Experiment and numerical simulation investigation on cavitation evolution and damage in the throttling section of pressure reducing valve

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Abstract
For the phenomenon of widespread and serious cavitation damage in the throttling section of pressure reducing valve under high temperature and high pressure in the chemical technology process of petroleum and coal, according to actual coordination structure widely applied between the valve core and valve seat, the cavitation throttling section with symmetrical contraction and expansion was made, and the visualized cavitation water tunnel experimental apparatus was designed and constructed. The cavitation evolution process with time under different cavitation numbers was recorded by the high-speed photography, the variation law of cavitation damage length and area with time was investigated by using aluminum film as cavitation damage carrier. Based on the experimental cavitation characteristic length \( L^* \), the evaporation coefficient \( F_v \), and condensation coefficient \( F_c \) in the Zwart–Gerber–Belamri cavitation numerical model were modified, and the cavitation damage region was predicted by the gas phase condensation rate of numerical simulation. The results show that with the decrease of cavitation number, the characteristic length of cavitation strip increases; the cavitation characteristic length fluctuates greatly at \( \sigma = 1.22 \), and there are cavitation cloud periodic formation, shedding, collapse, and disappearance at the tail of the cavitation strip on the upper valve seat; the cavitation damage length of the upper and lower valve seat remains unchanged with time, and the cavitation damage area increases approximately linearly with time; the initial position and length of cavitation damage predicted by the gas phase condensation rate are basically consistent with the experimental results, which verifies the accuracy of the modified numerical simulation.

KEYWORDS
cavitation damage experiment, gas condensation rate, numerical model modification, unsteady evolution process, visualized experimental apparatus
1 INTRODUCTION

The pressure reducing valve mainly changes the flow area and local resistance by changing the fitting distance of the internal key throttling element to achieve the momentum dissipation and pressure reduction of the fluid medium inside the valve, which is widely applied to petroleum, coal chemical industry, nuclear power, and other process industries.1–4 With the modernization of chemical technology and the exacerbation of process parameters, the pressure-reducing valve is facing complex and severe working conditions, such as high temperature, high-pressure difference, and high-speed flow.5,6 When the fluid medium flows relative to the throttling element inside the valve at high speed, cavitation is easy to occur. When the cavitation bubble collapses, it will release huge pulse pressure to impact the material surface of the core throttling element, which will not only reduce valve performance and damage valve structure but also cause the failure of the downstream piping system and seriously restrict the long-term safe operation of the device.7,8 Therefore, it is necessary to investigate the cavitation evolution and damage in the throttling section of the pressure-reducing valve.

A large number of literature studies show that the pressure drop of the pressure-reducing valve is mainly accomplished by the narrow throttling section; when the pressure after throttling is lower than the saturated vapor pressure, cavitation will be induced. Therefore, cavitation generally occurs in the low-pressure region behind the throttling section.9,10 Most scholars have carried out cavitation research on the throttling section of the pressure-reducing valve for this phenomenon.11,12 Han et al.13 numerically investigated the flow rate and cavitation characteristics of three kinds of typical throttling structures of the poppet valves and found that the error is less than 6.5% between the experimentally measured flow rate of the whole throttling valve and the simulated flow rate of the throttling section under different inlet pressure and opening, which shows that the study on the throttling section can replace the study of the whole poppet valve to a certain extent. The final results reveal that the two-stage throttle valve can effectively suppress the occurrence of cavitation. The mechanism of mechanical energy transfer and loss in unsteady cavitation flow and the effect of cavitation on energy loss of a control valve with different pressure ratio conditions were numerically investigated by Xu et al.14 The results show that the contribution of energy loss is much greater in the region of valve seat throat where strong throttling and severe cavitation occur. Wang et al.15 numerically studied the cavitating flow in a control valve with a perforated cage and discussed the effects of some parameters on the cavitation; the results show that the increase of the throttling length reinforces the cavitation, more step throttling is effective to suppress the cavitation. Liang et al.16 numerically analyzed the unsteady cavitation process inside a water hydraulic poppet valve under different inlet pressure; the results show that the existence of a groove at the valve throttling section can reduce the intensity of cavitation. The above literature not only analyzes the factors affecting cavitation but also discusses the measures to avoid cavitation, which lays a theoretical foundation for the research of this paper.

The design of the experimental apparatus in this paper refers to the literature that observing the evolution of cavitation morphology with the high-speed camera is a common and popular method. Liu et al.17 designed an optical test rig to visualize the unsteady cavitation flow under different cavitation numbers and the cavity length was defined based on high-speed camera technology; analysis shows that the smaller the cavitation number, the smaller the frequency of cavity length fluctuations and the larger the mean cavity length, the cavitation intensity is stronger at the lower cavitation. Osterman et al.18 had designed and set up the visualization cavitation experimental apparatus taken by the high-speed camera and experimentally predicted the operating condition at which cavitation first appeared. In the following literature, the cavitation damage location predicted by the experimentally modified numerical model is mainly concentrated in the region of cavitation collapse, which provides inspiration for this paper to predict the cavitation region by using the gas phase condensation coefficient. Ou et al.19 numerically analyzed the cavitation flow characteristic and damage of pressure relief valve by using the Schneer–Sauer cavitation model; the results prove that there exists severe cavitation at the region of the downstream bushing and the valve disc, and the pressure gradient and backflow toward the head of the disc are obtained. Amirante et al.20 experimentally and numerically investigated the effects of cavitation upon the performance of a hydraulic proportional directional valve. The validated numerical models were employed to predict the position where cavitation occurred to improve the design of the valve.

The throttling section with symmetric contraction and expansion used in the experiment is designed according to the actual structure of the pressure-reducing valve studied by the research group.19,21 The structure is also basically the same as that of the throttling section of the black water angle valve and liquid level control valve in our previous investigation, and the size is slightly different.22–24 Although previous studies have systematically simulated the depressurized
flow characteristics and cavitation erosion failure of the pressure-reducing valve, there is still a lack of specific experimental verification. In this paper, the visualized cavitation experimental equipment is designed and constructed to observe the cavitation evolution process photographed by the high-speed camera. Image gray processing technology is used to display the length and area of cavitation damage. The numerical simulation results of the experimentally modified cavitation model are consistent with the experimental results, and the reasons for the experimental phenomenon are explained.

2 | CAVITATION EXPERIMENT AND NUMERICAL MODEL

2.1 | Design and construction of the experimental device

The experimental device of visualized cavitation water tunnel is shown in Figure 1, which is a circulating waterway composed of a power system, constant temperature system, control system, and supporting pipeline system, and each device is connected through the DN50 circular pipe. Centrifugal pump 1 pumps water from water storage tanks 9, and the outlet of the centrifugal pump is divided into two channels, one of which flows back to the water storage tank through reflux regulating valve 10, and the other is treated with constant temperature through cooler 2 and heater 3. The temperature and flow rate are measured by temperature sensor 4 and flowmeter 5, and then generates cavitation in visualized test section 6. Pressure sensor 7 is used to monitor the pressure before and after the visualized test section, and the water finally flows into the water storage tank through outlet regulating valve 8 for circulation experiment. The continuous operation of the experimental equipment will lead to a gradual increase in the water temperature in the pipe. Cooler 2 and heater 3 are used to maintain the water temperature in the experiment. The measured signals, such as temperature, flow rate, and pressure are converted and processed by recording instrument 11 in real-time to display and record each data. Reflux regulating valve 10 can adjust the flow rate of the main circuit, the outlet regulating valve 8 can adjust the downstream pressure of the visualized test section, so as to obtain different forms of cavitation.

Figure 2A shows the three-dimensional structure model of the visualized test section. The flow domain inside the test section is a square cavity, and the square conversion section 10 times longer than the inner diameter of the circular tube is set in front of the experimental section to ensure the full development of incoming flow. The valve spool and valve seat constitute the throttling section with symmetric contraction and expansion. The valve spool and valve seat are detachable structures, which can adjust the size of the throttling section to investigate the cavitation characteristics of the pressure-reducing valve under different openings. Figure 2B is the design drawing of the throttling section, the total length of the observation section is 430 mm, the total height of the throttling section is 40 mm, the minimum height of the contraction is 4.4 mm, the distance of the horizontal wall surface between the upper and lower valve seat is 19 mm, and the width of the visualized experimental section is always 10 mm. Figure 3 shows the valve seat used in the experiment, and the length of the horizontal wall of the valve seat is 34 mm.

2.2 | Experimental process and cavitation characterization

Before the experiment, keep the two regulating valves fully open to inject water into the water storage tank. Stop injecting water after observing that the visualized
test section is filled with water. Keep the outlet regulating valve fully open to maintain outlet pressure at a constant atmospheric pressure. The reflux regulating valve is gradually closed to increase the pressure and flow rate upstream of the visualized test section; the cavitation morphology at different times (0.002 s for each photograph interval $\Delta t$) under different cavitation numbers $\sigma$ was observed by high-speed photography. The shooting frequency of high-speed photography is 500 FPS, and the resolution is 640 × 240 pixels. The definition of the cavitation number $\sigma$ is shown in Equation (1). The experimental operation conditions of different cavitation numbers are shown in Table 1. According to the research conclusions of most scholars, the smaller the cavitation number $\sigma$ is, the more obvious the cavitation phenomenon is, and the larger the cavitation number is, the weaker the cavitation phenomenon is.25–27

The experimental results are a series of cavitation images at different times taken by high-speed photography. The images are processed in gray to analyze the cavitation flow characteristics. Each image can be processed into a matrix of corresponding pixel values. The pixel value matrix of the image can be calculated and postprocessed through the image processing technology of MATLAB software to eliminate the possible impact of...

**FIGURE 2** Model of the visualized experimental section: (A) three-dimensional model and (B) design drawing.

**FIGURE 3** Experimental valve seat.

**TABLE 1** Cavitation number under different experimental working conditions

| Parameter | 1   | 2   | 3   | 4   | 5   |
|-----------|-----|-----|-----|-----|-----|
| $Q$ (m³/h) | 5.10 | 5.45 | 5.84 | 6.02 | 6.42 |
| $P_1$ (MPa) | 0.096 | 0.110 | 0.125 | 0.132 | 0.154 |
| $V_a$ (m/s) | 16.10 | 17.20 | 18.43 | 19.00 | 20.26 |
| $\sigma$ | 1.49 | 1.40 | 1.31 | 1.27 | 1.22 |
light strength and reflection during shooting. The postprocessing method is shown in Equation (2). The image after processing is shown in Figure 4. Black represents the liquid phase, and its pixel value is 0. The larger the pixel value is, the more serious the cavitation is. The image is divided into three regions: throttling region, cavitation region, and expansion region. The dimensionless parameters $X^* = X/L_N$ and $Y^* = Y/L_N$ are used in the analysis process to facilitate the characterization of cavitation length and display the evolution process of cavitation morphology, where $L_N = 22.58$ mm is the total length of the image. The meaning of the cavitation characteristic length $X^*$ and $Y^*$ is the ratio of the current horizontal and vertical coordinate to the total length of the image. The cavitation horizontal characteristic line in Figure 4 is obtained by statistical processing of the row and column elements of the pixel matrix. The upper and lower horizontal characteristic lines pass through a series of the continuous maximum value of the pixel matrix corresponding to the two cavitation strips.

$$\sigma = \frac{2(P_1 - P_v)}{\rho V_a^2}, \quad (1)$$

where $\sigma$ is the cavitation number, $P_1$ is the upstream inlet pressure of the visual experimental section; $P_v$ is the saturated vapor pressure at the experimental temperature; when the experimental temperature $T = 30 \pm 1$°C, the saturated vapor pressure $P_v = 4247$ Pa; $V_a$ is the average velocity in the inlet rectangular channel; $\rho$ is the density of water. $I_N$ is the gray value of the image after processing; $I$ is the gray value of the image taken during cavitation; $I_0$ is the gray value of the image without cavitation.

### 2.3 Cavitation characteristic length

Under different cavitation numbers, the ordinate values of cavitation characteristic lines of upper and lower valve seats vary with time as shown in Figure 5A. The ordinate values of cavitation characteristic lines of the upper valve seat show small-amplitude oscillation with time, while the ordinate values of cavitation characteristic lines of the lower valve seat are relatively stable with time. The average ordinate value of 20 cavitation characteristic lines at different times in Figure 5A is shown in Figure 5B, with the decrease of cavitation number, the average ordinate value of cavitation characteristic lines of upper and lower valve seats moves to the valve seat wall surface as a whole, respectively.

To eliminate the influence of light reflection from the external environment, the gray value on the cavitation characteristic line is statistically processed with a certain pixel value as the threshold to obtain the characteristic

$$I_N = \frac{I - I_0}{I_0}, \quad (2)$$

FIGURE 4 Cavitation image after gray processing ($\sigma = 1.40$).

FIGURE 5 Variation curves of cavitation characteristic lines: (A) different times and (B) different cavitation numbers.
length of the cavitation strip through which the characteristic line passes, which is compared with the cavitation length measured by the image shown in Figure 6. The cavitation characteristic length $L^*$ obtained by the gray value statistical processing method is basically consistent with the measured length of the characteristic strip in the image, which verifies the accuracy of the image processing method to a certain extent, and provides an analytical basis for the characterization of cavitation range under different cavitation numbers in this paper.

The variation of cavitation characteristic length with time under different cavitation numbers is shown in Figure 7. The cavitation characteristic length of both upper and lower valve seats increases with the decrease of cavitation number. Under the same cavitation number, the cavitation characteristic length of the lower valve seat is slightly larger than that of the upper valve seat. The variation amplitude of cavitation characteristic length of lower valve seat is smaller than that of upper valve seat with times.

### 2.4 Numerical model

The computational fluid dynamics (CFD) method was used to simulate the cavitation process for explaining the cavitation evolution phenomenon in the experiment. The grid division of the two-dimensional cavitation throttling section with the same size in the experiment is...
shown in Figure 8. The mesh of the narrowest section is encrypted. The grid independence of the cavitation throttling section is verified. When the number of grids exceeds 114,468, the average velocity of the narrowest throttling section remains unchanged at 17.198 m/s, which is basically the same as the average velocity of 17.20 m/s measured by the flow meter in the experiment. The cavitation steady trial results show that the \( y^+ \) value of the boundary layer of upper and lower valve seat horizontal wall surface is between 2 and 25, which meets the requirement of RNG \( k-\varepsilon \) turbulence model for \( y^+ \) value of about 30. Therefore, it is accurate to use the number of grids to simulate cavitation. The numerical model and solution method are shown in Table 2. The VOF multiphase flow model was used to capture the interface of gas–liquid conversion, and Zwart–Gerber–Belamri (Z-G-B) cavitation model was used to transiently simulate the cavitation evolution process. The implicit formulation is used to improve the solution range, the solution method of all gradient terms is set as least-squares cell-based, PRESTO! pressure interpolation format and the second-order upwind scheme is used for momentum and turbulence-related terms to improve the calculation accuracy and convergence.

### RESULTS AND DISCUSSION

#### 3.1 Experimental cavitation evolution

The evolution process of the experimental cavitation phenomenon with time at \( \sigma = 1.49 \) is shown in Figure 9. Cavitation occurs on the horizontal wall surface of the valve seat behind the narrowest section and constantly develops and evolves along the horizontal wall surface of the valve seat. Due to the influence of gravity, the cavitation strip of the lower valve seat is close to the horizontal wall surface of the lower valve seat, and the cavitation characteristic length does not change significantly with time, so it does not have obvious periodicity. While the cavitation strip of the upper valve seat deviates from the horizontal wall surface, the cavitation characteristic length varies periodically with time. The characteristic length of cavitation strip of upper valve seat increases gradually in Images 1–4, decreases to the shortest in Images 4–6, increases gradually again to the longest in Images 6–10, decreases again to the shortest in Images 10–12, and increases to the longest in Images 12–15. Therefore, the evolution period of the cavitation strip of the upper valve seat is

| Multiphase flow model | Turbulence model | Cavitation model | Formulation | Gradient | Pressure | Solution scheme |
|-----------------------|-----------------|-----------------|-------------|----------|----------|-----------------|
| VOF                   | RNG             | Zwart–Gerber–Belamri | Implicit    | Least squares cell-based | PRESTO! | Second-order upwind |
$6\Delta t = 0.012$ s. When $\sigma = 1.49$, the cavitation strip of the upper valve seat has a typical periodic evolution of cavitation, but the cavitation cloud does not fall off.

The evolution process of the experimental cavitation phenomenon with time at $\sigma = 1.40$ is shown in Figure 10. With the increase of inlet pressure and flow velocity, the cavitation number decreases, and the characteristic length of cavitation strips of upper and lower valve seat increases, hence the cavitation phenomenon is more obvious. The cavitation strip of the upper valve seat is close to the horizontal wall surface, but still has a certain distance from the horizontal wall surface of the upper valve seat. The characteristic length of cavitation strips of upper and lower valve seats fluctuates within a small range over time and no longer shows obvious periodic variation. Therefore, when $\sigma = 1.40$, the characteristic length of cavitation strips of upper and lower valve seats fluctuates in a small range with no obvious period.

The evolution process of the experimental cavitation phenomenon with time at $\sigma = 1.22$ is shown in Figure 11. With the substantial increase of inlet pressure and flow velocity, both the upper and lower cavitation strips are close to the horizontal wall surface of the valve seat, and a stable cavitation region appears in the center of the flow field behind the head of the valve core. The characteristic length of cavitation strips of upper and lower valve seats increases significantly, which has exceeded the length of the horizontal wall surface. Due to the influence of gravity, the cavitation strip of the lower valve seat continues to develop along the 15° inclined wall surface. The periodic formation, development, shedding, and collapse of cavitation clouds occur at the tail of the cavitation strip of the upper valve seat. The tail of the cavitation strip of the upper valve seat forms the cavitation cloud in Images 1–3, the cavitation cloud falls off, develops, and collapses downstream with the flow in Images 4–7. The cavitation cloud begins to form again at the tail of the cavitation strip in Images 8–10, and gradually falls off, develops, and collapses again in Images 11–14. Therefore, the period of formation, development, shedding, and collapse of cavitation cloud is $7\Delta t = 0.014$ s. When $\sigma = 1.22$, the characteristic length of the cavitation strip is the longest and the oscillation is relatively large, accompanied by the periodic formation, falling off, development, and collapse of cavitation cloud at the same time.

According to the above description of the experimental cavitation evolution process under different cavitation numbers, three different types of typical cavitation phenomena can be summarized. (1) The characteristic length of the cavitation strip of the upper valve seat varies periodically with time, and there is no cavitation cloud at the tail of the cavitation strip. (2) The characteristic length of cavitation strip of upper and lower valve seats fluctuates in a small range without an obvious period over time. (3) The characteristic length of cavitation strip of upper valve
FIGURE 10  Evolution process of experimental cavitation phenomenon at $\sigma = 1.40$ ($\Delta t = 0.002$ s).

FIGURE 11  Evolution process of experimental cavitation phenomenon at $\sigma = 1.22$ ($\Delta t = 0.002$ s).
seat is the longest and fluctuates greatly, accompanied by the periodic formation, shedding, development, and collapse of cavitation cloud at the same time. At $\sigma = 1.49$, the characteristic length of cavitation strip of upper valve seat is short and presents an obvious periodic varies, while the characteristic length of the cavitation strip of lower valve seat is short without significant variation, the tail of cavitation strip of upper valve seat is not generated cavitation cloud. At $\sigma = 1.40$, The characteristic length of the cavitation strip of upper and lower valve seats fluctuates within a small range over time and no obvious period, and there is also no formation of cavitation cloud at the tail of the cavitation strip of the upper and lower valve seats. At $\sigma = 1.22$, the length of the cavitation strip of the upper and lower valve seats is the longest and shows large-scale oscillation, the periodic shedding of the cavitation cloud at the tail of the upper valve seats can be observed in the experiment.

The variation curve of cavitation characteristic length with cavitation number is shown in Figure 12. When $\sigma = 1.72$, the primary cavitation first occurs on the horizontal wall surface of the lower valve seat, while there is no cavitation on the horizontal wall surface of the upper valve seat; with the decrease of cavitation number, the characteristic length of cavitation strip of lower valve seat increases slowly. When $\sigma = 1.55$, the primary cavitation begins to occur on the horizontal wall surface of the upper valve seat, and with the decrease of cavitation number, the characteristic length of the cavitation strip of the upper valve seat is quickly close to that of the lower valve seat. When $1.33 < \sigma < 1.44$, the characteristic length of the cavitation strip of the upper valve seat exceeds that of the lower valve seat, and the cavitation strip is close to the horizontal wall surface of the upper valve seat and develops further in the downstream flow field. When $\sigma = 1.33$, the primary cavitation occurs at the head of the valve spool, forming the cavitation strip at the center of the flow field downstream of the valve spool. When $\sigma < 1.33$, the characteristic length of cavitation strip of lower valve seat is longer than that of upper valve seat, at this time, the periodic shedding of cavitation cloud at the tail of cavitation strip of upper valve seat leads to the oscillation of cavitation characteristic length. In summary, the primary cavitation of the upper and lower valve seat will occur successively under different cavitation numbers. The cavitation strip close to the horizontal wall surface of the valve seat can grow and develop to a longer distance. The characteristic length of the cavitation strip will gradually increase with the decrease of cavitation number, and the growth rate will also gradually increase.

### 3.2 Experimental cavitation damage

The cavitation damage experiment and cavitation experiment were carried out separately. The soft aluminum film is pasted on the wall surface where the valve seat contacts the flow field. As a soft carrier, the aluminum film can show the results of cavitation damage in a short time. The thickness of both double-sided adhesive tape and the aluminum film is 0.05 mm, so as to reduce the impact on the cavitation field after the aluminum film is pasted. MATLAB software is used to eliminate the influence of external brightness by the same gray processing on the surface of aluminum film after cavitation damage, as shown in Figure 13. Two typical cavitation numbers $\sigma = 1.40$ and $\sigma = 1.22$ were selected for cavitation damage.
experiments with different duration. The experimental results show that there is no trace of cavitation damage at the head of the valve spool under two different cavitation numbers. When $\sigma = 1.40$, the horizontal wall surfaces of the upper and lower valve seats also have no trace of cavitation damage. When $\sigma = 1.22$, the horizontal wall surfaces of the upper and lower valve seats have obvious traces of cavitation damage, while the inclined wall surfaces have no trace of cavitation damage. It indicates that the shedding and collapse of cavitation cloud do not cause cavitation damage to the inclined wall surfaces of the upper and lower valve seats, but dissipates in the flow field of the expansion section far from the valve seat wall surface.

Cavitation damage images of the horizontal wall surface of the upper and lower valve seat with different duration at $\sigma = 1.22$ are shown in Figure 13. With the continuous increase of cavitation damage time, the cavitation damage length of upper and lower valve seats remains basically unchanged, the cavitation damage length of upper and lower valve seats is stable at 0.108 and 0.110, respectively, and the actual cavitation damage length does not exceed the characteristic length of cavitation strip. So only will cavitation near the wall surface of the valve seat produce cavitation damage. In the whole process of cavitation. The number of cavitation damage spots within the cavitation characteristic length increases gradually, the number of cavitation damage spots of the lower valve seat is always more than that of the upper valve seat.

The characteristic length and area of cavitation damage spots are obtained by the identification and statistical method of image pixels shown in Figures 14 and 15. The maximum value of ordinate 0.29 in Figure 14 is the total characteristic length of the horizontal wall surface of the valve seat. The cavitation characteristic length and area of cavitation damage spots are obtained by the identification and statistical method of image pixels shown in Figures 14 and 15. The maximum value of ordinate 0.29 in Figure 14 is the total characteristic length of the horizontal wall surface of the valve seat.
The length of the horizontal wall surface of the upper and lower valve seat at different times is basically the same and remains unchanged, the variation law of cavitation characteristic length is the same as that of the cavitation image in Figure 13. The area of cavitation damage spots increases approximately linearly within 5–45 min, and increases relatively small within 45–60 min. The reason for this phenomenon is that the newly generated cavitation damage spots on the aluminum film may coincide with the previous cavitation damage spots within the same cavitation characteristic length, resulting in the statistical deviation of cavitation damage spots. The area of cavitation damage spots of the horizontal wall surface of the upper valve seat in each period is larger than that of the lower valve seat.

### 3.3 Modification of cavitation model

The evaporation coefficient \( F_v \) and the condensation coefficient \( F_c \) in the Z–G–B cavitation model have a significant influence on the numerical simulation results. Therefore, according to the cavitation experimental results, the evaporation and condensation coefficient is corrected. Cavitation experimental phenomenon at \( \sigma = 1.40 \) displays stable adhesion cavitation with small oscillation, which can provide the stable experimental cavitation characteristic length to be compared with the cavitation characteristic length under different evaporation and condensation coefficients of numerical simulation. Thus, the calculation results of default coefficients \( F_v = 50, F_c = 0.01 \) of the Z–G–B cavitation model are compared with experimental results at \( \sigma = 1.40 \) shown in Figure 16. The cavitation characteristic length of the upper valve seat in the numerical simulation is significantly longer than the experimental cavitation characteristic length, while the cavitation characteristic length of the lower valve seat in the numerical simulation is shorter than the experimental cavitation characteristic length. Therefore, the default evaporation and condensation coefficient in the cavitation model cannot accurately predict the experimental results, so it is necessary to modify the evaporation and condensation coefficient in the cavitation model.

The evaporation and condensation coefficients in the cavitation model are changed separately, eight combination schemes of the evaporation and condensation coefficients are designed according to the references.\(^{28–30}\) The distribution law of gas-phase volume fraction in numerical simulation is shown in Figure 17, and the cavitation characteristic length is shown in Table 3. According to the comprehensive analysis of Figure 17 and Table 3, with the increase of the evaporation coefficient, both the cavitation length and intensity of upper and lower valve seat increase, the growth rate of the cavitation characteristic length of upper valve seat is significantly greater than that of the lower valve seat. When the condensation coefficient is increased alone, the cavitation characteristic length of the upper valve seat is shortened. When the condensation coefficient is reduced to \( F_c = 0.001 \) from the default value of \( F_c = 0.01 \), the cavitation characteristic length of the lower valve seat increases significantly, while when the condensation coefficient is increased on the basis of the default value of \( F_c = 0.01 \), the cavitation characteristic length of lower valve seat changes little.

According to Table 3, the cavitation characteristic length of the upper valve seat is closest that of the experiment at \( F_v = 5, F_c = 0.01 \), while the cavitation characteristic length of the lower valve seat is closest to that of the experiment at \( F_v = 200, F_c = 0.01 \). The cavitation characteristic length of the upper and lower valve seats is closest to that of the experiment at \( F_v = 50, F_c = 0.1 \). Therefore, two combination schemes of \( F_v = 5, \)
FIGURE 16  Comparison of cavitation characteristic length at $\sigma = 1.40$: (A) experiment and (B) numerical simulation ($F_v = 50$, $F_c = 0.01$).

FIGURE 17  The cavitation phenomenon and gas-phase volume fraction of upper and lower valve seats under different combinations of the evaporation and condensation coefficients.

TABLE 3  The cavitation characteristic length of upper and lower valve seat under different combinations of evaporation and condensation coefficients

| $F_v$ | 0.5 | 5  | 50  | 200 | 50 | 0.001 | 0.01 | 0.1  | 0.5  | Experimental value |
|-------|-----|----|-----|-----|----|-------|------|------|------|---------------------|
| $F_c$ | 0.01| 0.229| 0.273| 0.373| 0.290| 0.273| 0.196| 0.165| 0.225|
| Upper valve seat | 0.109| 0.113| 0.131| 0.184| 0.394| 0.131| 0.148| 0.135| 0.175|
$F_v = 200, F_c = 0.1$ were numerically simulated and compared with experimental cavitation characteristic length. As shown in Figure 18, the cavitation characteristic length of upper and lower valve seats at $F_v = 200, F_c = 0.1$ are 0.224 and 0.177, respectively, which are closest to experimental cavitation characteristic lengths 0.225 and 0.175, and the errors with experimental cavitation characteristic lengths are 0.4% and 1.1%, respectively. Comparison of cavitation characteristic length between experiment and numerical simulation at different times is shown in Figure 19. The variation law of cavitation characteristic length of upper and lower valve seats in numerical simulation is the same as that in the experiment; the cavitation characteristic length first increases and then decreases, which is due to the shedding of cavitation cloud at the tail of cavitation strip. The maximum error of the cavitation characteristic length of the upper and lower valve seats in the experiment and numerical simulation occurs at the time when the cavitation cloud falls off, and the maximum error of the cavitation strip of the upper and lower valve seats is 9.31% and 6.94%, respectively.

3.4 Simulation cavitation evolution

The modified cavitation model was used to numerically simulate the unsteady cavitation cloud shedding phenomenon at $\sigma = 1.22$ in the previous experiment, the time step of numerical simulation is 0.002 s, which is the same as the experimental shooting frequency. The evolution process of the cavitation phenomenon with time is shown in Figure 20, which is basically consistent with the cavitation evolution process photographed by high-speed photography in the previous experiments. Both the numerical simulation results and the experimental results have obvious periodicity, the seven moments of the time interval $\Delta t = 0.002$ s is a complete period. The cavitation cloud is gradually formed at the tail of the cavitation strip of the upper valve seat in Images 1–3. The cavitation cloud falls off, develops, and collapses in the expansion region in Images 4–6. The cavitation strip recovers to its original length and prepares for the start of the next cycle in Image 7. During the whole cycle, there is no shedding of cavitation cloud at the tail of the cavitation strip of the lower seat after the cavitation strip enters the expansion region, but the cavitation strip slightly shortens and recovers to the original length. The cavitation region at the head of the valve core also accomplished the process of growth, dissipation, and recovery. In the whole process of
numerical simulation, the cavitation strip behind the valve core head between upper and lower valve seats in the experiment has not been found. It is analyzed that the reason for this phenomenon may be the asymmetry of the upper and lower valve seats caused by installation. Combined with the streamline static pressure contours and the velocity variation curve of the expansion region inlet in Figure 21, the causes of the above phenomenon are analyzed. There are low-pressure regions below the saturated vapor pressure 4247 Pa on the horizontal wall surface of upper and lower valve seats and the head of valve core, where cavitation phase transition occurs. As the high pressure of the upper valve seat in the expansion region is closer to the horizontal wall surface than that of the lower valve seat, the generated reflux shear velocity of the upper valve seat is larger than that of the lower valve seat and has a greater shear effect on the cavitation strip, leading to the shedding of cavitation clouds at the tail of the cavitation strip. Finally, the shedding cavitation cloud collapses and dissipates in the high-pressure area. The cavitation strip of the lower valve seat is closer to the horizontal wall surface than that of the upper valve seat under the action of gravity, so the shear effect of backflow fails to force the generation of detached cavitation cloud at the tail of the cavitation strip of the lower valve seat.

3.5 Simulation cavitation damage

On the basis of correctly simulating the cavitation evolution process, the phase transformation rate is used
to predict the cavitation damage region. The positive value of the phase transformation rate represents the evaporation of the liquid phase, and the negative value represents the condensation of the gas phase. The absolute value of the phase transformation rate reflects the intensity of phase transition. The condensation rate contours in the contraction and expansion section at $\sigma = 1.40$ are shown in Figure 22. The region with a high condensation rate is mainly concentrated in front and edge of the cavitation strip. Since only gas-phase condensation near the horizontal wall surface of the valve seat is likely to cause cavitation damage, the phase transformation rate of the horizontal wall surface of the upper and lower valve seats is extracted as shown in Figure 23. Dimensionless abscissa $X^*$ for the total characteristic length of the horizontal wall surface of valve seat ranges from 0.09 to 0.38, while the phase transformation rate of upper and lower valve seat with $X^*$ between 0.112 and 0.168 is negative. The amplified curve shows that the maximum value of gas-phase condensation rate appears on the horizontal wall surface of the lower valve seat, which is 33 kg/m$^3$/s. In the cavitation damage experiment with $\sigma = 1.40$, there is no trace of cavitation damage on the horizontal wall surface of the lower valve seat. Therefore, the value of gas-phase condensation rate of 33 kg/m$^3$/s is selected as the critical cavitation damage value to predict the cavitation damage region.

The phase transformation rate of the upper valve seat in one cycle is shown in Figure 24. The high evaporation rate of the liquid phase is concentrated in the front and tail of the horizontal wall surface of the upper valve seat, a large number of cavitation bubbles are generated here. While the condensation of gas-phase only occurs in front of the horizontal wall surface of the upper valve seat, the value of phase transformation rate is negative, it indicates that previous generated cavitation bubble collapse here. The value of gas-phase condensation rate of 33 kg/m$^3$/s without cavitation damage is selected as the critical value, the characteristic length $X^*$ range of gas condensation rate greater than 33 kg/m$^3$/s between 0.11 and 0.208 is magnified. The value of gas-phase condensation rate at $T_1$–$T_3$ is less than 33 kg/m$^3$/s, the value of gas-phase condensation rate at $T_4$–$T_7$ is much greater than the value of critical cavitation damage gas phase condensation rate of 33 kg/m$^3$/s. The experimental cavitation damage region of the horizontal wall surface of the upper valve seat in 60 min under the same cavitation number $\sigma = 1.22$ is compared, and it is found that the start position and length of cavitation damage in the experiment are basically consistent with that of numerical simulation.

The same comparison method is used to predict the cavitation damage region of the lower valve seat shown in Figure 25. The value of gas-phase condensation rate of the lower valve seat is always greater than that of the upper valve seat in the whole cycle, and the value of gas-phase condensation rate of the lower valve seat in the whole cycle is greater than that of critical cavitation damage of 33 kg/m$^3$/s, and the characteristic length $X^*$ greater than the value of gas-phase condensation rate of critical cavitation damage of 33 kg/m$^3$/s ranges from 0.10 to 0.22. This is consistent with the conclusion that the area of cavitation damage spots of the lower valve seat is larger than that of the upper valve seat obtained in Figure 15. The predicted initial position and length of cavitation damage are basically consistent with those of the cavitation experiments on the wall surface of the lower valve seat. Therefore, it is accurate to use the gas phase condensation rate to characterize and predict the cavitation damage region.

4 | CONCLUSION

In this paper, the visualized cavitation water tunnel experimental apparatus is designed and constructed to conduct the experiment of cavitation evolution and
damage, respectively, and the modified cavitation numerical model is used to predict the cavitation damage region.

1. When $\sigma = 1.49$, the cavitation characteristic length of upper and lower valve seats is short, and the cavitation characteristic length of upper valve seat fluctuates significantly; When $\sigma = 1.40$, the cavitation characteristic length of upper and lower valve seats increases without obvious periodic fluctuation; when $\sigma = 1.22$, the cavitation characteristic length of upper and lower valve seats is the longest and the oscillation is relatively large with the periodic collapse of cavitation cloud.

2. The cavitation evolution process of the unsteady numerical simulation of the modified cavitation model is the same as that in the experiment. There are cavitation strips below the saturated vapor pressure on the horizontal wall surface of upper and lower valve seats after throttling, the shear effect of high-pressure reflux in the expansion region leads to the periodic oscillation of cavitation strip and the formation of cavitation cloud.

3. The cavitation damage length of upper and lower valve seats remains basically unchanged with time, the cavitation damage area increases approximately linearly with time, the cavitation damage area of the lower valve seat is always larger than that of the upper valve seat. The initial position and length of cavitation damage predicted by the gas phase condensation rate are consistent with that in the experiment.
NOMENCLATURE

\( F_c \) condensation coefficient
\( F_v \) evaporation coefficient
\( I \) gray value during cavitation
\( I_0 \) gray value without cavitation
\( I_{SN} \) gray value after processing
\( L_N \) image total length
\( L^* \) cavitation characteristic length
\( P_i \) upstream inlet pressure
\( P_v \) saturated vapor pressure
\( Q \) flow rate
\( T \) temperature
\( V_a \) evaporation source terms
\( X^* \) cavitation characteristic abscissa
\( Y^* \) cavitation characteristic ordinate
\( \Delta t \) shooting time interval

GREEK SYMBOLS

\( \sigma \) cavitation number
\( \rho \) water density

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