Numerical Simulation and Analysis of the dynamic Behaviours on the Spring-loaded Pressure Relief Valve

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Abstract. In this paper, in engineering practice, the computational fluid dynamics method was adopted to study the dynamic characteristics of the spring-loaded pressure relief valve. The effects of different parameters on the dynamic performance were investigated by CFD simulation. In the simulation, the damping coefficient has little influence on the discharge time and reseating pressure of the relief valve. With the decrease of spring stiffness, the reseating time of pressure relief valve increases, and reducing the spring stiffness can effectively reduce the reseating pressure. The reseating pressure decreases with the rise in the distance between the upper adjusting ring and the sealing face. This simulation results can provide a reference for the design and optimization of the structural parameters of the spring-loaded pressure relief valve.

1. Introduction

The pressure relief valve (PRV) is the accessory of equipment, device and pipeline as overpressure protection, and is the last passive safety measure in the pressure system to prevent the pressure of equipment, device and medium in the pressure system from exceeding the specified value [1]. When the working pressure inside the pressure system exceeds the setting pressure of the pressure relief valve, the pressure relief valve will open automatically and discharge the excess medium. When the system pressure returns to normal, the pressure relief valve will automatically close, which will prevent the medium from continuing to be discharged, resulting in excessive waste of media in the system.

In recent years, with the development of CFD technology, CFD has become an effective method to study the dynamic performance of valve [2]. People have started to model the flow conditions of valves to improve the design method or ensure the correct operation under difficult test conditions. For example, Dempster et al. [3] use the commercial code Fluent for CFD analysis to determine the characteristics of a conventional gas spring PRV operating at 10–20 bar. For a certain range of disc lifts, the CFD calculation results of mass flow and force are in good agreement with the experimental data.

Chen et al. [4] calculated the flow field shape in the 3D model of the pressure relief valve by numerical simulation or experiment, and the influence mechanism of the flow field parameters during the opening process of the pressure relief valve, but did not consider the effects of the spring stiffness, damping coefficient and other structural parameters of the pressure relief valve. Song et al. [5–7] first put forward the method of transient CFD to analyze the dynamic characteristics of pressure relief valve. They pointed out that the dynamic analysis of spring pressure relief valve can be described by using dynamic grid technology and CFD transient simulation and the reseating pressure process could be
accurately captured. However, the influence of movable parts related to valve disc on the opening process of valve disc was not considered.

Despite these advances in PRV simulation, few attempts have been made to integrate CFD technology into the design process. This study examines the influences of the spring stiffness and the damping coefficient between parts of the valve, as well as the upper adjusting ring on the PRV’s performance.

2. Model and simulation analysis
The simulation was performed using the commercial software ANSYS Workbench 14.0[8]. High resolution, second order backward Euler, and high-resolution options were used for the advection scheme, transient scheme, and turbulence discretization respectively. The convergence criteria were set so that the residual root mean square (RMS) error values were strictly below $10^{-5}$. In order to reduce the number of grid elements and computing time, the semi-symmetric model and variable time step were used in the simulation., the structural meshes were generated by using moving meshes to ensure that there is no element with a negative volume or poor quality at any iteration step. A three-dimensional CFD based model which was consist of 4 parts (inlet vessel, disc, body and outlet) was established to simulate the dynamic performance of the PRV. The main structure of the pressure relief valve model studied in this paper is shown in Fig. 1. The entire flow field model was divided into several domains while using the ICEM mesh methodology, as shown in Fig. 2. Dry saturated steam was used as the working medium.

![Figure 1. Detailed structure of PRV.](image1)

![Figure 2. Mesh model and position relationship between each domain.](image2)
2.1. Valve disk dynamics

According to Newton’s second law, the second-order ordinary differential equation derived can be used to calculate the motion process of the valve disc. These are expressed by Eq. (1)-(4); the mass of the moving parts $m_{\text{movable}}$ is defined by Eq. (2).

$$
y_{t+\Delta t} = \frac{F_{\text{flow}} - \xi y_t - F_0 - F_{0.5} - G + \frac{2m_{\text{movable}}}{\Delta t^2} y_t + \frac{2m_{\text{movable}}}{\Delta t} \dot{y}_t}{m_{\text{movable}} + k} \tag{1}
$$

$$
m_{\text{movable}} = 0.5m_{\text{spring}} + m_{\text{spindle}} + m_{\text{disk-holder}} + m_{\text{disk}} + m_{\text{bearing-seating}} + m_{\text{adjusting-sleeve}} \tag{2}
$$

$$
G = (m_{\text{spring}} + m_{\text{spindle}} + m_{\text{disk-holder}} + m_{\text{disk}} + 2m_{\text{bearing-seating}} + m_{\text{adjusting-sleeve}}) \times g \tag{3}
$$

$$
F_0 = \Delta y_0 \times k \tag{4}
$$

where $m_{\text{spring}}$, $m_{\text{spindle}}$, $m_{\text{disk-holder}}$, $m_{\text{disk}}$, $m_{\text{bearing-seating}}$, and $m_{\text{adjusting-sleeve}}$ are the masses of the spring, spindle, disk holder, disk, bearing seating, and adjusting sleeve, respectively. $\dot{y}_t$ is the disk velocity; $y_t$ is the disk lift; $F_{\text{flow}}$ is the force applied by the flowing fluid; $\Delta t$ is the time step determined in CFX; $k$ is the stiffness of the spring; $\Delta y_0$ is the initial compression of the spring; $F_{0.5} = 0.5 \text{ mm} \times k$. In the first calculation step, the initial lift of 0.5mm is used to establish the continuous flow field. ANSYS CFX expression language (CEL) was used to solve the Eqs. (1)-(4) and coupled the equations with CFD simulation.

2.2. Boundary conditions

The computational grid and boundary conditions are shown in Fig. 2. The reference pressure in each region was defined as atmospheric pressure. The initial set pressure is 17.2 MPa. The initial pressure in body, disc and outlet were set at 3.45 MPa. In the dynamic simulation process, the inlet of the vessel changes from constant pressure (17.2 MPa) state to wall state. On this basis, considering the action of the real vessel control valve, the dynamic simulation was carried out.

3. Results and discussions

3.1. Effect of the damping coefficient

In this section, the operation performance of pressure relief valve under different damping coefficients ($\xi=0 \text{ Ns/m}, \xi=5000 \text{ Ns/m}, \xi=10000 \text{ Ns/m}$) was simulated. The spring stiffness and the distance between the upper adjusting ring and the sealing face ($h$) were set as 3529 N/mm and 0mm respectively. The simulation results are shown in Fig. 3. It can be seen from the figure that when the damping coefficient increases from 0Ns/m to 10000 Ns/m, the opening time of the pressure relief valve increases from 19 ms to 21 ms. The total emission time increases slightly, from 701 ms to 712 ms. And the reseating pressure reduces slightly, from 12.787 MPa to 12.849 MPa. It can be seen that the damping coefficient has little influence on the discharge time and reseating pressure of the relief valve, so in order to facilitate calculation and analysis, the value of the damping coefficient was set as 0 Ns/m in the later simulation.
3.2. Effect of the spring stiffness

In this section, the dynamic performance of the pressure relief valve under different spring stiffness (k=3529 N/mm, k=3881 N/mm, k=4058 N/mm) was studied. As shown in Figure 4, with the decrease of spring stiffness, the reseating time of pressure relief valve increases from 433 ms to 726 ms, and the reseating pressure decreases from 14.715 MPa to 12.787 MPa. Correspondingly, the opening time of the pressure relief valve was reduced from 37 ms to 19 ms. Therefore, reducing the spring stiffness can effectively reduce the reseating pressure.

3.3. Effect of the position of the upper adjusting ring

For high temperature and high-pressure relief valves, the reseating pressure can be adjusted by changing the position of the adjusting ring. Nowadays, most of the adjustment rings are located by engineers relying on their own work experience and repeated attempts. So, it is very important to understand the working principle of the adjusting ring and to understand how it affects the dynamic characteristics of the pressure relief valve.

As shown in Figure 1, the distance between the lower edge of the upper adjusting ring and the sealing surface of the valve disc was set as \( h \), and it can be changed when the upper adjusting ring rotates. In order to explain the working principle of the adjusting ring theoretically, the operation performance of the pressure relief valve under different adjusting ring positions (\( h=0 \) mm, \( h=5 \) mm, \( h=10 \) mm) was simulated respectively in this section.

As shown in Fig. 5, the reseating pressure of the pressure relief valve decreases from 12.787 MPa to 12.695 MPa as \( h \) increases from 0 mm to 10 mm. And with the increase of \( h \), the reseating time of
pressure relief valve increases from 726 MS to 764 Ms. It can be seen that the reseating pressure of the relief valve by adjusting the upper adjusting ring.

Figure 5. The inlet vessel pressure (a) and lift (b) as a function of discharge time of PRV with $h$ ($\xi=0$ Ns/m, $k=3529$N/mm)

4. Conclusion
A complex pressure relief valve incorporating upper adjusting ring has been studied in an attempt to predict the valve operating characteristics.

The following are the results of the study. In the simulation, the damping coefficient has little influence on the discharge time and reseating pressure of the relief valve. With the decrease of spring stiffness, the reseating time of pressure relief valve increases, and reducing the spring stiffness can effectively reduce the reseating pressure. The reseating pressure decreases with the rise in the distance between the upper adjusting ring and the sealing face. This simulation results can provide a reference for the design and optimization of the structural parameters of the spring-loaded pressure relief valve.

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