Numerical simulation and experimental analysis of labyrinth valve flow characteristics based on CFX

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Abstract. Focused on a particular type of labyrinth regulating valve, with its three-dimensional solid model solid works established its internal flow model as the research object. Divided and generate computational grid by pre-processing software Gambit. Application method CFX internal fluid flow control valve characteristics simulation, the valve flow characteristics of flow field visualization results. According to the simulation results analysis labyrinth valve flow characteristics of the internal flow field obtained under different openings in the spool of the valve flow characteristic curve and the same ideal opening under pressure and quality of the relationship between the flow curves for the new follow-up study valves. It was shown by the comparison of the simulation data to those of experimental measurement that the former was well consistent with the latter, providing a basis for further optimization and design of the control valves.

Keywords. Numerical simulation; minimum flow regulating valve; internal flow field; flow characteristics; flow capacity

1. Introduction
Labyrinth valve is a high temperature and high pressure regulator and is widely used under severe operating conditions for example, nuclear power, petrochemical, metallurgy industries [1, 2]. In order to prevent and solve cavitation, vibration and noise, labyrinth valve core is usually adopted multilevel structure. Under the condition of high temperature and high pressure, the multilevel structure can reduce the fluid pressure gradually and no cavitation producing. When the labyrinth valve is closed, it can be able to withstand static pressure up to 56 MPa or higher.

There are many studies about engineering application of labyrinth valve. For example, Jin Duowen [3] introduced the selection and calculation methods of labyrinth valve used in power plants. Tao Zhengliang et al [4] analyzed the relationship between flow characteristic and control performance of control valve in power station using three-dimensional numerical simulation and experimental analysis method. Gilaad et al [5] studied the throttle area, shape and flow direction of labyrinth valve, and finally the results show that the main form of labyrinth channel energy dissipation was the local loss of water head caused by changes in the shape of the throttle section and medium flow direction. In
addition, many domestic and foreign scholars established different mathematical models to study the flow characteristics of valves [6-12].

In the paper, the numerical calculation of internal flow passage of a certain type of labyrinth valve is conducted under different openings from 10% to 100%. Through the comparative analysis of the calculated results and the experimental results and can be considered as the reference to optimize and design that kind of valve.

2. Methodology

2.1. Labyrinth valve internal flow field model

In the study, the labyrinth valve Nominal Diameter is 25 mm, Nominal Pressure is ANSI2500 (42MPa). In working condition, the fluid flows in from the side and out from the bottom. The rate of flow is regulated by changing the flow area of fluid through the sleeve could also be changed to regulate the flow. According to the three-dimensional modelling software Solidworks and the geometry size and assembly relationships among valve parts, the internal structure of the valve is shown in figure 1. The flow passages at different openings are extracted by the combination and then are distinguished. The solid model of the flow passage with 100% opening is selected as a typical example in figure 2.

![Figure 1. The internal structure of valve.](image1)

![Figure 2. Schematic diagram of flow passage of control valve with 100% opening.](image2)

One hand for this paper mainly studies the internal flow field and characteristics of valve, the core components of which are the sleeve parts, on the other hand in order to simplify the mesh generation
and reduce the required memory of computer computing, and simplify the flow passage of it to do some research on flow characteristics just like figure 3.

**Figure 3.** The simplified schematic diagram of flow passage with 100% opening.

2.2. **Grid dividing**
The above simplified three-dimensional geometric solid model was imported into the pre-processing grid division software Gambit to determine computational domain, symmetrical plane, inlet boundary and outlet boundary by unstructured grid dividing, in the process of which, the mixed hexahedron grid was adopted in the grid dividing of flow passage. When the grid space was set to 0.75, the number of grids was 2567602. The Schematic diagram of grid dividing of flow passage with 100% opening is in figure 4. The boundary conditions of inlet and outlet are respectively set to be the inlet flow rate and the pressure outlet. When performing the same grid partitioning for different openings (a total of ten), the mesh files under different openings will be obtained.

**Figure 4.** Schematic diagram of grid dividing for complete flow passage in control valve.

3. **Comparison of numerical simulation results and experimental results**
After the mesh files exported by pre-processing software are read in CFX-Pre, set fluid property as water and set the symmetrical plane and the boundary conditions of inlet and outlet pressure, and then initialize the flow field, set control parameters, define the number of iterations and set the location of destination files to export. Operate on CFX-Solver Manager and calculate later. Finally check the result on CFD-Post.

3.1. **Flow field simulation at 100% opening**
The numerical calculation was performed under the boundary condition that the mass flow rates of inlet and outlet were set to 3.75 kg/s and the outlet static pressure was set to 1 MPa. The pressure nephogram of the entire flow model, the velocity contour plot of the flow model XY plane and XZ plane and the velocity vectors of XY plane and XZ plane are taken out for analysis.

- The entire internal flow field.
Figure 5. The pressure nephogram of flow model.

Figure 6. The flow velocity contour plot of the model.

- Distribution in XY plane.

Figure 7. Cloud-chart of pressure in XY plane.

Figure 8. The velocity contour plot in XY plane.
• Distribution in XZ plane.

**Figure 9.** Cloud-chart of pressure in XZ plane.

**Figure 10.** The velocity contour plot in XZ plane.

The velocity vectors of XY and XZ plane is respectively in figure 11 and figure 12.

**Figure 11.** Velocity vectors of XY plane.

**Figure 12.** Velocity vectors of XZ plane.
It can be seen from the pressure nephogram of figure 5, figure 7 and figure 9 that the inlet pressure and outlet pressure are evenly distributed, approximately 1.76706 MPa and 1 MPa respectively, while the pressure differential between them is relatively large, and that the pressure drop in front and rear of the valve is mainly used for overcoming the resistance of the flow passage, particularly that from the throttling element installed on the sleeve parts. In addition, it is obvious from the cloud-chart of pressure in XY plane and XZ plane that the pressure is progressively reduced in the throttling element, in particular, the pressure drop in the first stage is the most and decreases gradually.

It can be seen from the velocity contour plot of figure 6, figure 8 and figure 10 that the inlet velocity and outlet velocity are also evenly distributed, in which the inlet velocity is 6.304 m/s and the outlet velocity is 8.259 m/s. The inlet velocity fluctuates slightly mainly because the computational domain selected at the entrance of the pipe was too short so that the fluid medium rebounded with backflow and a few vortexes after hitting the sleeve wall, however, the distribution is relatively stable to the whole. The outlet velocity is higher than the inlet velocity due to the inconsistency of the diameter of the inlet and outlet pipelines. According to the continuity equation, the velocity increases correspondingly as the flow area at the throttling element decreases rapidly. When the maximum velocity reaches 23.797 m/s, the pressure will decrease rapidly with it.

From the velocity vectors of figure 11 and figure 12, the fluid medium first flows separately and then becomes a confluence in the orifice of the throttling element, and the energy is consumed by repeated collisions to achieve a gradual reduction in pressure. However, the erosion to the throttling element is very severe from the figure above, not only because the fluid medium swirls in the orifice, but also due to the large pressure. Therefore, the requirements to the material of the throttling element are relatively high. In addition, the velocity beneath the entrance is relatively high from the velocity vectors of XY plane while the velocities of both the entrance and the exit are also really high from the velocity vectors of XZ plane, that is to say, the erosion to the sleeve parts close to the fluid entrance is also very serious.

The flow rate for 100% opening was numerically calculated in the same way and process except the only changed inlet flow rate. A total of three simulations were conducted to obtain the flow coefficient value $C_v$ at 100% opening respectively, its formula is $C_v = \frac{Q}{P_{\Delta}}$, where $Q$ is the volume flow rate, its unit is $m^3/h$, $P_{\Delta}$ is the pressure differential between the front and rear of the valve, its unit is bar. $10^5$ pa. The average of the three was taken as the final flow coefficient value under this opening. The results of the flow coefficient values calculated after the unification of units are shown in table 1.

### Table 1. Results of numerically simulated and computed flow rates for 100% opening.

| Opening (%) | Inlet flow rates (kg/s) | Export static pressure (100KPa) | The pressure differential between the front and rear (100KPa) | $C_v$ value of flow coefficient |
|-------------|-------------------------|--------------------------------|-------------------------------------------------------------|-------------------------------|
| 100         | 3.25                    | 10                             | 0.593                                                       | 0.286                         |
| 100         | 3.75                    | 10                             | 0.796                                                       | 0.067                         |
| 100         | 4.25                    | 10                             | 0.439                                                       | 1.667                         |

The flow coefficient is averaged

The same simulation method was used to simulate the flow rates under different openings for three times and the averages were finally obtained. The summary results of that are shown in table 2.
3.2. The analysis of pressure drop vs flow rate
The relation curves between pressure drop and flow rate have been plotted by means of the simulation and calculation of different inlet flow rates, varying pressure differential between the valve front and rear as well as the flow coefficient. The values of simulation for different openings from 10% to 100% are obtained to plot the curves of pressure drop and flow rate as shown in figure 13.

The following points can be seen clearly from figure 13:

- In the case of the same inlet mass flow rate, the pressure differential of the valve will decrease as the opening increases. Specifically, the flow area will increase as the opening increases, while the pressure drop decreases in presence of the constant flow rate.
- At the same opening, the larger the flow rate is, the greater the pressure differential between the inlet and outlet of the valve will be.
- When given the same pressure differential, the larger the opening is, the greater the flow rate of the valve will be.
- The pressure differential of the valve is relatively large in a small opening, however, it will decrease with the increasing opening and tend to be stable. When the opening is above 80%, it almost coincides.

![Figure 13. Curves of pressure drop vs flow rate for differently openings.](image)

3.3. Experimental investigation for different openings
Through working with the cooperative unit, the test of the flow characteristics of the modeled valve has been conducted in your high pressure laboratory, and the schematic diagram of test rig is depicted in figure 14.

![Figure 14. Schematic diagram of test rig.](image)
1. booster pump; 2. sluice valve; 3. water-storage tank; 4. pressure gauge; 5. flow meter; 6. test valve; 7. pressure circulation pump

Table 2. Simulation result for different openings.

| Opening (%) | Inlet flow rates (kg/s) | Export static pressure (100KPa) | The pressure differential between the front and rear (100KPa) | Outlet flow rates (kg/s) | Cv value of flow coefficient | Average |
|-------------|------------------------|---------------------------------|---------------------------------------------------------------|--------------------------|-------------------------------|---------|
| 10          | 3.25                   | 10                              | 589.986                                                       | 3.25019                  | 0.557                         | 0.556   |
| 20          | 3.75                   | 10                              | 787.872                                                       | 3.74701                  | 0.556                         | 0.556   |
| 30          | 4.25                   | 10                              | 1011.2                                                        | 4.25024                  | 0.556                         | 0.556   |
| 40          | 3.75                   | 10                              | 118.093                                                       | 3.24997                  | 1.24                          | 1.25    |
| 50          | 4.25                   | 10                              | 156.645                                                       | 3.74981                  | 1.25                          | 1.25    |
| 60          | 3.75                   | 10                              | 201.285                                                       | 4.25018                  | 1.25                          | 1.25    |
| 70          | 4.25                   | 10                              | 57.179                                                        | 3.25101                  | 1.79                          | 1.79    |
| 80          | 3.25                   | 10                              | 85.1461                                                       | 3.75045                  | 1.79                          | 1.79    |
| 90          | 3.75                   | 10                              | 97.573                                                        | 4.24983                  | 1.79                          | 1.79    |
| 100         | 4.25                   | 10                              | 31.3899                                                       | 3.25098                  | 2.41                          | 2.41    |
|             | 3.25                   | 10                              | 101.2                                                         | 4.25018                  | 2.40                          | 2.41    |
|             | 3.75                   | 10                              | 53.8809                                                       | 4.25016                  | 2.40                          | 2.40    |
|             | 4.25                   | 10                              | 17.8987                                                       | 3.25108                  | 3.20                          | 3.20    |
|             | 3.25                   | 10                              | 23.7403                                                       | 3.74979                  | 3.20                          | 3.20    |
|             | 3.75                   | 10                              | 30.3359                                                       | 4.2503                   | 3.21                          | 3.21    |
|             | 4.25                   | 10                              | 14.944                                                        | 3.25021                  | 3.49                          | 3.49    |
|             | 3.25                   | 10                              | 19.8814                                                       | 3.75043                  | 3.50                          | 3.50    |
|             | 3.75                   | 10                              | 25.5209                                                       | 4.24985                  | 3.51                          | 3.51    |
|             | 4.25                   | 10                              | 10.0049                                                       | 3.25011                  | 4.28                          | 4.28    |
|             | 3.25                   | 10                              | 13.3354                                                       | 3.74995                  | 4.27                          | 4.27    |
|             | 3.75                   | 10                              | 25.1407                                                       | 4.25018                  | 4.27                          | 4.27    |
|             | 4.25                   | 10                              | 7.9891                                                        | 3.24899                  | 4.78                          | 4.78    |
|             | 3.25                   | 10                              | 10.667                                                        | 3.75023                  | 4.78                          | 4.78    |
|             | 3.75                   | 10                              | 13.6691                                                       | 4.24976                  | 4.78                          | 4.78    |
|             | 4.25                   | 10                              | 6.7519                                                        | 3.25077                  | 5.21                          | 5.21    |
|             | 3.25                   | 10                              | 8.9831                                                        | 3.75063                  | 5.21                          | 5.21    |
|             | 3.75                   | 10                              | 11.4932                                                       | 4.24943                  | 5.22                          | 5.22    |
|             | 4.25                   | 10                              | 5.8107                                                        | 3.25021                  | 5.61                          | 5.61    |
|             | 3.25                   | 10                              | 7.7406                                                        | 3.74987                  | 5.61                          | 5.61    |
|             | 3.75                   | 10                              | 9.9796                                                        | 4.25053                  | 5.60                          | 5.60    |
|             | 4.25                   | 10                              | 7.7406                                                        | 3.74987                  | 5.61                          | 5.61    |
The whole system is shown above. The booster pump is responsible for pressurizing the water-storage tank, and the pressure gauges are used to measure the pressure values at both ends of the test valve and that in the water-storage tank, which provides sufficient water for the test. The sluice valves are used to control the flow rate of each pipeline, while the test valve, known as the labyrinth multistage depressurization regulating valve, is the object of this study. The flow meter can accurately measure the actual flow rate through the valve, and the pressure circulation pump is the power source to provide the pressure in the front of the valve.

The experiments of the flow rate were repeated many times for different openings and the experimental data is presented in table 3.

### Table 3. Flow rates for experiments with differently openings.

| opening (%) | pressure differential $\Delta P$ (kgf/cm²) | flow rates $Q$ (m³/h) | $C_v$ value of flow coefficient |
|-------------|---------------------------------------------|------------------------|--------------------------------|
| 10          | 0.999                                       | 0.271                  | 0.314                          |
| 20          | 0.997                                       | 0.722                  | 0.835                          |
| 30          | 1.019                                       | 1.416                  | 1.621                          |
| 40          | 0.998                                       | 1.895                  | 2.188                          |
| 50          | 1.017                                       | 2.475                  | 2.842                          |
| 60          | 0.999                                       | 2.89                   | 3.348                          |
| 70          | 1.009                                       | 3.402                  | 3.917                          |
| 80          | 1.004                                       | 4.137                  | 4.784                          |
| 90          | 1.011                                       | 4.466                  | 5.136                          |
| 100         | 0.998                                       | 5.038                  | 5.834                          |

### 3.4. Comparison and analysis between the simulation and experiment

The flow coefficient is one of the most important indexes of valve. The simulated flow coefficient $C_v$ and the experimental flow coefficient $C_v$ at different openings are respectively averaged as the relative $C_v$. According to the formula for ideal linear flow characteristics $Q/Q_{\text{max}} = \frac{R-1}{R} \frac{H}{H_{\text{max}}}$, the known ideal adjustable ratio $R$ of the valve, which is 50, is substituted into the formula to obtain the ideal data relative $C_v$ at different openings. All results are summarized in table 4 and are finally drawn into the flow characteristic curve for comparison, as shown in figure 15.

Both the calculated results and experimental results show that the valve presents linear flow characteristic, approximately a straight line on a rectangular chart. It can be seen obviously from Fig. 15 that the trends of the idealized characteristic curve, the numerical simulation characteristic curve and the test characteristic curve are basically consistent, completely conforming to the linear flow characteristic. It indicates that it is reasonable to use the numerical simulation software CFD for solving this kind of labyrinth regulating valve, and at the same static opening, the flow characteristic curve obtained by computer simulation and that of the test are distributed on both sides of the idealized characteristic curve. The relative flow of numerical simulation is slightly higher than that of the experiment. There is a certain error between the characteristic curve drawn by simulation on the software and that drawn according to the experimental data. Here are the main reasons:
First, the aim of this paper is to study and analyze the labyrinth multi-stage depressurization valve with very complex valve structure, it is hence difficult to set up a model. This research simplified some of the results. Specifically, only the internal flow field of the valve was selected for analysis, in other words, a relatively ideal flow passage model had been simulated. This makes the flow resistance coefficient of the model smaller than that of the actual valve. Finally, the phenomenon that the calculated flow coefficient is fairly large will appear.

Next, when using the numerical simulation software CFD to calculate, the given properties of the medium are ideal and deterministic, no changing with the process. In fact, the stability of the medium, which cannot be maintained by the experimental apparatus varies from time to time as the valve is working. That is to say, the medium will generate friction with the continued experiment when flowing in a pipe, which causes the change of the temperature and the reduction of medium viscosity and also has an impact on the flow resistance coefficient.

Finally, while doing the experiment, the adjustment accuracy of the test bench still exists deviation on the reading, and in addition, the relative travel of the test valve cannot be controlled completely and accurately. It means that there may be errors at each opening, making a big difference to the results. Although there are many uncertain influencing factors, the simulation results are finally considered to be reliable because the errors are all within the allowable range from the whole simulation and experimental results.

### Table 4. Summary of simulations and tests.

| Relative opening | Simulate relative value of $C_v$ data | Relative values of $C_v$ data were tested | Relative value of ideal $C_v$ data |
|------------------|--------------------------------------|------------------------------------------|----------------------------------|
| 10%              | 0.0998                               | 0.054                                    | 0.118                            |
| 20%              | 0.223                                | 0.143                                    | 0.216                            |
| 30%              | 0.319                                | 0.278                                    | 0.314                            |
| 40%              | 0.430                                | 0.375                                    | 0.412                            |
| 50%              | 0.570                                | 0.487                                    | 0.51                             |
| 60%              | 0.626                                | 0.574                                    | 0.608                            |
| 70%              | 0.761                                | 0.671                                    | 0.706                            |
| 80%              | 0.852                                | 0.820                                    | 0.804                            |
| 90%              | 0.929                                | 0.880                                    | 0.902                            |
| 100%             | 1                                     | 1                                        | 1                                |
4. Conclusions

- At a certain opening, the pressure drop at the inlet and outlet of the labyrinth valve will increase with the increasing of the flow rate. The pressure drop is mainly concentrated on where the throttling element of the sleeve components throttles and decreases step by step, which in the first stage is the greatest.
- Given the same inlet flow rate, the corresponding pressure drop will decrease as the opening of the labyrinth valve increases. That’s mainly because the flow area will increase with the increasing valve opening, but the inlet flow rate is set to be a constant value, which leads to the reduction of the flow velocity according to the equation of continuity. Therefore the pressure loss used to convert to kinetic energy will also get smaller, and then the pressure drop will decrease.
- At the same differential pressure, the flow rate will increase as the valve opening increases because the flow area will also increase with it.
- By the use of the numerical simulation software CFX, we come to a conclusion that the three-dimensional visualization of the internal flow field of a labyrinth valve provides reliable reference for the design and structure optimization of this kind of valve, and it also has the significance for designing a new type of energy-saving and low-consumption valve.

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