Research Article

Numerical Simulation and Experimental Research of Cavitation Jets in Dual-Chamber Self-Excited Oscillating Pulsed Nozzles

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Self-excited oscillating pulsed cavitation jet has many advantages, such as easy operation, simply maintenance, and low investment costs. Based on the structural parameters of the traditional Helmholtz and organ pipe single-chamber self-excited oscillating pulsed nozzles, Helmholtz + Helmholtz, organ pipe + organ pipe, and Helmholtz + organ pipe dual-chamber self-excited oscillating pulsed nozzles with different structures are established in series, and the internal flow field of the dual chamber is studied to obtain the best combination nozzle by comparing numerical simulation and erosion experiments. The results indicate that the cleaning effect is the best when adopting the combined structure of Helmholtz + organ pipe, which brings out the largest volume fraction of the nozzle cavity with higher gas content and higher kinetic energy with larger jet velocity. By comparing the erosion experiments, it is found that the flushing area and erosion depth of the nozzle with the ratio of cavity and wall \((D/a)\) of 2.50 is significantly higher than the nozzle with the ratio of cavity and wall \((D/a)\) of 5.00. The pulse pressure of the flushing target increases by 0.0044 MPa, the pressure amplitude of the former changes significantly in the same cavitation cycle, and the cleaning effect is best.

1. Introduction

Self-excited oscillating pulsed cavitation jet is a new type of water jet technology, which is widely used in cleaning the mud at the bottom of oil tanks or ships, oil and gas production, and other fields. Cavitation is the process of the cavitation bubbles' production, development, and collapse caused by the local pressure in the liquid being less than the saturated vapor pressure at the same state and temperature. High-speed jet flows into the narrow nozzle with complex turbulence and the change of medium density, producing cavitation jets and cavitation bubbles. The jets containing the cavitation bubbles impinge on the object, causing cavitation bubbles near the surface to break up, while the collapse of cavitation bubbles will produce great pressure and stress concentration, reaching high speed, high pressure, and high temperature conditions.

Sun et al. [1] added an expansion tube at the nozzle's outlet that could enhance the cavitation the effect of cavitation. Based on numerical simulation of Helmholtz nozzle, the effects of the height of the cavity resonator, the width of the cavity resonator, the angle of the expansion pipe, and pump pressure on the cavitation jet were studied. Wang et al. [2] established a cavitation model of the self-excited oscillating pulsed jet. When a large area of the cavitation bubbles collapsed in the cavitation jet, the jet had an obvious atomization effect. Tong et al. [3] numerically simulated the wall impact process of the hollow oil droplet in the conveying airflow based on the VOF method. Shervani-Tabar et al. [4] studied the influence of the cavitation effect on the nozzle of a direct-injection diesel engine spray penetration’s length and droplet distribution through numerical calculation. Chen et al. [5] proved by numerical simulation that the corrosion of steel by cavitation jet was caused by cavitation bubble collapse, which caused the high-energy shockwave and transient high temperature. Yao et al. [6] studied the factors of different depth environments, which had an effect on the cavitation jet produced by
cavitating spray head; using theoretical analysis and numerical simulation methods, the paper analyzed the difference in vacuoles of different environments. Through summarizing the variation of phase volume fraction and velocity, the conclusions were reached that the greater the pressure of the cavitating spray head, the larger the variation of phase volume, and the greater the underwater depth, the smaller the length of vacuoles in the same conditions. Alehossein et al. [7] simulated the formation and collapse of cavitation bubbles by solving the Rayleigh–Plesset equation. Giussani et al. [8] described the development of a single-fluid solver that could accurately capture the evolution of the three fluids and capture an approximation of the volume of fluid (VOF). Piscaglia et al. [9] also introduced the development of a dynamic two-phase volume fluid solver, used it to study the physical characteristics of the primary jet breaking and flow transient caused by the nozzle geometry during the opening process of the high-pressure ejector, and discussed the applicability constraints of the two-phase solver cavitation model in the flow simulation inside the ejector nozzle. Peng et al. [10] added quartz sand particles to the underwater cavitation jet to enhance its cavitation strength and erosion ability and verified the improvement of the cavitation strength and erosion ability of the particle underwater cavitation jet through high-speed photography, cavitation noise measurement, and erosion tests.

The research of Yuan et al. [11] showed that since cavitation was highly sensitive to the imposed boundary conditions, the simulations that limited internal problems were qualitatively and quantitatively incorrect and could not reveal the principles behind phenomena such as hydraulic flipping and supercavitation. Ma et al. [12] analyzed the oscillation characteristics of the self-oscillating water jet produced by a series of Helmholtz nozzles with different structures through spectrum analysis and studied the cavitation effect by analyzing the noise power spectrum, finding that compared with organ tube nozzles and cone nozzles, the self-oscillating water jet produced by Helmholtz nozzles had high-frequency pressure oscillations and strong cavitation effects. To evaluate the self-excited oscillation intensity, mass loss, and surface morphology of the eroded sample of the water jet, Liu et al. [13] conducted erosion experiments under the conditions of inclination angles of $a = 0^\circ$, $5^\circ$, $15^\circ$, and $30^\circ$. Ahmed et al. [14] proposed and verified a numerical framework based on interface capture to study cavitation and external jet formation; they performed numerical simulations on the development of cavitation and supercavitation and qualitatively compared the liquid and vapor structures obtained in the experiment and simulation. Liu et al. [15] raised the erosion ability of cavitation jets under nonsubmerged conditions and proved that the annular cavitation nozzle had an enhancement effect on the jet cavitation in the atmosphere domain. The research of Liao et al. [16] showed that the cavitation erosion on the aluminum specimens was mostly caused by mechanical forces due to the high-frequency pressure pulse generated when the cavitation bubbles collapsed, and just a fraction of the reason was caused by microjets. Chen et al. [17] proposed an optimization platform for a water jet cavitating nozzle in order to raise its axial maximum vapor volume fraction. Rachakonda et al. [18] presented and validated a computational approach to predict external spray characteristics for flashing and cavitating nozzles.

To track the liquid-gas interface, Edelbauer et al. [19] applied a three-component system consisting of liquid, vapor, and gas for the VOF simulation of the liquid disintegration. Qu et al. [20] designed a plurality of orthogonal experiments. Experiments proved that compared with other structural parameters, the suction nozzle diameter made the greatest impact on the jet performance. Brinkhorst et al. [21] researched the transparent Herschel Venturi-tube configuration. Under choked conditions, they proved the overall stable flow behavior and put forward a correlation for the calculation of the actual flow rate. Ghorbani et al. [22] analyzed how both microchannels and minichannels affect the effect of turbulence energy at high Reynolds numbers, and wall shear stress, turbulence kinetic energy, and various locations' average velocity at the micro/minichannels were investigated. Chavan et al. [23] proceeded from nozzle dimensions and wall shape and studied the numerical optimization of converging and diverging cavitating nozzles. They improved the CFD technique by using two-phase flow simulations. Örley et al. [24] explored the primary breakup of cavitating liquid jets through implicit large-eddy simulations (LES).

Most of the above studies are based on single-chamber self-excited oscillating pulsed nozzles, studying the nozzle structural parameters and the internal cavitation characteristics, so as to explore its cleaning ability and atomization effect. However, there are few studies on dual-chamber self-excited oscillation pulsed nozzles. Therefore, in this paper, on the basis of the traditional single-chamber self-excited oscillating pulsed nozzles in this paper, three kinds of dual-chamber self-excited oscillating pulsed nozzles with different structures are created in series. The internal flow field is studied through numerical simulation and experimental study, and the cavitation effect and cleaning ability are analyzed. After the optimal combination is obtained, the optimization design of its structural parameters is carried out to obtain the optimal structural size parameters, which further improves the cleaning effect of the cavitation nozzles and provides a useful reference for the design of the existing cavitation nozzles. The cleaning effect and erosion performance are verified through experimental study.

2. Mathematical Model

2.1. Turbulence Model. The flow field in this paper has a vortex ring structure, so the $k$-$\varepsilon$ turbulence model is used in this paper, and the $k$-$\varepsilon$ turbulence model includes the standard $k$-$\varepsilon$ turbulence model, the RNG $k$-$\varepsilon$ turbulence model, and the realizable $k$-$\varepsilon$ turbulence model.

According to the model parameters of Wang et al. [2], the corresponding geometric model is established. Numerical simulation is carried out for the three turbulence models, and their velocity streamlines are shown in Figure 1.
The RNG $k$-$\varepsilon$ turbulence model performs well in homogeneous shear flow—particularly and has a better ability to capture small size vortices at the end of the shear layer and the edge of the nozzle, which is suitable for jet impingement and other complex fluid flow phenomena [25].

Because the RNG $k$-$\varepsilon$ turbulence model can better reflect the internal flow field, this model is selected in the simulation and its equation is as follows:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + \rho \varepsilon, \tag{1}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{C_{1\varepsilon} G_k - C_{2\varepsilon} \rho}{k} \varepsilon^2, \tag{2}
\]

where $\mu_{eff} = \mu + \rho C_s k^2 / \varepsilon$ is the revisionary turbulent viscosity; $G_k$ is turbulent kinetic energy term generated by velocity gradient; $\alpha_k$ and $\alpha_\varepsilon$ are the turbulent Prandtl numbers; and $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are the constant terms.

2.2. Geometrical Model. Figure 2 shows that the traditional Helmholtz and organ pipe self-excited oscillating pulsed nozzles’ cutaway view. The geometrical model is based on the traditional Helmholtz and organ pipe self-excited oscillating pulsed nozzles, and dual-chamber self-excited oscillating pulsed nozzles are connected by series. The physical models are shown in Figures 3–5.

The main geometric parameters of the nozzles are as follows: the length of nozzle inlet is $l_1 = 30$ mm; the distance between the anterior chamber and posterior chamber is $l_2 = 30$ mm; the diameter of nozzle inlet is $d_1 = 8$ mm; the diameter of the middle flow passage is $d_2 = 15$ mm; the diameter of nozzle outlet is $d_3 = 15$ mm; the diameters of self-excited oscillation pulse chambers are $D_1 = 100$ mm and $D_2 = 60$ mm; the length of self-excited oscillation pulse chamber is $L = 60$ mm; the angle of wall collision is $\alpha = 120^\circ$; and the characteristic sizes of axial nozzles are $a = 20$ mm and $b = 40$ mm.

2.3. Grid Independence Verification. In this paper, ICEM software is used to establish the finite element model and divide the geometrical model of dual-chamber self-excited oscillating pulsed nozzles’ mesh. First, the geometric models are established and the boundary names are determined, including inlet “IN” (water flows into the cavity from the
nozzle inlet), outlet “OUT” (water flows out the cavity from the nozzle outlet), “WALL” (the inside walls of the nozzle), and symmetric boundary. Because the nozzle is an axisymmetric structure and in order to reduce the calculation time greatly, half of the two-dimensional finite element model is used for numerical simulation.

Before the numerical simulation of cavitation, and to improve the calculation accuracy, the mesh encryption is carried out in the chamber and the results of different grid numbers are compared after the convergence. BZ_he grid numbers 40931, 26544, and 18769 are divided, and the results of grid independence verification are shown in Table 1. 100 monitoring points are selected at the nozzle outlet, which is used to observe the average velocity of the monitoring points. The arrangement of monitoring points in the cross section at the exit is shown in Figure 6.

It can be found that the errors of the three results are less than 5%, and the influences of the grid number on the simulation results are negligible. The grid number selected in this paper is 26544, as shown in Figure 7.

3. Numerical Simulation

The flow field inside the nozzle is investigated by the cavitation jet numerical simulation. The inlet condition is pressure inlet, for which the parameter is set to 11.01325 bar, and the outlet condition is pressure outlet, for which the parameter is set to 1.01325 bar. The initial phase is water at room temperature, the second phase is water vapor, and the saturated vapor pressure is set to 0.0354 bar. The calculation process adopts a transient model, the discrete scheme adopts first-order upwind, and the numerical algorithm adopts PISO (Pressure Implicit with Splitting of Operators).

3.1. Numerical Simulation Analysis. The simulation results of Helmholtz, organ pipe, and three nozzles with different structures are shown in Figure 8. When comparing the water vapor phase volume fraction of single- and dual-chamber self-excited oscillation pulse nozzles, it can be observed that the cavitation phenomenon is obvious in the dual chamber and the cavitation bubbles are larger and symmetric, which is more conducive to improving the cleaning effect and the
Table 1: Grid independence validation.

<table>
<thead>
<tr>
<th>Class number</th>
<th>Mesh number</th>
<th>The average speed of outlet (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40931</td>
<td>24.67</td>
</tr>
<tr>
<td>2</td>
<td>26544</td>
<td>25.51</td>
</tr>
<tr>
<td>3</td>
<td>18769</td>
<td>26.13</td>
</tr>
</tbody>
</table>

Figure 6: Arrangement of monitoring points in cross section at the exit.

Figure 7: Grid division of Helmholtz + organ pipe cavitation nozzles.

Figure 8: Continued.
energy gathering and output, so the dual-chamber nozzle is better than the single chamber nozzle.

It can be seen that cavitation bubbles appear first in the separation area of the anterior chamber and grow constantly. With the jet squirting the posterior chamber, the cavitation bubbles in the separation area of the posterior chamber also move and continue to grow. The cavitation bubbles interact with the main power jets, causing the water vapor phase to mix with water phase in the chamber, and the volume fraction of the water vapor phase increases gradually on both sides.

100 reference points of the dual-chamber self-excited oscillating pulsed nozzles are extracted uniformly along the central-axis line, and the distribution of water vapor phase volume fraction is shown in Figure 9. The water vapor phase volume fraction of the Helmholtz + organ pipe dual-chamber self-excited oscillating pulsed nozzle is the largest and has the best symmetry, which is more conducive to the energy gathering and output and is beneficial to improving the cleaning effect. Therefore, preliminary results show that the Helmholtz + organ pipe dual-chamber self-excited oscillating pulse nozzle is the optimum structure.

3.2. Velocity and Turbulence Kinetic Energy Analysis. As can be seen from Figures 10 and 11, cavitation is prone to occur at structural mutation. When the high-pressure water jet passes through the resonant cavity, the outlet channel becomes smaller, resulting in the pressure wave, which continuously reflects the pressure wave to the inlet. When the standing wave frequency is the same as the natural frequency of the cavity, the resonance will make the cavitation effect more intense.

There are also symmetric vortex ring structures and streamlines in the chambers, and the vortex ring structures produce a certain periodic impedance to jets, producing the oscillating pulsed jets. Due to the existence of vortex ring structures, there is a region of low pressure in the chambers. Cavitation occurs in low-pressure area when pressure is lower than saturated vapor pressure. At the same time, the velocity of the Helmholtz + organ pipe dual-chamber self-excited oscillating pulsed nozzle is higher, so the kinetic energy is higher and the cleaning effect is better.

Cloud images of turbulent kinetic energy distribution are shown in Figure 12. Because the cavitation bubbles collide with the nozzle wall, the jet in the cavity interacts with the air, resulting in energy displacement. It can be seen in Figure 12 that the turbulent kinetic energy changes dramatically and is concentrated where the flow channel cross section suddenly changes and a large amount of turbulent kinetic energy can improve the cleaning performance of the nozzle.

The turbulent kinetic energy along the diameter direction at the exits of three nozzles is extracted, as shown in Figure 13. The turbulent kinetic energy of the Helmholtz + organ pipe dual-chamber self-excited oscillating pulsed nozzle is significantly higher than of the other combinations of nozzles. Eventually, the best combination nozzle is the Helmholtz + organ pipe dual-chamber self-excited oscillating pulsed nozzle.

3.3. Influence of the Change of the Ratio of Cavity and Wall (D/a) on the Internal Flow Field. In order to further explore Helmholtz + organ pipe self-excited oscillating pulsed
nozzle, set a dimensionless ratio of cavity and wall \((D/a)\), where \(D\) is the diameter of the resonant cavity and \(a\) is the axial characteristic size of the nozzles, as shown in Figure 1. The ratios of cavity and wall \((D/a)\) are 5.00, 3.33, 2.50, 2.00, 1.67, 1.43, 1.25, 1.11, 1.00, and 0.72 for numerical simulation, as shown in Table 2. In this paper, the different ratios of cavity and wall \((D/a)\) are obtained by giving \(a\) and \(D\) with different parameters. The influence of different ratios on the self-oscillating pulse cavitation jet is analyzed by changing the proportions of parameters.

As shown in Figure 14, when the ratios of cavity and wall \((D/a)\) are 5.00 and 2.50, the water phase volume fraction of dual-chamber self-excited oscillating pulsed nozzles is the minimum and has the better symmetry, while the degree of cavitation is the maximum in the meantime. The nozzles with the ratios of cavity and wall \((D/a)\) of 5.00 and 2.50 form symmetrical cavitation bubbles in the posterior chamber, which reduces energy loss greatly and increases the degree of cavitation. The dual-chamber self-excited oscillating pulsed nozzles with the ratios of cavity and wall \((D/a)\) of 5.00 and 2.50 are selected as the better series nozzles.

100 monitoring points are selected evenly along the diameter of the nozzle outlet’s cross section, and the velocity distribution at various monitoring points is shown in Figure 15. It is observed that when the ratios of cavity and wall \((D/a)\) are 5.00 and 2.50, the velocity of dual-chamber self-excited oscillation pulsed nozzles at the outlet is higher. The average velocity of 100 reference points is taken in each group, and the nozzle’s ratio of cavity and wall \((D/a)\) of 2.50 is finally determined as the best series nozzle.

![Figure 10: Cloud images of velocity distribution and streamlines of dual-chamber self-excited oscillating pulsed nozzles. (a) Organ pipe + organ pipe, (b) Helmholtz + Helmholtz, and (c) Helmholtz + organ pipe.](image)
4. Experimental Verification

In order to verify the cleaning effect of the dual-chamber self-excited oscillating pulsed nozzle, the experimental device of the cavitation jet is built as shown in Figure 16. The nozzles with the ratios of cavity and wall \((D/a)\) of 5.00 and 2.50 make a contrastive analysis under the same conditions. A 3D printer is used to print the cavity of cavitation nozzles, as shown in Figure 17.

To avoid the too short distance, the cleaning target distances are set to 500 mm and 800 mm, respectively. The cleaning effect of the cavitation nozzles is shown in Figure 18. It can be seen that the nozzle with the ratio of cavity and wall \((D/a)\) of 2.50 has a larger cleaning area and a greater erosion depth. Meanwhile, from the pressure pulsation of the cleaning target in Figure 19, the pressure pulsation of the nozzle with the ratio of cavity and wall \((D/a)\) of 2.50 is increased by about 0.0044 MPa and the amplitude of...
Figure 13: Turbulent kinetic energy distribution of different dual-chamber self-excited oscillating pulsed nozzles.

Table 2: The ratios of the cavity and wall (D/a).

<table>
<thead>
<tr>
<th>Group\parameter (mm)</th>
<th>D</th>
<th>a</th>
<th>D/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>20</td>
<td>5.00</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
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<td>3.33</td>
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<td>2.50</td>
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<td>2.00</td>
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<td>1.67</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>70</td>
<td>1.43</td>
</tr>
<tr>
<td>7</td>
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<td>80</td>
<td>1.25</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
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<td>9</td>
<td>100</td>
<td>100</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Figure 14: Continued.
Figure 14: Cloud images of the water volume fraction distribution of dual-chamber self-excited oscillating pulsed nozzles. (a) \(D/a = 5.00\); (b) \(D/a = 3.33\); (c) \(D/a = 2.50\); (d) \(D/a = 2.00\); (e) \(D/a = 1.67\); (f) \(D/a = 1.43\); (g) \(D/a = 1.25\); (h) \(D/a = 1.11\); (i) \(D/a = 1.00\).

Figure 15: Velocity distribution of dual-chamber self-excited oscillating pulsed nozzles.

Figure 16: Experimental device of the cavitation jet.
pressure pulsation is significantly changed in the same cavitation cycle. Therefore, the former’s cleaning effect is better than the nozzle with the ratio of cavity and wall \((D/a)\) of 5.00.

5. Conclusion

The structural parameters and internal cavitation characteristics of dual-chamber self-excited oscillation pulsed nozzles were studied, and the conclusions are as follows:

(1) Water vapor phase volume fraction, jet velocity, and turbulent kinetic energy of the Helmholtz + organ pipe dual-chamber self-excited oscillation pulse nozzle are the largest, and the interior of the chamber forms symmetrical vortex ring, which is conducive to the generation of pulse jet and the cleaning effect.

(2) The cavitation effect changes due to the dimensionless ratios of the cavity and wall \((D/a)\). When the ratio of cavity and wall \((D/a)\) of the Helmholtz + organ pipe

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Figure 17: Cavitation nozzles. (a) \(D/a = 2.50\). (b) \(D/a = 5.00\).

Figure 18: Cleaning effect. (a) \(d = 500\) mm. (b) \(d = 800\) mm.

Figure 19: The pressure pulsation of the cleaning target. (a) \(D/a = 5.00\). (b) \(D/a = 2.50\).
The dual-chamber self-oscillating pulsed nozzle is 2.50, the average velocity and the kinetic energy at the outlet are higher and the water volume fraction in the cavity is the smallest, so the cavitation degree is obvious.

(3) By comparing and contrasting the nozzle with the ratio of cavity and wall (D/a) of 5.00, the pressure pulsation of the nozzle with the ratio of cavity and wall (D/a) of 2.50 is increased by about 0.0044 MPa and the amplitude of pressure pulsation is significantly changed in the same cavitation cycle. The experiments indicate that the nozzle with the ratio of cavity and wall (D/a) of 2.50 has a larger cleaning area and a greater erosion depth, so the cleaning effect is the best.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**References**


