Value of number | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---------------------------|---|---|---|---|---|---|---|---|---|---|
| $X_i$ (mm)                | 10| 11| 12| 13| 14| 15| 16| 17| 18| 19.399 |
| $Y_i$ (mm)                | 3.477| 3.153| 2.876| 2.637| 2.439| 2.289| 2.200| 2.137| 2.090| 2.030 |

Fit the above data and get the curve of spool valve as shown in Figure 8 below.

![Figure 7](image7.png) **Figure 7.** Change of flowrate in different stiffness coefficient of spring.  
![Figure 8](image8.png) **Figure 8.** Curve of spool valve.

3.2. CFX Characteristic Analysis
Figure 9 and Figure 10 show the CFX flow field simulation model for the spool valve and valve body.

![Figure 9](image9.png) **Figure 9.** CFX simulation of spool valve.  
![Figure 10](image10.png) **Figure 10.** CFX simulation of valve.

3.2.1. Modal Analysis
Modal analysis of flow balance spool valve is carried out, and the first four mode modal vibration is shown in Figure 11. The result indicates that the spool valve has a higher frequency, which is different from the spring and the natural frequency of the system, tremor will not happen. It illustrates the spool valve has good stability.
3.2.2. Stress Analysis
Stress analysis is carried out under the maximum operating pressure of valve. Figure 12 shows that the import and export distribution is relatively uniform. The inlet has high pressure distribution. The maximum pressure occurs at the valve body inlet and spool valve throttling. After the spool valve, the fluid pressure distribution is uniform, and showing the gradual decrease of the trend. The pressure change is gentle; the purpose of steady flowrate is achievement.

3.2.3. Velocity Field Analysis
Velocity field analysis is carried out under the maximum operating pressure of valve. Figure 13 shows that the velocity field of valve is stable. The spool valve line has the maximum flow velocity. The velocity of valve is basically controlled below 2.588m/s, and the flow rate is recommended to the noise reduction requirements. The velocity field is stable without obvious fluctuation.

4. Experiment
Experiment system of dynamic balance valve consists of water tank, filter, pump, pressure sensor, flowmeter, ball valve, regulating valve, data processing center and so on[9], as seen in Figure 14.

In the range of work pressure, five typical different pressure (20kPa, 65kPa, 110kPa, 155kPa and 200kPa) and flowrate are selected for data recording in Table 3. During the test, valve air noise is highest at 56.7dB (A).

Figure 15 shows the comparison of simulation flowrate and test flowrate. The experimental results are consistent with the trend of simulation analysis. And experiments show that the flow control accuracy is within 5%.
Table 3. Table of experiment data.

| p (MPa) | 20  | 65  | 110 | 155 | 200 |
|---------|-----|-----|-----|-----|-----|
| Q (m³/h)| 9.93| 10.21| 10.10| 10.03| 10.08|

Figure 14. Experiment system of valve.

Figure 15. Comparison of simulation flowrate and test flowrate.

5. Appendices

Generally some understandings are obtained for designing of the dynamic flow balance valve.

- It is recommended to enlarge the stroke of spool valve and reduce the lateral face flow area.
- There exist local optimal solutions to the parameters of spool valve and springs for better characteristics of the valve. Oversize or undersize will deteriorate the behaviors of the valve.
- Choose small spring stiffness according to the valve size.
- The valve has a good flowrate stability (output flowrate variation under 5%) and small air noise.

Some experimental work was carried out and the conclusions above were well verified.

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