Research on the Flow Resistance Coefficient of a Multi-Hole, Secondary Pressure-Reducing Sleeve Valve

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Abstract

To solve the problem of valve noise, a multi-hole sleeve valve with secondary pressure-reducing function is presented in this paper. During the flow design of the valve, the flow resistance coefficient of the valve served as an important parameter. Because of two pressure-reducing components assembled to a multi-hole sleeve valve, the flow resistance coefficient of the valve changed. Thus, correction of the flow resistance coefficient had to be affected. In this paper, the relationship between the flow rate and flow resistance coefficient of the valve was first mapped and established. Then, the flow rate of the sleeve was obtained using SolidWorks simulation software. Locally refined finite element mesh technology was applied to the simulation to improve simulation accuracy. A parallel flow test platform for the regulating valve was established, and the flow rate of the multi-hole sleeve valve was detected at different openings, thus, verifying the reliability of the numerical simulation results. Finally, the simulation flow rate of the valve at different openings was substituted into the mapping relationship formula, in this way, the flow resistance coefficient of the sleeve valve was obtained. By using the modified flow resistance coefficient, the flow rate characteristics of the multi-hole, secondary pressure-reducing sleeve valve were efficiently and accurately established.

1 Introduction

A regulating valve is a control composite that assists in controlling the flow rate, throttling, and stabilizing pressure in a control system[1−3]. In recent years, alongside the development of science and technology, the requirements for the performance of regulating valves have also continuously improved. Environmental protection requirements, particularly reducing noise pollution of the regulating system, have also been put forward. When fluid flows through the throttle hole of the regulating valve, as the flow area decreases, the flow velocity increases, and the pressure difference between the two sides of the throttle holes rises. This can cause significant noise and effect damage to control equipment[4−5].

The sleeve valve[6−7] is a specially structured regulating valve. The valve plug moves up and down in a cylindrical sleeve to change the flow area, thereby controlling the flow rate of the valve. To control and reduce pressure difference and noise, the throttle holes of sleeve valves have been designed as the labyrinth [8−9], window[10] and multi-hole types[11]. However, the labyrinth throttle hole type significantly restricts flow rate. The window-type sleeve valve has a poor noise reduction ability. In this paper, a multi-hole sleeve valve with a secondary pressure-reducing function is presented. A set of pressure-reducing components were assembled inside and external to the throttle holes, respectively, so that it had low noise, good dynamic stability, and other advantages. However, when we designed the flow characteristics of the valve, the flow channel and the pressure-reduction components had a significant impact on the flow resistance coefficient. A large error occurred when we employed a traditional flow resistance coefficient to calculate the flow rate at different openings. However, calculating using the finite element method, or simulation method, can be very complex. Additionally, each simulation required significant time to complete and hardware with powerful computational capabilities. As such, it was necessary to establish an efficient theoretical method to design the flow rate of the multi-hole, secondary pressure-reducing sleeve valve. In the theoretical calculation process, the flow resistance coefficient of the valve directly affected the calculation accuracy.

Accordingly, in this paper, the flow rate of the valve at each opening was obtained by numerical simulation. The simulation results were verified using a flow rate test. Then, the simulation flow rate was substituted into the mapping relationship equation between the flow rate and the flow resistance coefficient of the valve. In this manner, the flow resistance coefficient of the sleeve valve was obtained. The modified flow resistance coefficient can be used to design this type of valve with different flow and diameter characteristics.

2 Structural Description Of The Multi-hole, Secondary Pressure-reducing Sleeve Valve

The structure of the multi-hole secondary pressure-reducing sleeve valve is shown in Fig. 1.

1- the valve body, 2- the valve seat with noise reduction cage, 3- external noise reduction cage, 4- multi-hole sleeve

5- pressure cage, 6- valve plug, 7- valve rod, 8- bonnet.

It included eight major components: the valve body, the valve seat with noise reduction cage, external noise reduction cage, multi-hole sleeve, pressure cage, valve plug, valve rod, and a bonnet. The outer surface of the valve plug and the inner surface of the multi-hole sleeve represented fitted surfaces. Under the action of the external actuator, the valve rod was able to drive the valve plug to move up and down, in this manner, the throttle holes on the multi-hole sleeve were exposed to form an effective fluid area. The size and layout of these holes were able to realize the different flow characteristics of the regulating valve. When the pressure difference between the two sides of the throttle holes was large, flash evaporation and cavitation could occur[12–13], giving rise to significant noise and vibration. To reduce the valve noise, a valve seat with a noise reduction cage and an external noise reduction cage was assembled on both sides of the multi-hole sleeve.

3 Flow Calculation Of The Multi-hole, Secondary Pressure-reducing Sleeve Valve

The flow rate through the throttle holes was calculated according to hydromechanics. Based on the thickness of the sleeve, the throttle holes on the multi-hole sleeve were typically thin-walled. These thin-walled holes were short with minimal frictional resistance. The flow rate was minimally affected by temperature and viscosity changes and, as such, was relatively stable.

The ideal fluid passed through a thin-walled hole, as shown in Figure 2.

First, we assumed that fluid energy loss had been ignored when the fluid passed through the flow channel. According to the law of the conservation of energy, the total energy of the fluid at the inlet of the valve was equal to the total energy of the fluid at the outlet. In the cross-sections □ and □, according to the Bernoulli equation, the energy of the fluid can be expressed as follows:

$$\frac{p_1}{\rho g}+\frac{\alpha_1 v_1^2}{2g}+h_1=h_2+\frac{p_2}{\rho g}+\frac{\alpha_2 v_2^2}{2g}+\xi\frac{v_c^2}{2g}$$

1

where the pressure difference of the fluid in cross-sections □ and □: $\Delta p = p_1 - p_2$;

p_1, p_2 is fluid pressure in the cross-sections□and □, respectively;

h_1, h_2 is the potential energy of the fluid in cross-sections □ and □, respectively;

v_1, v_2 is the flow velocity of the fluid passing through cross-sections □ and □, respectively;

ρ is the density of fluid;

ξ is the flow resistance coefficient;

a_1, a_2 is the kinetic energy correction coefficient in cross-sections □ and □, respectively;

The diameter of cross-sections □ and □ is d; the diameter of the contraction section of the thin-walled hole is d_0. Owing to $d \gg d_0$, thus, $v_1 \approx 0$. When the fluid flowed through the contraction section of the thin-walled hole, the flow velocity was uniform, thus, $a_1 = a_2 = 1$, and the fluid potential energy in cross-sections □ and □ was equal, i.e., $h_1 = h_2$.

According to Eq. (1), the flow velocity of the fluid flowing through cross-section □ was obtained as follows:

$$v_2=\frac{1}{\sqrt{\xi}}\sqrt{\frac{2\Delta p}{\rho}}$$

2

The sectional area of the thin-walled hole is A_e, and the sectional area of cross-sections□and□ is A. According to Eq. (2), the flow rate of the fluid passing through the hole was obtained as follows:

$$q_v=A_e v_2=\frac{A_e}{\sqrt{\xi}}\sqrt{\frac{2\Delta p}{\rho}}$$

Equation (3) shows the flow rate of the fluid through the sleeve valve was closely related to density ρ of the fluid, effective flow area A_e, pressure difference Δp, and flow resistance coefficient ξ.

When the fluid flowed through the valve seat with the noise reduction cage, the external noise reduction cage, and the throttle hole of the multi-hole sleeve, their combined multi-hole structure caused part of the energy to be lost and reduced fluid pressure, changing the flow resistance coefficient. Accordingly, a large error will be observed when using traditional flow resistance coefficient ξ to calculate the flow rate of the valve, which must be corrected.

4 Flow Simulation Of The Multi-hole, Secondary Pressure-reducing Sleeve Valve

4.1 Establishing the simulation model

Prior to the flow simulation calculation, a virtual simulation model of the multi-hole, secondary pressure-reducing sleeve valve was created using SolidWorks software (2016), as shown in Fig. 2. The nominal diameter of the valve was 80 mm.

Same-stepped holes were equally distributed around the valve seat and were also equally distributed on the external noise reduction cage. These small holes were prevent flash evaporation and cavitation, and could effectively reduce the pressure and noise caused by the fluid. The flow area of these holes had be 5% larger than that of the throttle holes when the sleeve valve was fully open. This enabled them to reduce pressure and noise caused by the fluid to a satisfactory degree, without affecting the flow rate of the sleeve valve.

1- the valve body, 2- the valve seat with noise reduction cage, 3- external noise reduction cage, 4- multi-hole sleeve

5- pressure cage, 6- valve plug, 7- valve rod, 8- bonnet.

4.2 Finite element mesh

The SolidWorks flow Simulation module was used to set the global finite element mesh to the highest level, as shown in Fig. 3.

4.3 Boundary conditions and simulation settings

Based on the definition of flow capacity Kv of the regulating valve[14–16], the simulation boundary conditions were set. When the regulating valve was fully opened, pressure difference Δp at the inlet and outlet of the valve was 100 KPa, and the fluid density was 1000 kg/m^3 (room temperature water); flow capacity Kv was the flow rate of fluid that passed through the valve in 1 h. The pressure at the inlet of the valve was set to 201,325 Pa, the pressure at the outlet was 101,325 Pa, and the roughness of the inside surface of the valve body was *Ra*25. The insertion target was the volume flow rate through the cross-section of the valve outlet.

4.4 The flow rate simulation analysis

The above model was used to simulate the multi-hole, secondary pressure-reducing sleeve valve. Its flow capacity was $Kv = 38.06$. The maximum stroke of the valve plug was 38 mm. The model of the valve that conformed to linear flow characteristics was tested in the simulation.

4.4.1 Static pressure distribution of the fluid inside the valve. When the valve was fully opened, the static pressure distribution cloud diagram of the internal fluid on the symmetrical section was obtained, as shown in Fig. 4.

4.4.2 Flow rate simulation of the valve. The volume flow at the outlet of the valve was monitored. Following the iterative calculation, the volume flow rate at an opening ranging from 10–100% was obtained.

The simulation flow rate was compared with the theoretical standard flow rate, which met the standard linear flow characteristics. The curve subsequently obtained is shown in Fig. 5.

The maximum error occurred at an opening of 10%, the error value was 5.55%, and the minimum error occurred at an opening of 100%. At 90% and 100% openings, the flow rate of the valve was lower than the standard value, the flow of other openings was slightly larger than the standard value. The software simulation method was used to effectively verify whether the flow rate of the valve met the specified flow characteristics. However, following the mesh refinement, the number of finite element meshes increased sharply, and each calculation required an extended period to finish iteration prior to achieving convergence. Concurrently, hardware support with powerful computing capabilities was required. As such, using software simulations to design the valve flow rate presented some limitations.

5 Test Analysis Of The Multi-hole, Secondary Pressure-reducing Sleeve Valve

5.1 Introduction to the test system

1. 1. backwater pipe; 2. electric pressure control valve; 3. manual ball valve; 4. test point of regulating valve;
2. 5. pressure gauge; 6.electromagnetic flowmeter; 7. diverging pipeline; 8. surge tank; 9. expansion joint;
3. 10. pipeline pump; 11. diverging pipeline;12. water storage tank

To test whether the regulating valve met the rated flow characteristics[17–18], a parallel flow rate test system with recyclable fluid equipment was designed, as shown in Fig. 6. The system comprised a water storage tank, parallel multi-stage pump, a surge tank, parallel test area, and a backwater pipe. The parallel test area comprised multiple test pipelines connected in parallel, which were able to test the regulating valves with nominal diameter, ranging from DN15 to DN450. When a pipeline was active, the manual ball valves (3) at both ends of the remaining pipelines were closed. During the test, the regulating valve was connected to the position indicated by 4 in Fig. 6. The pressure gauges (5) were set at the inlet and outlet of the tested regulating valve, and the data were transmitted to the computer. The computer controlled the pipeline pump (10) through the inverter to adjust the water pressure. If a greater pressure was required, several pipeline pumps could function simultaneously in parallel, as shown in Fig. 7. The electric pressure control valve (2) was set at both sides of the tested regulating valve to regulate the pressure at the inlet and outlet of the valve.

When the pressure difference met the requirements, the flow rate at different openings of the tested valve could be read from the electromagnetic flowmeter. The fluid of each test line was sent back to the water storage tank through the return pipe.

5.2 Test data analysis

The tested multi-hole, secondary pressure-reducing sleeve valve had the same parameters as the simulation model. The pressure difference between the inlet and outlet of the valve was 100 KPa. The flow rate of each opening from 10–100% was observed from the electromagnetic flowmeter, as shown in Table 1.

Table 1
Test flow rate at different opening

i %	q_v m^3/h	i %	q_v m^3/h
10	4.30	60	25.07
20	8.48	70	29.84
30	13.25	80	33.27
40	16.75	90	36.50
50	20.60	100	39.57

Table 1 shows that the flow characteristics of the multi-hole, secondary pressure-reducing sleeve valve essentially conformed to its linear characteristics. When the valve was fully open, the flow rate was 39.57 m^3/h, and its Kv was 39.57, which was slightly higher than the rated flow rate of $Kv = 38.06$; the error was 4.30%. The flow rate obtained from the test was compared with the flow rate of standard linear flow, and with the simulation flow rate, as shown in Fig. 8.

6 Correction Of The Flow Resistance Coefficient

According to Eq. (3), the following equation was obtained:

4

$$\xi_i = \frac{2\Delta p A_{ei}^2}{\rho q_{vi}^2} \qquad (i=1\sim10)$$

where ξ_i is the flow resistance coefficient of each opening;

q_{vi} is the flow rate of each opening;

A_{ei} is the flow area of the throttle holes of each opening.

i is the opening, i.e., i = 1 to 10.

The pressure difference at the inlet and outlet of the valve can be given as Δp = 100 KPa, and the fluid density as ρ = 1000 kg/m^3 (room temperature water). According to Eq. (4), q_{vi}, A_{ei}, and ξ_i of the multi-hole, secondary pressure-reducing sleeve valve at different openings could be calculated, as shown in Table 2.

Table 2
Numerical examples of different openings

i	q_v	A_e	ξ_i	i	q_v	A_e	ξ_i
%	**m^3/h**	***10^{-4}m^3**		**%**	**m^3/h**	***10^{-4}m^3**	
10	4.74	1.81	3.78	60	23.31	6.70	2.14
20	8.28	2.41	2.20	70	27.25	7.81	2.13
30	12.39	3.57	2.15	80	30.78	8.80	2.12
40	15.84	4.61	2.20	90	34.20	9.92	2.18
50	19.52	5.58	2.12	100	37.94	11.05	2.20

Table 2 indicates that at openings of 20–100%, the flow resistance coefficient value ξ of the multi-hole, secondary pressure-reducing sleeve valve was roughly 2.2. At a 10% opening, the value of the flow resistance coefficient ξ was 3.78. Both the simulation results and test data reflected that the flow resistance coefficient was larger and the flow rate smaller. Therefore, based on current study, the value of the flow resistance coefficient ξ of the multi-hole, secondary pressure-reducing sleeve valve was determined as a constant value, i.e., 2.2. When we designed the flow rate of the valve, to avoid the flow rate at a 10% opening from being insufficient, the flow resistance coefficient could be increased 1.5 times, that is, this could be achieved by increasing the flow area. According to the above research, as long as the effective fluid area of the throttle holes was known, a multi-hole, secondary pressure-reducing sleeve valve conforming to different flow characteristics and different C_V values could be obtained.

7 Conclusions

(1) It is concluded that the flow resistance coefficient of the valve was 3.3 at a 10% opening, and 2.2 at an opening ranging 20–100%. By using the modified flow resistance coefficient, the multi-hole, secondary pressure-reducing sleeve valve could be designed more efficiently.

(2) Using the mesh refinement technology of the local space virtual model, the simulation of the flow rate of the multi-hole, secondary pressure-reducing sleeve valve was performed. Experiments verified that the error of the simulation results was within the allowable range. The simulation flow rates were also concluded as being reliable.

(3) A parallel flow rate test system with recyclable fluid equipment was designed. The system was able to test the flow rate of the regulating valves with different specifications. The ideal differential pressure data could be adjusted quickly during the test, and the test results were subsequently more reliable.

Declarations

Availability of data and materials

All data, models are available from the corresponding author by request.

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Authors' Contributions

Dong-tao Xu and Chang-rong Ge conceived, designed the study and. Xiang-rui Meng and Shu-fang Xu did flow simulation analysis. Dong-tao Xu and Xiao-guang Yu performed the experiments. Dong-tao Xu and Chang-rong Ge wrote the paper. Xiang-rui Meng and Shu-fang Xu reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Competing Interests

The authors declare no competing financial interests.

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Figures

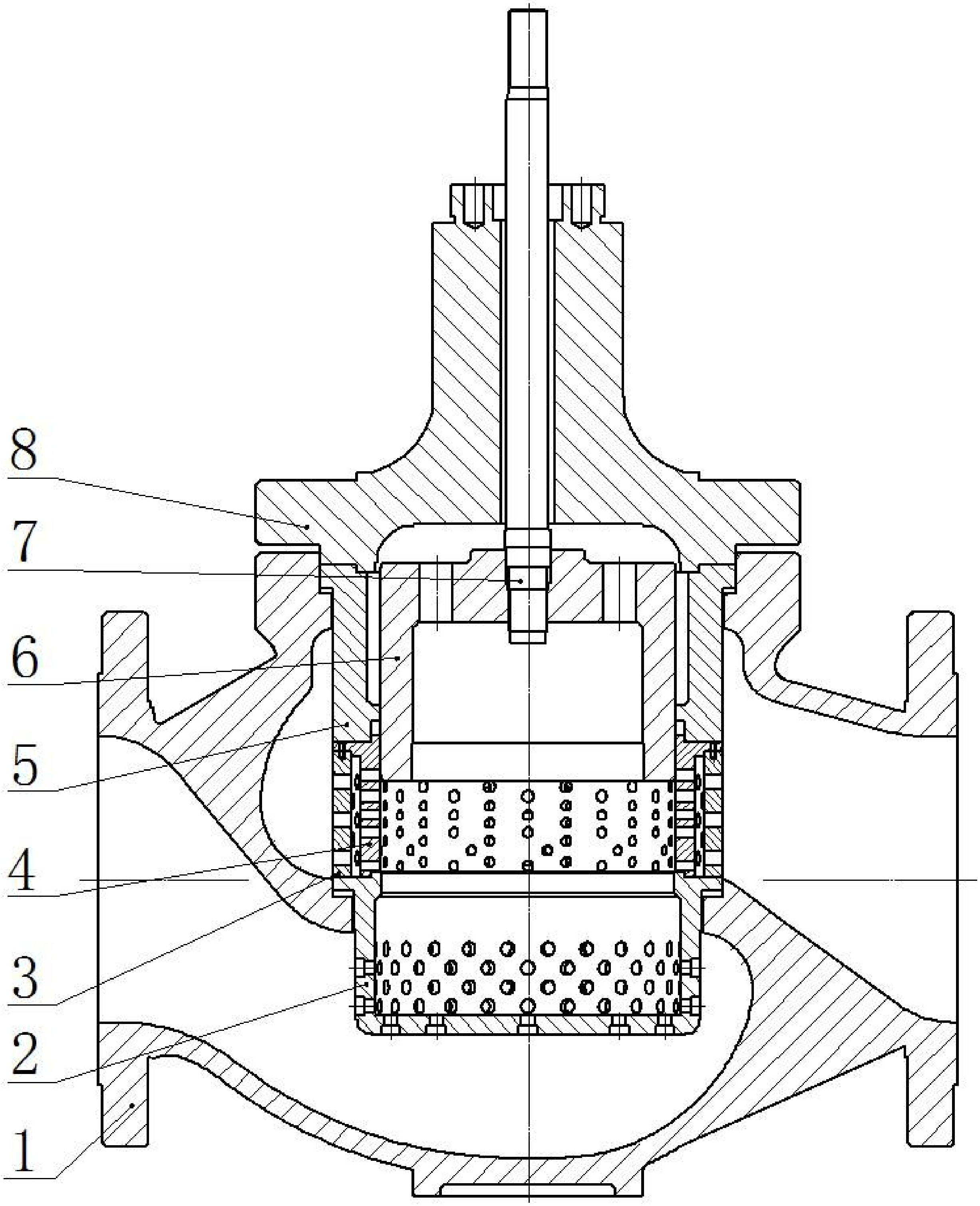

Figure 1

Figure 1. Multi-hole, secondary pressure-reducing sleeve valve 1- the valve body, 2- the valve seat with noise reduction cage, 3- external noise reduction cage, 4- multi-hole sleeve 5- pressure cage, 6- valve plug, 7- valve rod, 8- bonnet.

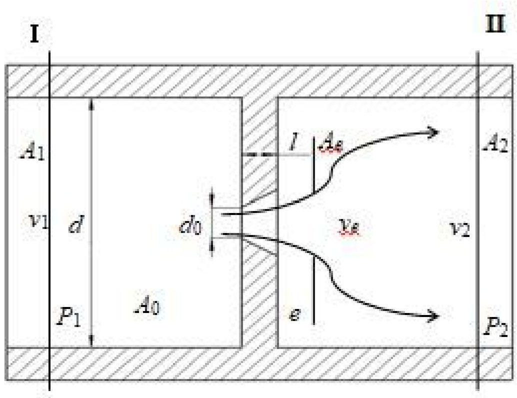

Figure 2

Fluid passing through thin-walled hole

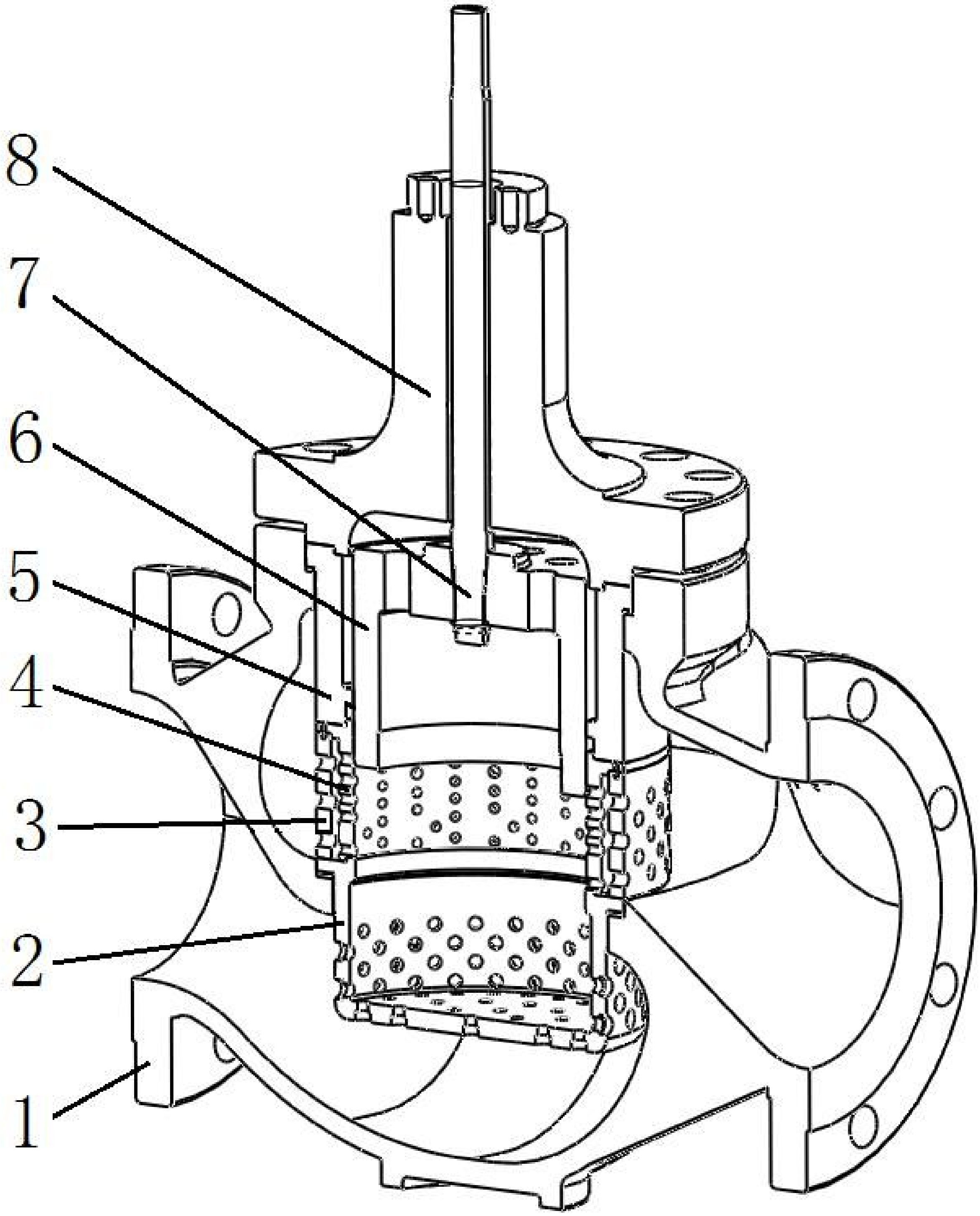

Figure 3

Simulation model of the multi-hole, secondary pressure-reducing sleeve valve 1- the valve body, 2- the valve seat with noise reduction cage, 3- external noise reduction cage, 4- multi-hole sleeve 5- pressure cage, 6- valve plug, 7- valve rod, 8- bonnet.

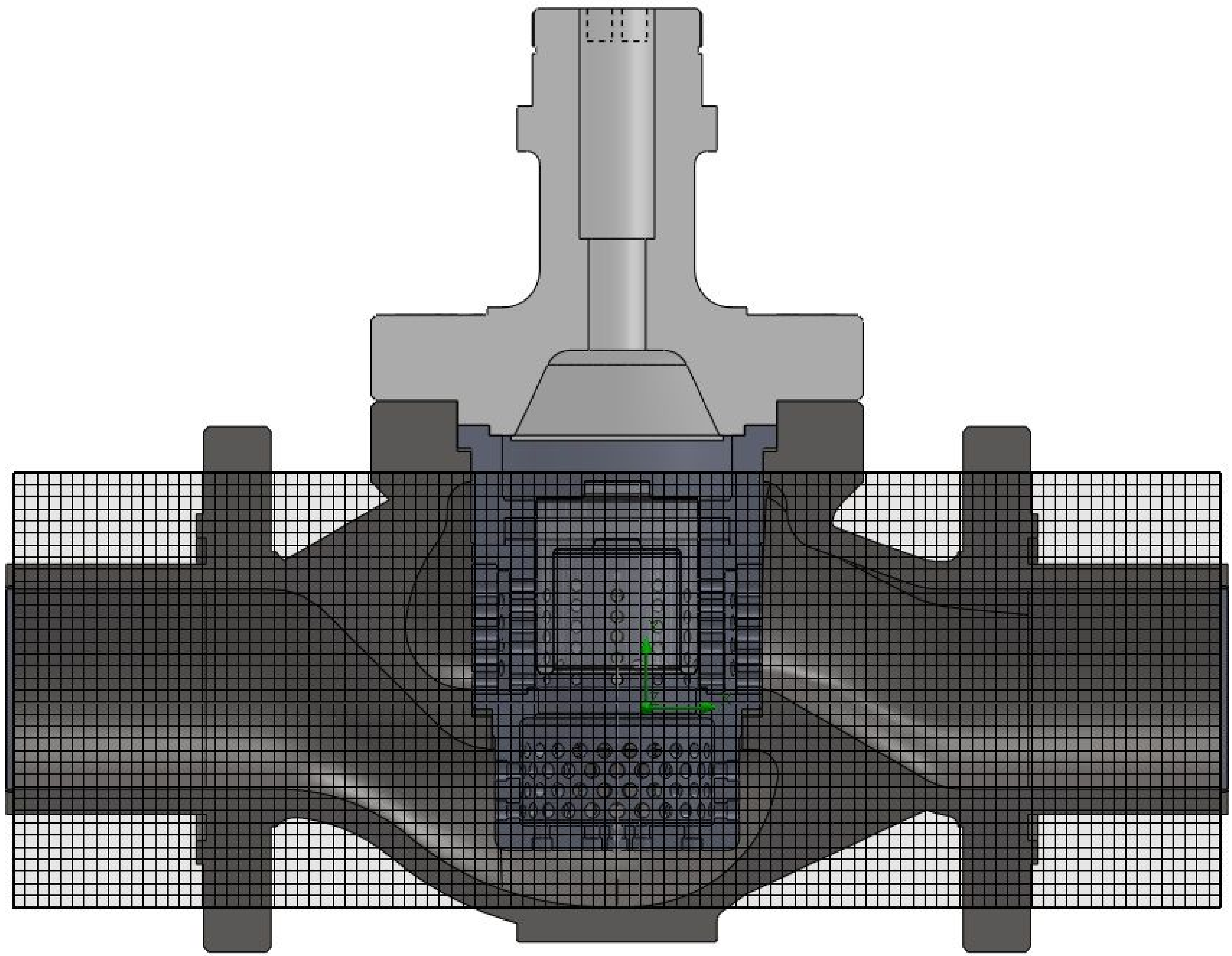

Figure 4

Finite element mesh of the model

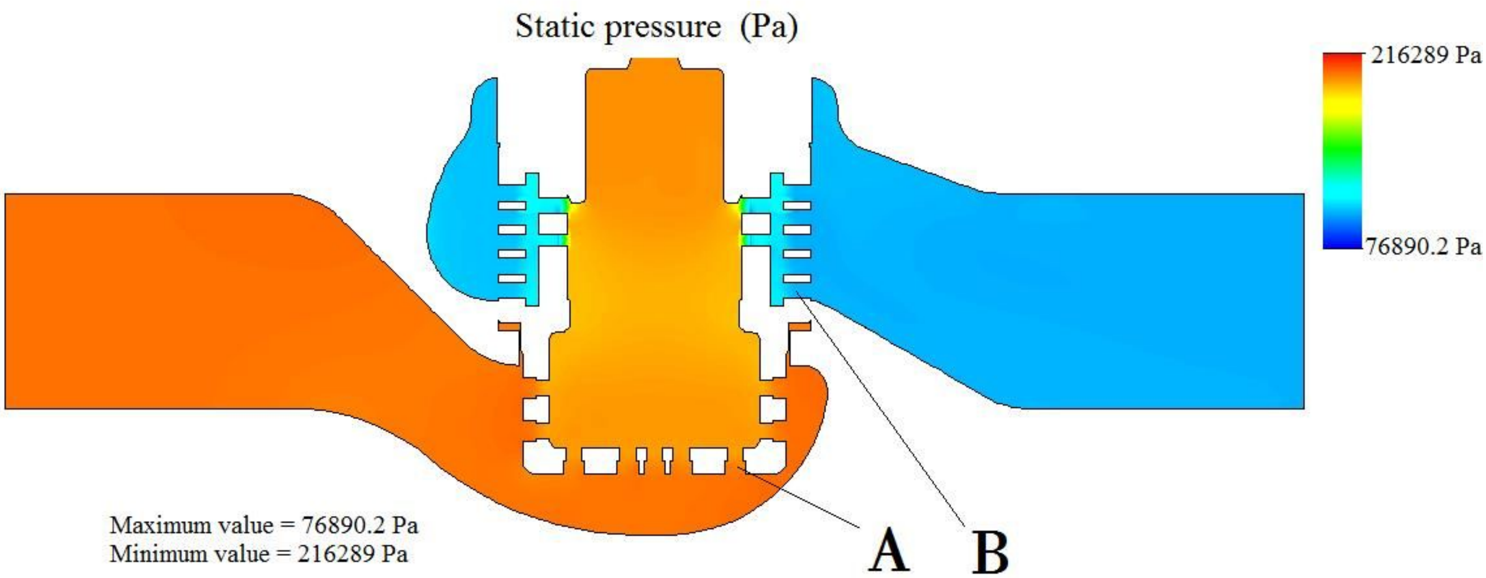

Figure 5

Cloud diagram of static pressure distribution

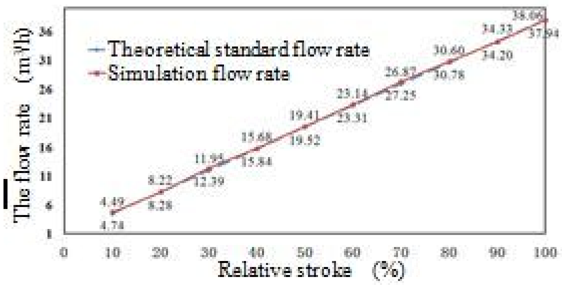

Figure 6

Comparison of simulated flow rate with standard data

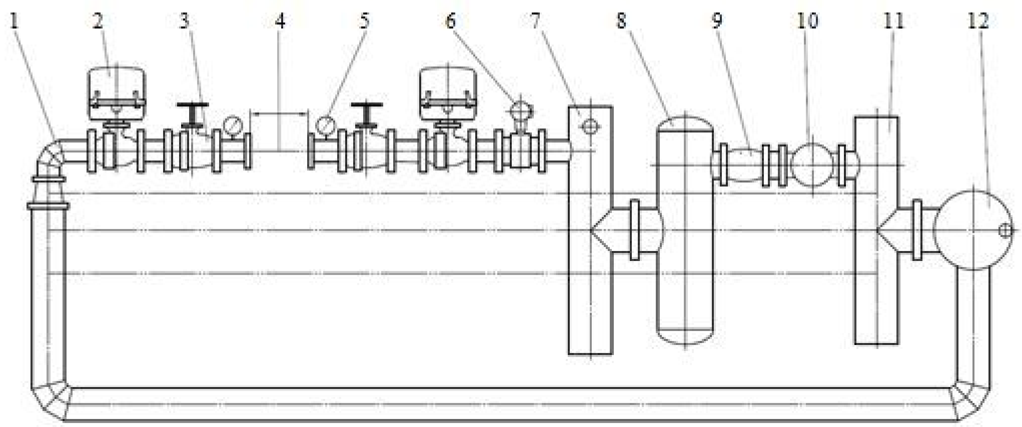

Figure 7

Regulating valve flow test system 1. backwater pipe; 2. electric pressure control valve; 3. manual ball valve; 4. test point of regulating valve; 5. pressure gauge; 6.electromagnetic flowmeter; 7. diverging pipeline; 8. surge tank; 9. expansion joint; 10. pipeline pump; 11. diverging pipeline;12. water storage tank

Figure 8

Pipeline pumps in parallel

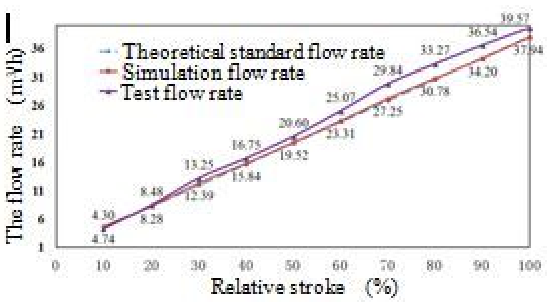

Figure 9

Comparison of the test flow rate with theoretical standard flow rate and simulation flow rate