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Enhancing Hydrodynamic Cavitation through Composite Rotor-Stator Design: Dual-Mode Cavitation Dynamics and Pollutant Degradation

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ABSTRACT: This study develops and investigates an innovative composite rotor-stator hydrodynamic cavitation device designed to enhance cavitation generation for wastewater remediation. The device integrates double-row stator shear teeth with cylindrical pits on the rotor, enabling the simultaneous generation of flow-separation and vortex cavitation in both radial and circumferential directions. Transient two-phase flow simulations conducted on two orthogonal cross-sections reveal the synergistic evolution and coupling of these two cavitation modes, overcoming the single-direction perspective adopted in previous studies. Rhodamine B degradation experiments are then employed to indirectly characterize cavitation intensity and assess the reactor performance. The effects of the main operating parameters on the decolorization efficiency are quantified using a Box-Behnken response surface methodology, which identifies rotational speed, initial pollutant concentration, and inlet velocity as the most influential parameters, in descending order of importance. The optimal operating conditions are predicted to be 3633.92 rpm, 1.05 m/s, and 11.13 mg/L, respectively, and are experimentally validated with high prediction accuracy.

KEYWORDS: Cavitation performance; composite structure; flow field performance; rotational hydrodynamic cavitation reactor; water treatment

1 Introduction

The issue of wastewater treatment has attracted a lot of attention worldwide. How to solve this problem efficiently and in an environmentally friendly way has become an important challenge for us. Common wastewater contains a large number of organic pollutants, and traditional treatment processes have limitations and inefficiencies in practical applications. Hydrodynamic cavitation (HC) has the advantages of large treatment scale, convenient operation, low energy consumption, and no secondary pollution, and is considered a promising advanced oxidation method for removing organic pollutants [1–4]. The cavitation phenomenon in hydrodynamic cavitation produces mechanical, chemical and thermal effects [5–7]. Mechanical effects contribute to the inactivation treatment of microbial cells. Chemical effects produce hydroxyl radicals with high oxidizing properties, which oxidatively decompose bacteria as well as degrade some chemicals. The high temperatures and pressures generated by the collapse of the vacuole are sufficient to open the O-H bonds in the water molecules, resulting in the direct cleavage of the water molecules into -H and -OH (hydroxyl radicals), which in turn generate highly oxidizing substances such as H₂O₂ and HO₂, which can oxidize other solutes. In addition, there is a high-temperature region near the collapse zone, which causes the liquid in this region to enter a supercritical state, in which the physical properties

of water have changed significantly, and the reaction rate can be increased significantly [8]. In addition, hydrodynamic cavitation is widely used in the fields of nanoemulsion production [9], food processing [10], and biomass pretreatment [11].

The device that produces hydrodynamic cavitation is known as an HCR (hydrodynamic cavitation reactor). Research on HCR was initially represented by venturi tubes as well as orifice plates. Although they have been widely used in laboratory research in recent decades, they generally have the disadvantages of a single structure, relatively poor cavitation effect, relatively low energy utilization, etc., and have not been used on a large scale in the industrial field. For this reason, many scholars have improved the basic structure of the venturi tube and orifice plate, and proposed the Swirling-type venturi bubble generator [12], a venturi-type microbubble generator with a microporous tube [13], and a modified bubble generator with an orifice and porous tube [14]. These cavitation generators with composite structures have a wide range of applications in biochemical aeration, ozone mixing and dosing, and air flotation for water purification in wastewater plants. In addition, various novel hydrodynamic cavitation reactors with novel structures and excellent performance have been proposed: vortex diode [15], cyclonic jet cavitation reactor [16], rotating hydrodynamic cavitation reactor [17].

Among them, rotary hydrodynamic cavitation based on a rotor and stator has proved to be a promising approach for efficient cavitation, as shown in Fig. 1. Badve et al. [18] used a rotating structural cavitator with an internal bore to study the effectiveness of using hydrodynamic cavitation for the treatment of wastewater from the wood processing industry. The effect of different operating parameters such as rotor speed, hydrogen peroxide concentration and residence time of the wastewater in the cavitation unit on Chemical Oxygen Demand (COD) removal was analyzed. Zupanc et al. [19] investigated the use of shear-induced hydrocavitation for the removal of pharmaceutical residues from wastewater. The optimum conditions were determined as temperature 50°C, cavitation time 15 min, and addition of hydrogen peroxide 0.34 g/L. Sun et al. [20] designed and developed a novel rotary HCR, which generates cavitation bubbles through the interaction of conical grooves on the high-speed rotor disk and grooves on the stator cover. The effects of flow rate, pump pressure and inlet water temperature on the thermal performance (heat generation rate and thermal efficiency) of the HCR were analyzed. Simulated wastewater containing *Escherichia coli* (*E. coli*) was tested for disinfection. The results showed a significant decrease in *E. coli* concentration at treatment temperatures above 54°C and a 100% disinfection rate was achieved within 14 min. Gostiša et al. [21] investigated the performance evaluation of a novel needle-disk rotary hydrocavitation generator. The cavitation mechanism of the needle disk was mainly due to local pressure reduction due to flow acceleration and separation behind the cylinders, and pulsating cavitation due to flow channels and Kamen vortex streets between the cylinders. Liu et al. [22] proposed the stacked cavitation theory and developed a novel rotational hydrodynamic cavitation generator equipped with a tapered rotor and internal flow channels. Combining numerical simulation and ozonation-coupled degradation experiments, they analyzed the synergistic effects of inertial force, shear force and pressure gradient force on cavitation evolution, which provides a theoretical basis for the scale-up design and parameter optimization of such devices. Xue et al. [23] also put forward the stacked cavitation theory and designed an innovative rotational hydrodynamic cavitation reactor with a tapered rotor and internal passages. Based on simulation and ozonation synergistic degradation tests, they explored the combined effects of inertial force, shear force and pressure gradient force on cavitation characteristics, offering theoretical support for the engineering scale-up and operational parameter optimization of cavitation equipment. Zhang et al. [24] developed two rotor-radial groove hydrodynamic cavitation reactors with different structural sizes. By means of Computational Fluid Dynamics (CFD) simulation and *E. coli* disinfection experiments, they comparatively

investigated the influences of structural dimension and rotational speed on cavitation volume, cavitation generation efficiency and water treatment performance. The results verified that the scaled-up reactor can achieve excellent cavitation and water treatment performance at relatively low rotational speeds. Zupanc et al. [25] from Dular's group proposed a pin-disc rotary cavitation device relying on the wake vortex behind cylindrical pins, which also belongs to single-mode cavitation structures and cannot realize dual-direction synergistic cavitation. Different from the above single-type designs, the composite tooth-pit geometry proposed in this paper integrates double-row stator shear teeth and mover cylindrical pits as a multi-layer composite layout, synchronously producing flow separation cavitation in radial gaps and vortex cavitation in circumferential pit-tooth channels, which greatly expands the continuous cavitation area and forms a differentiated structural innovation against existing single-structure reactors.

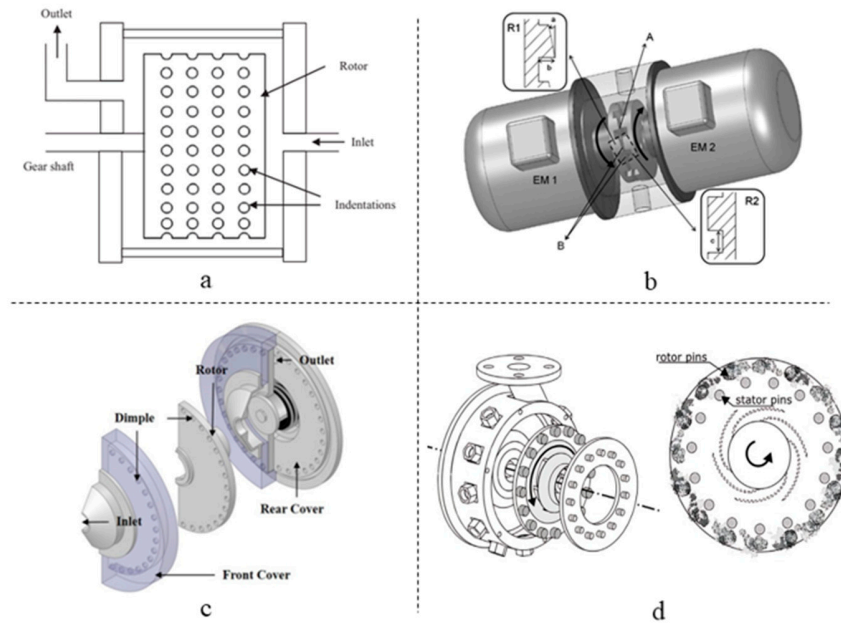


Figure 1: Typical rotor and stator cavitation generators (a) cavitation generator with internal hole [17]; (b) zigzag disc with a gap [18]; (c) disc with grooves [18]; (d) disc with pins [18].

Most existing research mainly focuses on experimental exploration to improve cavitation intensity, cut energy loss and enhance organic pollutant removal capacity. However, most previous devices adopt a single-tooth or single-pit configuration, which can only generate a single cavitation form within a single flow direction; meanwhile, relevant investigations lack systematic full-flow-field analysis, and unified quantitative evaluation indicators for cavitation performance are insufficient. Through comprehensive sorting of published literature, three typical inherent deficiencies can be summarized: single-structure reactors cannot realize multi-region synergistic cavitation, most flow field research only analyzes one independent cross-section without capturing dual-mode cavitation coupling rules, and most experimental works merely carry out single-variable tests without global multi-factor optimization targeting actual degradation performance.

To remedy the above research gaps, this work designs an innovative composite rotary cavitation generator improved on the basis of serrated disc structures. The stator is equipped with double-row teeth with cutting angles machined on both outer sides and bottoms, while the mover is arranged with double-row protrusions and cylindrical pits ahead of each tooth. The so-called composite design realizes

synchronous generation of two cavitation types (flow separation cavitation and vortex cavitation) along radial and circumferential dual flow directions, which fundamentally breaks the single-cavitation limitation of traditional single-type devices. To fully reveal its unique cavitation synergistic mechanism, this paper comparatively investigates multi-dimensional flow field characteristics including velocity, pressure, vapor volume fraction and turbulent kinetic energy from both radial and circumferential orthogonal planes. Taken together, the main novelties of this work lie in the proposed composite tooth-pit geometry for dual-mode and dual-directional synergistic cavitation, the comparative dual-orthogonal-plane flow-field analysis of coupled cavitation behaviors, as well as the multi-factor parameter optimization for pollutant degradation performance. These findings provide new insights and practical references for the development of high-efficiency rotary hydrodynamic cavitation reactors.

2 Numerical Modeling of Rotary Cavitation Generator

2.1 Structural Design of Rotary Cavitation Generator

A new rotary cavitation generator with a composite structure is designed in this paper as shown in Fig. 2, which is divided into a mover (Fig. 2a) and a stator (Fig. 2b). The mover has three turns of projections, again with 12 evenly distributed on each turn. The stator has two turns of tooth structure with 12 teeth evenly distributed in each turn, as shown in Fig. 2b. The outer diameter of the mover and stator is 160 mm, and the width of the center runner is 11.5 mm. The angle between each row of protrusions (toothed structure) and the center of the circle is 15° . A shear angle α is provided at the outer side of the stator tooth structure, and a shear angle β is provided at the bottom of the stator tooth structure, as shown in Fig. 3. All dimensions illustrated in Fig. 3 adopt millimeters (mm) as the unified unit. A cylindrical pit with a radius of R is provided between the movable protrusions, where the shear angles α and β are 5° and the radius R is 7 mm. When the movable protrusions are assembled with the stator, the gap is set to 1.5 mm to take into account the rotational stability as well as the reliability.

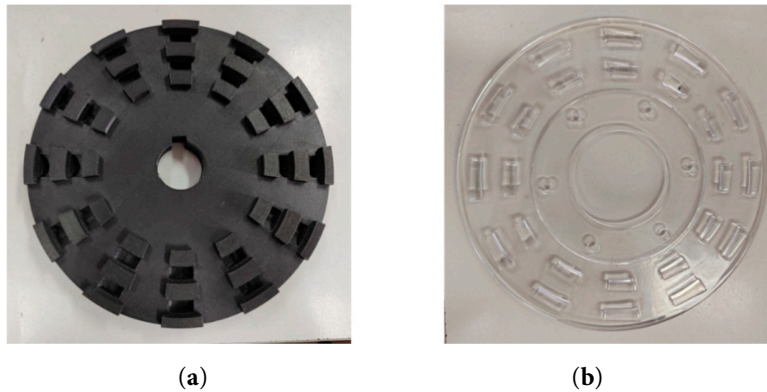


Figure 2: New rotary cavitation generator (a) mover; (b) stator.

The moving tooth flanks on the mover and the fixed tooth flanks on the stator repeatedly form a gap in the diameter direction during rotation of the mover, as shown in Fig. 4. This schematic illustrates the dual-direction dual-type composite cavitation mechanism unique to the tooth-pit integrated rotor-stator structure proposed in this study. The fluid inlet velocity through increases, and the static pressure of the liquid decreases. When the pressure is reduced to the saturation vapor pressure of the liquid, the liquid begins to vaporize to produce vacuoles. When the moving teeth on the mover overlap with the static teeth on the stator, cavitation is most pronounced. The pits on the mover and the bottom of the fixed teeth on

the stator repeatedly form a shape similar to a venturi in the circumferential direction during the rotation of the mover, resulting in cavitation. When the moving teeth on the stator are separated from the static teeth on the stator, the cavitation effect is most obvious. Liquid from the stator above the inlet enters the stator; with high-speed rotation, the liquid in the centrifugal force from the center like the periphery of the diffusion. The cavitation area consists of the side of the teeth, the bottom of the teeth, and the pit of the stator and the mover, due to the tooth structure and the pit of the stator and the mover. Compared with the single-structure rotary cavitation generator, this new rotary cavitation generator with a composite structure is characterized by many cavitation locations and an obvious cavitation effect.

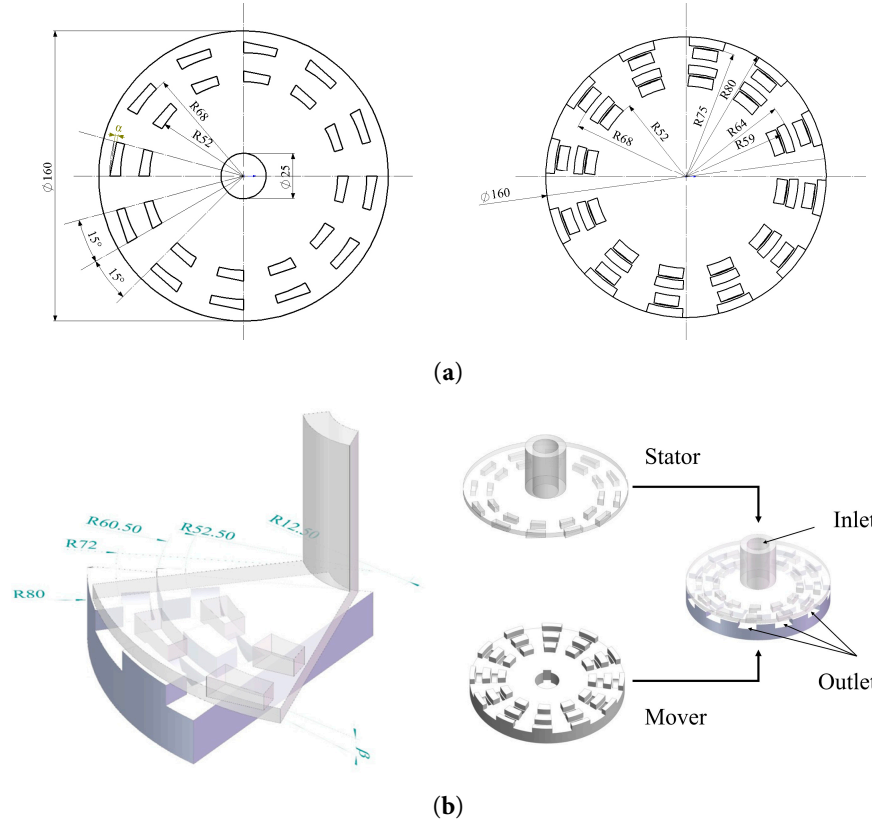


Figure 3: New rotary cavitation generator structure (a) two-dimensional front-view drawing, (b) three-dimensional isometric view (mm).

2.2 Control Equations and Model Selection

Cavitation flow is a non-constant flow, and the cavitation flow field is a multiphase flow field consisting of liquid water and vapor water, which satisfies the law of conservation of mass and the law of conservation of momentum. The continuity equation and momentum equation [26] for vapor-liquid two-phase mixtures are as follows:

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial (\rho_m u_j)}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial (\rho_m u_j)}{\partial t} + \frac{\partial (\rho_m u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu_m \frac{\partial u_i}{\partial x_j} \right) - \frac{\partial (\rho_m \overline{u_i u_j})}{\partial x_j} + \rho_m g_i \quad (2)$$

where $\rho_m = \rho_l \alpha_l + \rho_v \alpha_v$, $\mu_m = \mu_l \alpha_l + \mu_v \alpha_v$, ρ is the fluid density, μ is the coefficient of viscosity, α is the volume fraction, p is the pressure, u is the velocity, the subscript m is the mixing phase, the subscript l is the liquid phase, the subscript v is the gas phase, the subscript i is the direction of the coordinate, and the subscript j is the direction of the coordinate, g_i is the component of gravitational acceleration; $\overline{u_i u_j}$ denotes the Reynolds stress tensor.

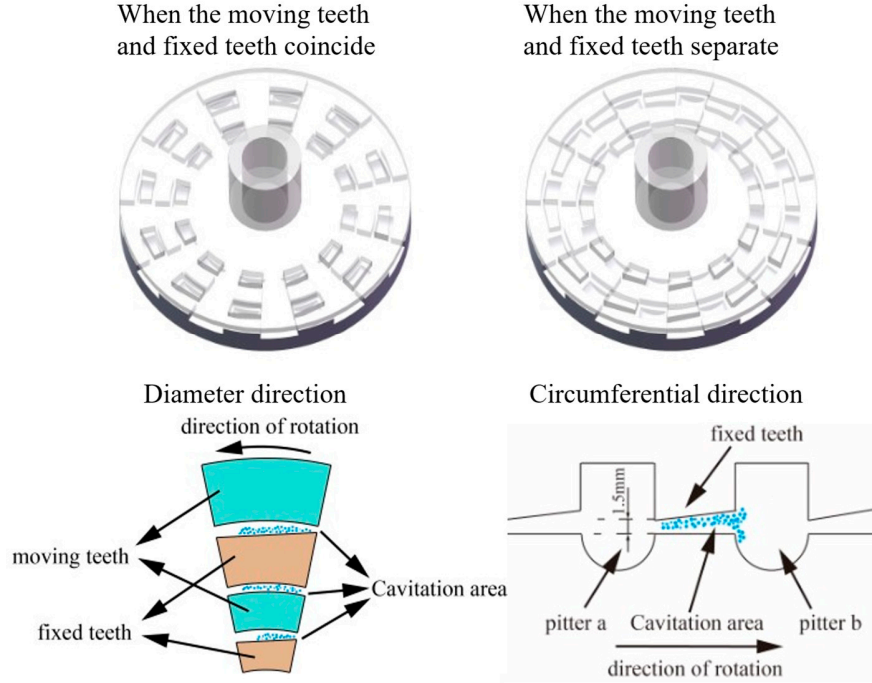


Figure 4: Mechanism of cavitation.

The validity of the turbulence model directly affects the accuracy of cavitation prediction, and a suitable turbulence model is the most important issue for performing numerical simulations. The SST $k-\omega$ (Shear-Stress Transport $k-\omega$ Model) model was chosen for this paper [27]. The model has high computational accuracy for the flow-solid separation phenomena at the wall. The $k-\varepsilon$ model is applied away from the wall surface to simulate fully developed turbulence. The $k-\omega$ model is retained near the wall to compute the boundary layer problem with larger pressure and velocity gradients. The SST $k-\omega$ model mainly consists of the turbulent kinetic energy k equation, the turbulence frequency ω equation, and the vortex viscosity equation are as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_i}(\rho U_j k) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] = P_k - \beta^* \rho k \omega \quad (3)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j \omega) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + 2(1 - F_1) \rho \frac{1}{\sigma_{\omega 2} \omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (4)$$

$$v_t = \frac{\mu_t}{\rho} = \frac{a_1 k}{\max(a_1, \omega, SF_2)} \quad (5)$$

where P_k is the turbulence generation rate, S is a fixed strain rate estimate, k is the turbulent kinetic energy, ω is the turbulence frequency, μ is the dynamical viscosity, the dissipation-term constant β^* of the turbulent kinetic energy k equation is 0.09, the production-term coefficient α is 5/9, the Turbulent Prandtl number σ_k

of k equation is 2, the Turbulent Prandtl number σ_ω of ω equation constant is 0.075, and the Cross-diffusion coefficient $\sigma_{\omega 2}$ of ω the equation in the SST k - ω model is 1/0.856.

The cavitation model is key to the numerical simulation calculation of cavitation, and the ZWART model was chosen in this paper [28]. It should be noted that the default empirical constants of the ZWART model were employed without specific calibration against the present device. While these default values have been extensively validated in the literature for aqueous cavitation problems, some quantitative uncertainty in the predicted cavitation intensity is expected. The validation results in Section 3.3 demonstrate that the simulation correctly captures the qualitative trends of cavitation development. The model is derived based on the Rayleigh-Plesset vacuole dynamics equation. This model is widely recommended due to its fast convergence and high accuracy. The form of this cavitation model is as follows:

$$\frac{\partial(\alpha_v \rho_v)}{\partial t} + \frac{\partial(\alpha_v \rho_v u_i)}{\partial x_i} = \dot{m}^+ + \dot{m}^- \quad (6)$$

where ρ_v denotes the vapor density, α_v denotes the volume fraction of the gas phase, $\dot{m}^+$ denotes the mass per unit time transformed from the liquid phase to the vapor phase during evaporation, and $\dot{m}^-$ denotes the mass per unit time condensed from the vapor phase to the liquid phase.

$$\dot{m}^- = C_{vap} \frac{3\alpha_{nuc}\rho_v(1-\alpha_v)}{R_B} \sqrt{\frac{2(p_v(T_\infty) - p)}{3\rho_l}} p \leq p_v(T_\infty) \quad (7)$$

$$\dot{m}^+ = C_{cond} \frac{3\alpha_v\rho_v}{R_B} \sqrt{\frac{2(p - p_v(T_\infty))}{3\rho_l}} p > p_v(T_\infty) \quad (8)$$

where the empirical constant C_{vap} obtained based on the aqueous medium cavitation test is 50, and the empirical constant C_{cond} obtained based on the aqueous medium cavitation test is 0.01, R_B denotes the average radius of the gas bubbles, which is generally taken as 1×10^{-6} m, the volume fraction of non-condensable gases α_{nuc} is 5×10^{-4} .

2.3 Boundary Conditions and Parameterization

To improve the simulation accuracy and computational efficiency, the actual designed model was simplified and treated as shown in Fig. 5. The periodic boundary is used to study the cavitation generation mechanism and the cavitation development process. The tooth structure of the rotor and stator is circumferentially uniform with typical geometric periodicity. After stable operation, the flow field and cavitation state of each periodic unit are basically identical. Periodic boundary conditions are applied herein to optimize computational efficiency, and this method is widely accepted for simulating such rotating machinery. The accuracy of the numerical model is verified by the comparative analysis between simulation results and experimental data. Due to the geometrical structure of the cavitation generator and the periodicity of the cavitation flow field, the periodic boundary simplifies the interaction area between the mover and stator to 1/6 of the original one. The fluid flows into the static part from the inlet, and then flows through the moving part, and then flows out of the outlet from the outflow area under the high-speed rotation. To ensure the stability of the calculation and the uniformity of the fluid inflow and outflow of the cavitation generator, two sections of extension piping are added to the inlet and outlet, and the length is 4 times of the inlet and outlet.

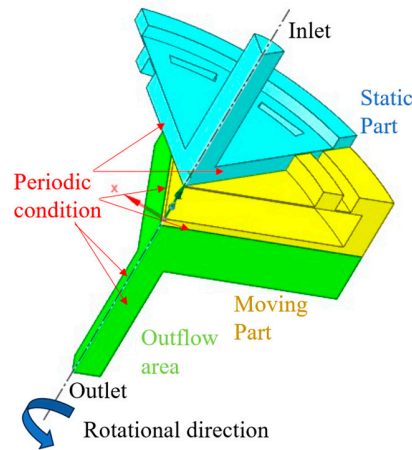


Figure 5: Boundary condition setting for simplified model.

In this simulation, water is used as the simulation medium, and the saturated vapor pressure is set to 3540 Pa corresponding to the experimental temperature of 25°C. The velocity inlet is 1 m/s, the outlet is set to be the pressure outlet, and the gauge pressure is 0. In the solution algorithm, the pressure-velocity coupled solution algorithm is selected to be Coupled, the pressure discretization method is selected to be PRESTO! [29], the momentum and volume fraction discretization methods are selected to be QUICK, and the other physical quantities are selected to be in second-order windward wind format. QUICK, and the second-order windward format were chosen for the other physical quantities. The calculations are performed using a non-stationary method, and the results of the stationary calculations are used as initial values. To accurately express the development of cavitation, the time 0.462 ms for 1° of rotor rotation is taken as the time step. To obtain an accurate result, a sufficient number of iteration steps is given for each iteration step, and the number of iteration steps for the total time step and the unit time step is specified as 200 & 300.

2.4 Validation of Computational Domain and Mesh Independence

The computational fluid domains static part, moving part, and outflow area are meshed by ANSYS Meshing 19.2 and ANSYS Fluent 19.2. The contact surface of the static part and the moving part is set as an interface. The rotating area of the mover is set as grid motion. The rotation direction is in the clockwise direction. Considering that unstructured meshes have obvious advantages over structured meshes in the generation of complex shapes, unstructured meshes are used. Among the unstructured mesh types, the polyhedral mesh is used as the meshing scheme to generate polyhedral meshes with a minimum orthogonal mass of 0.35, as it has advantages over tetrahedral and hexahedral meshes in terms of computation time and computation accuracy. The mesh and the local zoomed-in view are shown in Fig. 6a. All numerical simulations were performed on a high-performance computing workstation. The detailed hardware specifications are as follows: an Intel Core i9-12900K central processing unit with 16 physical cores (24 logical threads, 3.2 GHz base frequency, 5.2 GHz maximum turbo frequency), 64 GB DDR4 random-access memory (RAM), a 512 GB solid-state drive (SSD), and a 64-bit Windows 10 operating system. The CFD solver was run in parallel with 12 cores to balance computational efficiency and memory overhead.

The Body of Influence (BOI) local mesh refinement size was used for the inner and outer tooth regions as the mesh size control parameter. Two parameters, gas phase volume fraction and gas phase volume, were used as evaluation criteria, and the specific results are shown in Fig. 6b and Table 1. The results show that

the gap between gas-phase volume and gas-phase volume fraction decreases gradually with the gradual reduction of the grid encryption size. The relative error between the fine grids is within 1% under the comparison of medium and finer grid sizes. Therefore, the medium mesh is taken as the optimal mesh size when considering computational accuracy as well as computational resources in this study. For the mesh independence verification of the simplified model (steady-state flow field calculation), each mesh scheme took approximately 4.5 h to reach the convergence criterion: all scaled residuals dropped below 10^{-6} , and monitoring parameters including outlet pressure and vapor volume fraction remained stable. For the final selected finer mesh scheme, the transient cavitation flow simulation under a single working condition adopted a time step of 1×10^{-5} s. The total computational time was approximately 28 h to complete 5 full rotational cycles and obtain stable periodic cavitation flow characteristics.

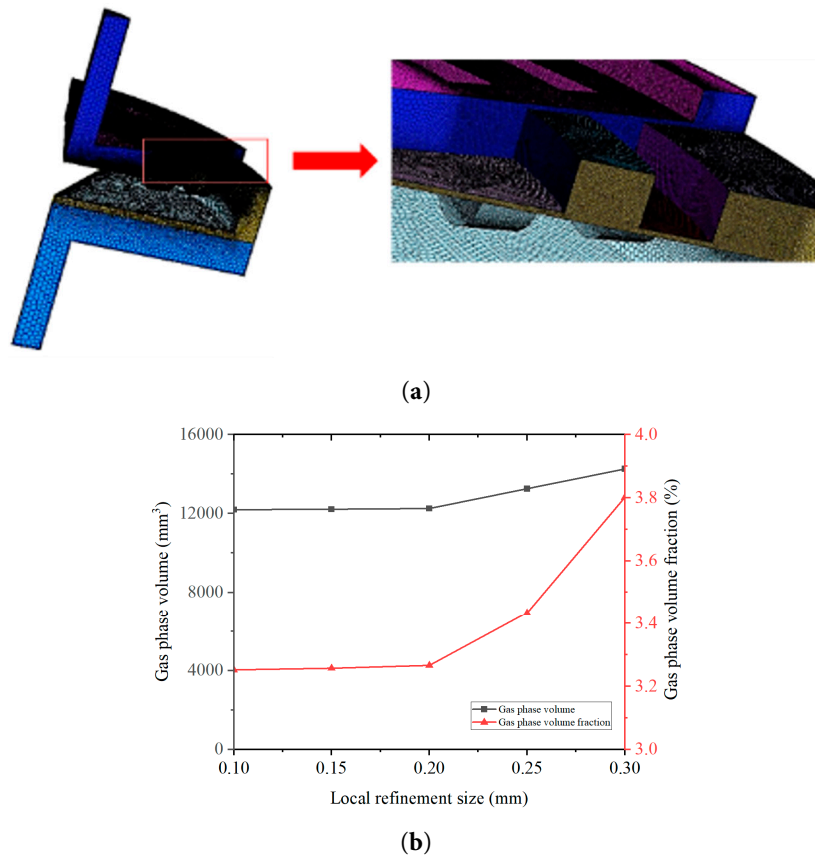


Figure 6: Mesh independence (a) grid and encryption zoom; (b) results of the grid-independence test.

Table 1: Results of the grid-independence test for the simplified model.

No.	Local Refinement Size (mm)	Number of Cells	Gas Phase Volume (mm ³)	Gas Phase Volume Fraction (%)
1	0.3	185,000	14,256.4	3.801
2	0.25	268,000	13,256.8	3.434
3	0.2	412,000	12,253.3	3.266
4	0.15	635,000	12,216.8	3.257
5	0.1	1,024,000	12,197.6	3.252

3 Experimental Verification

3.1 Experimental Setup

The experiments of the composite rotating hydrodynamic cavitation generator are carried out in closed loop as shown in Fig. 7, where a 1.5 kW, 380 V three-phase asynchronous motor was equipped with a WB620 vector frequency converter featuring a speed regulation range of 0–5000 rpm and a control accuracy of ± 1 rpm; an ISW40-160 circulating centrifugal pump guaranteed stable fluid delivery, while the LDG-DN40 electromagnetic flowmeter with a range of 0.8–12 m³/h and an accuracy of $\pm 0.5\%$ was used for flow monitoring. PT124G-210 pressure sensors installed at the inlet and outlet had a measuring range of 0–1.0 MPa and an accuracy of $\pm 0.4\%$. Besides, stainless steel ball valves and a 30 L anti-corrosion sealed water tank were applied for pipeline control and solution storage. All experimental devices were fully calibrated before tests to ensure the authenticity and reliability of experimental data, and the experimental operation process was kept the same as before.

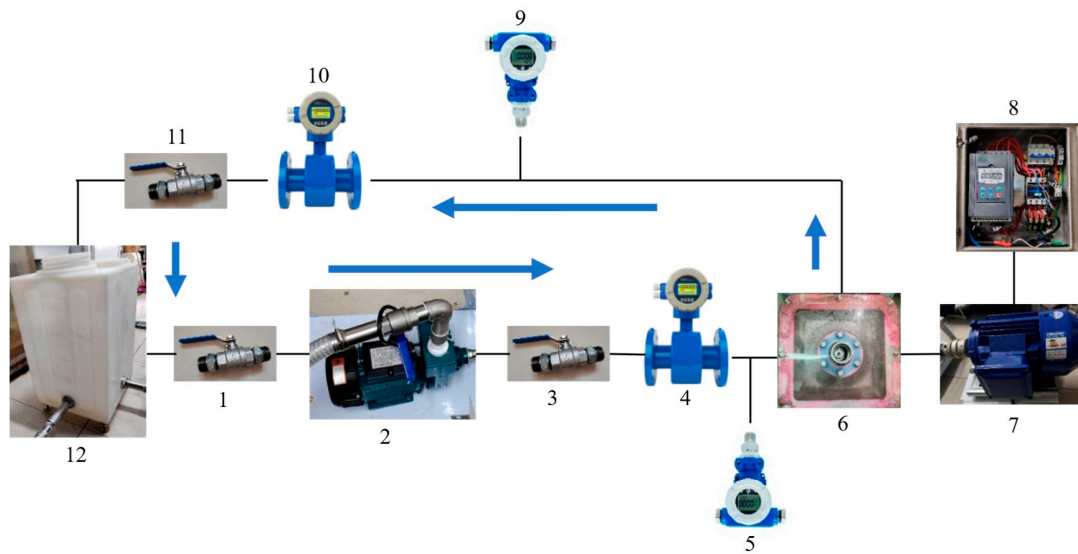


Figure 7: Experimental setup (No. 1 is a ball valve, No. 2 is a centrifugal pump, No. 3 is a ball valve, No. 4 is a solenoid flow meter, No. 5 is a pressure sensor, No. 6 is a cavitation generator, No. 7 is an electric motor, No. 8 is a frequency converter, No. 9 is a pressure sensor, No. 10 is a solenoid flow meter, No. 11 is a ball valve, and No. 12 is a water tank).

Prior to the start of the experiment, to ensure the safety and accuracy of the capacity, the ball valve No. 1 and No. 11 were closed, and the water tank was filled to 30 L. Afterward, the ball valve No. 1 and No. 14 were opened, and the flow rate was regulated through the adjusting valve No. 3. A solenoid flow meter No. 4 displays the flow rate in a range of 0.8–12 m³/h. A WB620 vector inverter No. 8 is used to control the motor speed. Pressure sensors (No. 5, No. 9) were used at the inlet and outlet to detect the data with a measuring accuracy of $\pm 0.4\%$. The solution passes through the inlet of the cavitation generator No. 6, driven by the centrifugal pump 2, and under the action of the movable and stator, the solution re-flows into the water tank No. 12.

3.2 Rhodamine B Decolorization Experiment

To study the decolorization performance of the composite rotary cavitation generator, rhodamine B aqueous solution (typical printing and dyeing wastewater) was chosen as the experimental object in this paper. The experimental steps were as follows: firstly, a fixed mass of rhodamine B powder was weighed by

an electronic balance, put into a dilution bucket, added deionized water to 15 L, and stirred well. Before the start of the experiment, to ensure the safety and accuracy of the volume, close ball valve 1 and ball valve 13, and then pour the solution in the dilution bucket into the experimental water tank of the decolorization system. Before each experiment, a low-power centrifugal pump was used for a 10 min cycle, at which time the reactor was kept at a low speed of 600 rpm to ensure that the solution was mixed uniformly, and the solution was sampled at the end to determine the initial concentration of the solution.

According to different requirements for rotational speed, inlet velocity, and initial concentration, adjusting the frequency converter to set the rotational speed of the compound rotary cavitation generator, adjusting the valve 3 to set the inlet velocity, and controlling the quality of rhodamine B powder can set the initial concentration. When the compound rotary cavitation generator is running for 20 min, 40 min, 60 min, 80 min and 100 min, adjust the frequency converter to steadily reduce the rotational speed to zero, take samples and retain them through the sampling port of the water tank, and measure the temperature of the solution at this time through a thermometer.

The standard curve of absorbance-concentration of rhodamine B solution has been measured by a UV spectrophotometer and the standard curve equation has been obtained:

$$Y_{RhB} = 0.25575C_{RhB} + 0.0587 \quad (9)$$

where Y_{RhB} is the absorbance value, C_{RhB} is the mass concentration of rhodamine B solution.

The concentration of rhodamine B solution can be obtained by measuring the absorbance of the sample retained rhodamine B solution, and then calculating the decolorization rate. The formula for calculating the decolorization rate is as follows:

$$\frac{C_{RhB0} - C_{RhB1}}{C_{RhB0}} \times 100\% = \frac{Y_{RhB0} - Y_{RhB1}}{0.25575C_{RhB0}} \times 100\% \quad (10)$$

3.2.1 Effect of Mover Speed on Decolorization Performance

90 mg of rhodamine B powder was dissolved in deionized water and configured into a rhodamine B solution with a volume of 15 L, which was stirred uniformly to obtain a rhodamine B solution with an initial concentration of 6 mg/L. The initial water temperature was set to 25°C. The initial inlet velocity was set to 1 m/s. The frequency converter was adjusted to control the motor speed at 3000 rpm, 3300 rpm, 3600 rpm and 3900 rpm, set the initial water temperature at 25°C and adjust the valve to set the initial inlet velocity at 1 m/s. The centrifugal pump was energized and started to work, so that the rhodamine B solution flowed through the cavitation generator for several times to be degraded finally. During the experiment, the solution was collected through the water valve of the water tank every 20 min for the measurement of absorbance, and the concentration and decolorization rate were determined from the absorbance, and the total cycle time was 100 min.

According to Fig. 8, after the solution was circulated under hydrodynamic cavitation for 100 min, the decolorization rate showed a tendency to increase and then decrease with the increase in rotational speed. When the rotational speed of the mover reaches 3000 rpm, the decolorization rate of the rhodamine B solution is only 16.5%; when the rotational speed is increased to 3600 rpm, the decolorization rate of the rhodamine B solution is 35.1% (experimental results are shown in Fig. 9), which rises significantly compared to the previous one, which is mainly due to the fact that as the rotational speed rises, it will strengthen the cavitation phenomenon of the flow separation on the side of the fixed teeth as well as on the ground. It also enhances the vortex cavitation in the kinematic pit, which promotes the release of -OH. When the

rotational speed was further increased to 3900 rpm, the decolorization rate was 32.5%, which was reduced compared with 3600 rpm, which was mainly due to the high rotational speed of the mover, which led to the generation of a super-cavitation phenomenon inside the cavitation generator, and it was easy to form a stable cavity, which led to the slowing down of the rate of the collapse of the vacuole, and ultimately reduced the rate of the reaction of the cavitator in the decolorization of the organic matter.

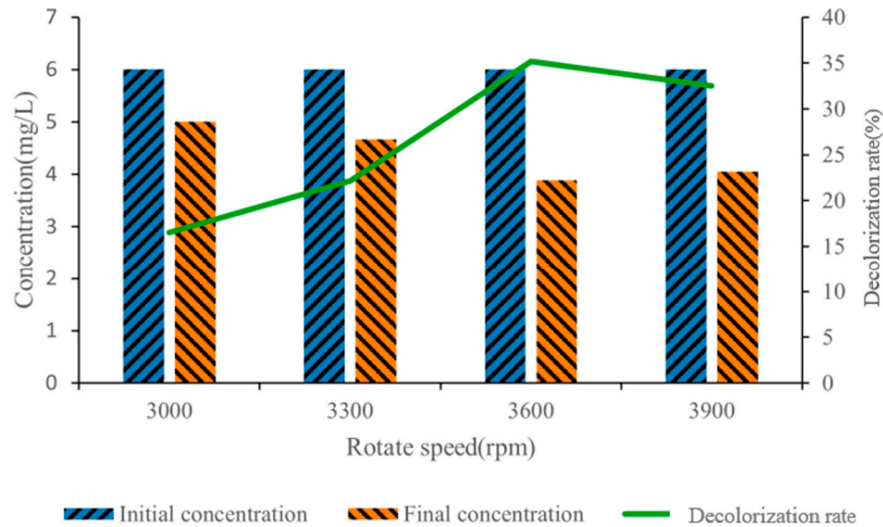


Figure 8: Changes in the concentration of rhodamine B solution and its final decolorization rate at different speeds.

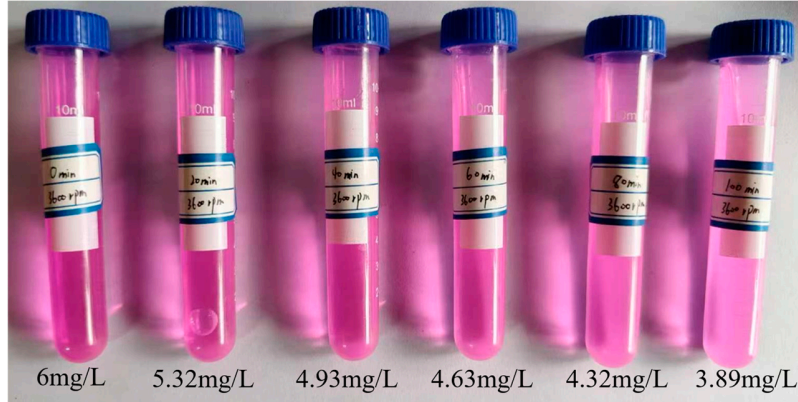


Figure 9: Variation of solution concentration at 3600 rpm.

3.2.2 Effect of Inlet Flow on Decolorization Performance

90 mg of rhodamine B powder was dissolved in deionized water to configure a rhodamine B solution with a volume of 15 L, which was stirred well to obtain a rhodamine B solution with an initial concentration of 6 mg/L. The motor speed was set to 3600 rpm. The motor speed was set to 3600 rpm, the initial water temperature was set to 25°C, and the initial inlet velocity was set to 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s. The centrifugal pump was energized and started to work, so that the rhodamine B solution flowed through the cavitation generator for several times to be degraded finally. During the experiment, the solution was collected through the water valve of the water tank every 20 min for measuring the absorbance, and the concentration and decolorization rate were found from the absorbance, and the total cycle time was 100 min.

According to Fig. 10, the decolorization rate of solutions with different inlet velocities shows a trend of increasing and then decreasing after circulating inside the cavitation generator for 100 min. When the inlet velocity is increased from 0.5 m/s to 1 m/s, the decolorization rate is elevated, and the higher inlet velocity will bring higher inlet velocity, resulting in more circulation of the solution. The turbulence effect in the cavitation generator will also be enhanced with the increase in inlet velocity, the kinetic energy of the fluid will be enhanced, and the probability of generating separation cavitation and vortex cavitation in the cavitation generator will be enhanced. When the inlet velocity is increased from 1 m/s to 2 m/s, the decolorization rate decreases from 35.17% to 31.83%, and the decolorization rate does not change much, showing a slightly decreasing trend. Although the increase in inlet velocity increases the number of cycles of the solution inside the cavitation generator, the overall effect is not obvious. This is mainly due to the fact that a larger inlet velocity causes the solution to have a greater radial velocity, and the solution will more easily leave the region of action between the mover and stator of the cavitation generator. Separate cavitation and vortex cavitation in the cavitation generator will be more dependent on the circumferential velocity of the solution, and the radial velocity of the solution will have an adverse effect on the formation of the circumferential velocity of the solution.

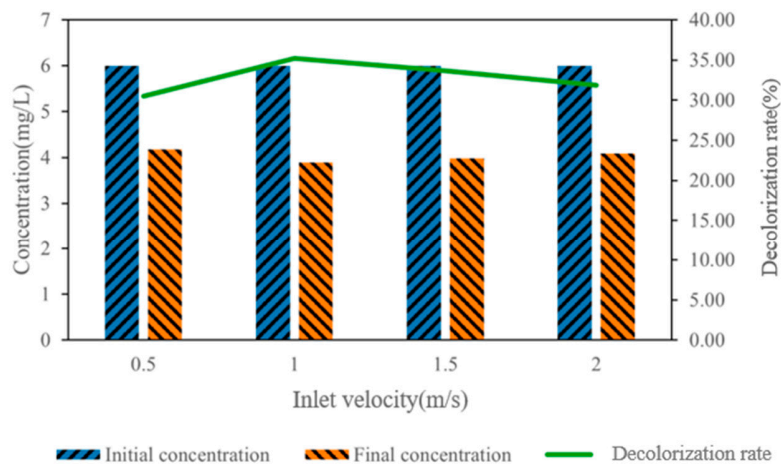


Figure 10: Changes in the concentration and final decolorization rate of rhodamine B solution at different inlet flows.

3.2.3 Effect of Initial Concentration on Decolorization Performance

60 mg, 90 mg, 120 mg of rhodamine B powder was dissolved in 5 L of deionized water, stirred well, then added 10 L of water to dilute to 4 mg/L, 6 mg/L, 8 mg/L rhodamine B solution, stirred well and then poured into the water tank. The motor speed was set to 3600 rpm, the initial water temperature was set to 25°C, and the initial inlet velocity was set to 1 m/s. The centrifugal pump was energized and started to work, so that the rhodamine B solution flowed through the cavitation generator several times to be degraded. During the experiment, the solution was collected through the water valve of the water tank every 20 min for the measurement of absorbance, and the concentration and decolorization rate were determined from the absorbance, and the total cycle time was 100 min.

According to Fig. 11, the decolorization rate of solutions with different concentrations showed an increasing and then decreasing trend after circulating inside the cavitation generator for 100 min. When the initial concentration of rhodamine B solution was 2 mg/L, the decolorization rate of rhodamine B solution was only 27.1%; when the initial concentration of rhodamine B solution was increased to 10 mg/L, the decolorization rate of rhodamine B solution was 42.9% (the experimental results are shown in Fig. 12),

which was increased compared with 2 mg/L. This was due to the low initial concentration, resulting in a low content of rhodamine B molecules in water, and the $\cdot\text{H}$ and $\cdot\text{OH}$ (hydroxyl radicals) produced by cavitation existed for a short period of time, which made it difficult to have a decolorization reaction with the rhodamine B molecules, and thus the decolorization rate was low. Further increase the concentration of rhodamine B solution to 14 mg/L, the decolorization rate is 36.5%, and 10 mg/L compared with the decline, which is mainly in a fixed size scale, fixed process conditions (rotational speed of the mover and the inlet velocity) conditions, the total amount of hydroxyl radicals produced by the cavitation generator as well as oxidizable substances will not change too much when the concentration of more than 10 mg/L, not enough to decolorization of all rhodamine B molecules, resulting in a decrease in the decolorization rate.

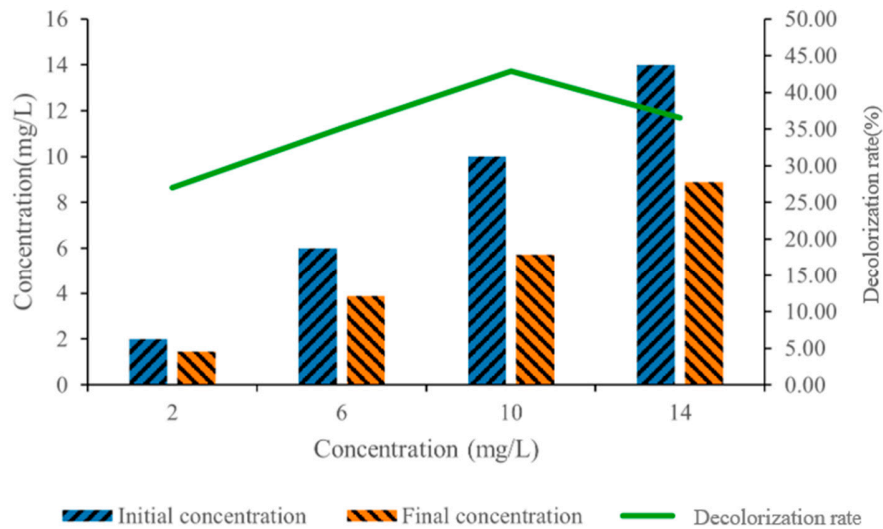


Figure 11: Changes in the concentration of rhodamine B solution and its final decolorization rate at different initial concentrations.



Figure 12: Variation of solution concentration at 10 mg.

3.3 Experimental Verification

In the actual shooting process, due to the obvious effect of turbulence inside the cavitation directional apparatus and the need to shoot the light through the stator, cover and lens, the transparency of the shooting is not good, and it is difficult to be verified directly. Therefore, with the chemical effect of cavitation, the high temperature and high pressure brought about by the collapse of cavitation bubbles will lead to the

decomposition of water vapor and the production of $\cdot\text{OH}$ and H_2O_2 with strong oxidizing properties through a series of chemical reactions, as shown in Eqs. (11)–(19). They can react with organic matter to break it down by oxidizing it. Based on this principle, rhodamine B solution was employed as a trapping agent for hydroxide after cavitation in this experiment to indirectly reflect the cavitation performance of the composite cavitation generator [30].



$$Y_{\text{RhB}} = 0.25575 C_{\text{RhB}} + 0.0587 \quad (20)$$

where Y_{RhB} is the absorbance value, C_{RhB} is the mass concentration of rhodamine B solution.

A UV-visible spectrophotometer (UV-1900i) was used to measure the absorbance values of 2 mg/L, 4 mg/L, 6 mg/L, 8 mg/L, and 10 mg/L solutions of Rhodamine B at the maximum absorption wavelength of 554 nm. Three measurements were taken and the average value was taken. The relationship curve between rhodamine B mass concentration and absorbance value obtained after data fitting and the relationship equation are shown in Fig. 13 with Eq. (20). Based on the difference in absorbance of the solution before and after decolorization and the standard curve, the difference in concentration of rhodamine B solution can be obtained, and then the decolorization rate can be solved. The decolorization rate of rhodamine B solution after fixed time cavitation treatment can be calculated by the following formula:

$$\frac{C_{\text{RhB}0} - C_{\text{RhB}1}}{C_{\text{RhB}0}} \times 100\% = \frac{Y_{\text{RhB}0} - Y_{\text{RhB}1}}{0.25575 C_{\text{RhB}0}} \times 100\% \quad (21)$$

where $C_{\text{RhB}0}$ is the concentration of rhodamine B solution before decolorization, $C_{\text{RhB}1}$ is the concentration of rhodamine B solution after decolorization, $Y_{\text{RhB}0}$ is the absorbance of rhodamine B solution before decolorization and $Y_{\text{RhB}1}$ is the absorbance of rhodamine B solution after decolorization.

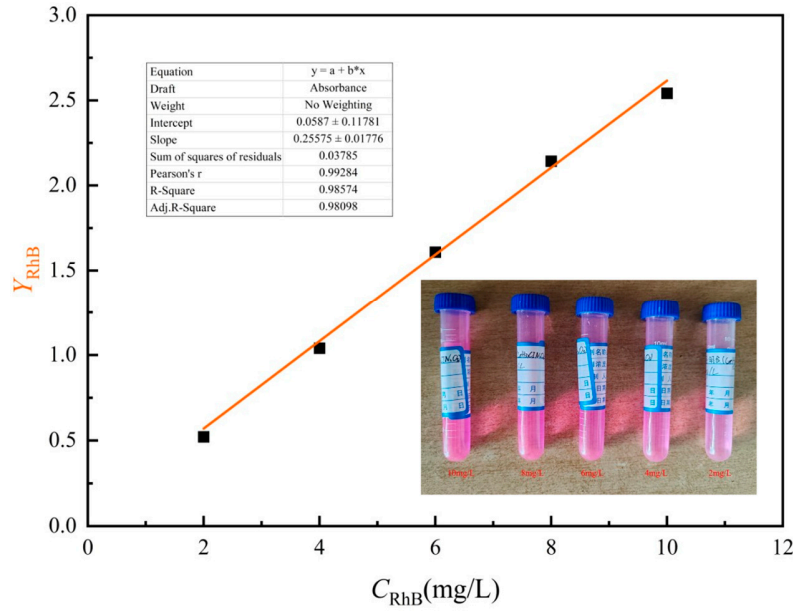


Figure 13: Linear fitting relationship between Y_{RhB} and C_{RhB} .

Rhodamine B powder was dissolved in water and then stirred repeatedly until it was completely dissolved during the test. As the centrifugal pump used for circulation itself also exists cavitation, to avoid its impact on the results of the experiment, the experiment to take the overall non-circulation. The cavitation generator was filled to carry out high-speed rotation experiments, in which the initial water temperature was controlled at 25°C, the volume of the solution was 1.425 L of the volume of the cavitation generator, and the experimental time was 120 min. 120 min of the solution was taken for the absorbance test. The rotational speeds were set to 2600 rpm, 2800 rpm, 3000 rpm, 3200 rpm, 3400 rpm, and 3600 rpm, as shown in Fig. 14. When the rotational speeds ranged from 2600 rpm to 3600 rpm, the decolorization rate and the cavitation volume maintained a similar growth trend, which proved the validity of the simulation model and results. Due to the strong turbulence effects inside the cavitation generator and the need for light to pass through the stator, cover, and lens, the transparency during imaging was poor, making direct high-speed visualization difficult under current experimental conditions. In future work, advanced high-speed imaging systems with optimized illumination (e.g., high-power pulsed LED) is used to capture the transient cavitation flow patterns inside the device, which will further validate the numerical simulation results and provide deeper insight into the cavitation mechanism. It is widely acknowledged that liquid temperature and system static pressure exert prominent regulatory effects on cavitation evolution. Raised temperature lowers saturated vapor pressure to promote bubble nucleation, while elevated system pressure can restrain supercavitation and expand the stable rotational speed range for cavitation reaction. To eliminate coupled interference from temperature and pressure variation in this work, all decolorization experiments were conducted under constant 25°C and fixed inlet gauge pressure, focusing on the independent influence of rotational speed, inlet velocity and pollutant concentration. Relevant gradient temperature and pressure tests will be carried out in our follow-up study to further optimize the stable operating window of the composite cavitation generator.

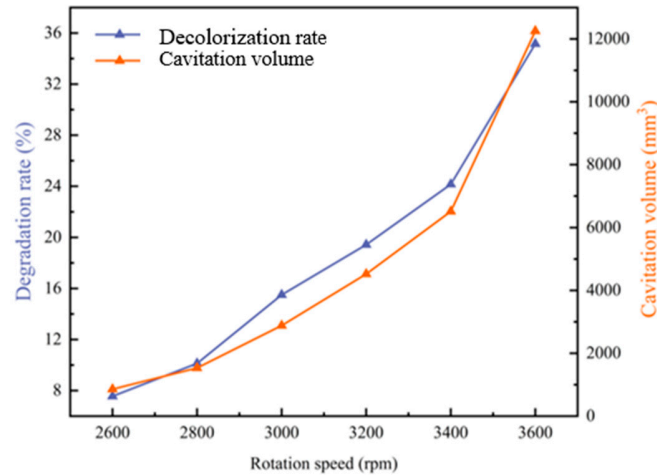


Figure 14: Decolorization rate and cavitation volume of rhodamine B solution.

4 Discussion

4.1 Flow Field Analysis

4.1.1 Radial Flow Field Analysis

To analyze the evolution pattern of the cavitation bubbles in the radial direction, an intermediate cross section parallel to the surface of the kinton was analyzed, as shown in Fig. 15. The time span selected was the five moments of the start-entry-exit of the kinton on the mover to be observed.

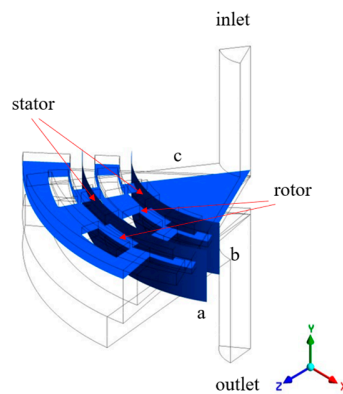


Figure 15: Three planes for calculating energy utilization options.

Fig. 16 shows the evolution of pressure, velocity, gas phase, and turbulent kinetic energy in the radial direction of the moving disk. The transient contour cloud fully reflects the coupled evolution law of radial separation cavitation, which cannot be captured via single-plane analysis in traditional research. At time T of 0.231 ms, the rotor rotates counterclockwise and the overflow section formed with the stator narrows. Fluid with a fluid velocity of 24.3 m/s flows through the flow channel gap, forming a flow separation phenomenon. When the liquid pressure is reduced to below the saturation vapor pressure, the low pressure region is generated on the side of the stator's tooth structure, and cavitation bubbles are generated in the in-flow separation zone. From 0.462 ms to 0.924 ms, the moving teeth and the fixed teeth are further staggered from further intersecting to completely intersecting, and the structure similar to that of a Venturi tube is gradually formed. The cavitation in the separation zone develops further, and the

cavitation area on the front and rear sides of the stator tooth structure increases further. Radial flow field cavitation phenomenon is dominated by separation cavitation, and a small amount of vortex cavitation. The circumferential velocity of the fluid between the moving teeth increases with the increase in diameter, and the peak of the circumferential velocity occurs in the gap region between the moving teeth and the stator teeth. Between the moving teeth, the fluid is subjected to inertial centrifugal force, which generates the flow velocity from the inner ring between the moving teeth to the outer ring between the fixed teeth. The movable teeth of the outer ring, due to their high rotational speed, generate the flow velocity from between the movable teeth of the outer ring to between the fixed teeth of the outer ring, so that a vortex is formed in a localized region between the fixed teeth, and the center of the vortex corresponds to a localized negative pressure region. At T is 1.155 ms, the overflow section formed by the rotor and stator increases, the static pressure recovers, the cloud cavitation wake bubble formed in the flow separation region gradually falls off, and the bubble collapses, resulting in the turbulence kinetic energy enhancement in the wake. Due to the influence of centrifugal force, some of the tail bubbles flow from the gap to between the stators, between the motors, and at the periphery of the cavitation generator, and collapse under the impact of the fluid. At T of 1.617 ms. Although the cavitation bubbles are not completely collapsed, the whole flow field will start to produce new bubbles again under the reduction of the gap. The cloud cavitation tail formed by flow separation still has bubbles coming off, forming a dynamic cycle in which the gas phase volume will gradually stabilize. Compared with single-structure cavitation reactors that only generate scattered single-direction cavitation bubbles, the staggered double-row tooth layout in this work continuously forms wide low-pressure separation zones in the radial clearance. The continuous vapor source produced by radial separation cavitation further coordinates with circumferential vortex cavitation to expand the total cavitation coverage area, which is the core structural advantage of the composite design proposed in this paper.

4.1.2 Circumferential Flow Field Analysis

Since the outer flow channel and the inner flow channel have similar flow field characteristics and cavitation characteristics, the outer flow channel is taken as the object of analysis. To analyze the evolution of cavitation bubbles in the circumferential direction, a cylindrical surface with the center point of the cavitation generator, a radius of 71 mm, and an angle of 80° is selected for observation (shown in Fig. 15). The distribution of velocities, pressures, gas phases, and turbulent kinetic energies of Pitter a and Pitter b are analyzed, as shown in Fig. 17. The periodic flow field distribution reveals the exclusive circumferential vortex cavitation synergistic effect brought by the composite pit-tooth matching design. The five moments correspond to the key phases of pit-tooth interaction in the circumferential direction and cover a complete interaction cycle. For analytical convenience, only the evolution pattern from Pitter a motion to Pitter b is analyzed. At T of 0.231 ms, macroscopically the pits on the mover and the fixed teeth of the stator are interlaced with each other, and from the cross-section Pitter a is interlaced with Fixed tooth a, and Pitter b is interlaced with Fixed tooth b. The flow channel forms a structure similar to that of a Venturi tube, and the velocity of the fluid out of the gap increases, forming a localized low-pressure region, and forming the flow-separated cavitation zone. The direction of cavitation development driven by the rotational speed spreads from the wedge angle at the bottom of the fixed tooth to the pit of the moving tooth. From T 0.462 ms to 0.924 ms, the process of Pitter a approaching fixed tooth a, the shear cavitation develops continuously, and the cavitation bubbles gathered at the bottom of fixed tooth a detach from the inside of Pitter a. The cavitation bubbles at the bottom of fixed tooth a detach from the inside of Pitter a. The pushing action of the Pitter wall produces a liquid flow direction inside the Pitter that is consistent with

the direction of rotation. At the same time, a vortex will be formed inside the Pitter because the absolute flow velocity is much lower than the rotor motion, forming a reverse flow with a speed of about 21 m/s. However, influenced by the separation cavitation at the bottom of the fixed tooth, this vortex is not large in size and the intensity of the resulting vortex cavitation is not large. From T 1.155 ms to 1.617 ms, which can be viewed as the process of the Pitter a leaving the fixed tooth a, an obvious phenomenon of turbulent kinetic energy growth can be observed at T 1.617 ms in the tail of the cavitation bubble aggregation. This is produced by the tangential velocity of the fluid on the one hand, and the collapse of the cavitation bubbles in the tail on the other hand. Throughout the flow, the flow field in the circumferential direction is dominated by separated cavitation, with a small amount of vortex cavitation present. The circular pits help the fluid flow smoothly from one pit to another under the driving of the mover, accelerating the fluid exchange and avoiding the occurrence of fluid clogging. The matching relationship between the stator tooth bottom and the cylindrical pits on the mover forms multiple Venturi-like channels in the circumferential direction, which induces stable vortex cavitation and prolongs the residence time of cavitation bubbles. This matching mode cannot be realized by traditional flat single-tooth or simple pit rotors, which reflects the unique synergistic cavitation mechanism brought by the composite tooth-pit integrated design.

In the field of hydrodynamic cavitation, cavitation number and rotational Reynolds number are standard dimensionless indicators to quantify cavitation intensity and turbulent shear intensity, which can support horizontal comparison among different reactor configurations. The current analysis mainly focuses on the intuitive distribution of vapor phase, pressure and turbulent kinetic energy under fixed experimental conditions, while systematic quantitative calculation of the above dimensionless parameters will be completed in our follow-up research.

4.2 Response Surface-Based Optimization of Process Parameters

4.2.1 Response Surface Experimental Program Design

In this section, the rotational speed, inlet velocity, and initial concentration of the composite rotary cavitation generator are taken as the influencing factors, and the Design-Expert 13.0 software is applied to design the experiments using the BBD for the three significant factors, namely, rotational speed, inlet velocity, and initial concentration. The response surface experimental factor and level design is shown in Table 2. A total of 17 experiments were conducted in this section and the experimental design and results are shown in Table 3.

Table 2: Experimental factors and horizontal design of response surfaces.

Level	Rotation Speed A (rpm)	Inlet Velocity B (m/s)	Initial Concentration C (mg/L)
−1	3300	0.5	6
0	3600	1	10
1	3900	1.5	14

Table 3: Experimental design and results.

No	Rotation Speed A (rpm)	Inlet Velocity B (m/s)	Initial Concentration C (mg/L)	Decolorization Rate (%)
1	3300	0.5	10	28.3
2	3900	0.5	10	32.8
3	3300	1.5	10	30.6
4	3900	1.5	10	31.8
5	3300	1	6	28.3
6	3900	1	6	30.3

Table 3: Cont.

No	Rotation Speed A (rpm)	Inlet Velocity B (m/s)	Initial Concentration C (mg/L)	Decolorization Rate (%)
7	3300	1	14	29.5
8	3900	1	14	35.8
9	3600	0.5	6	34.4
10	3600	1.5	6	36.7
11	3600	0.5	14	37.2
12	3600	1.5	14	39.1
13	3600	1	10	42.6
14	3600	1	10	41.8
15	3600	1	10	42.9
16	3600	1	10	42.5
17	3600	1	10	42.8

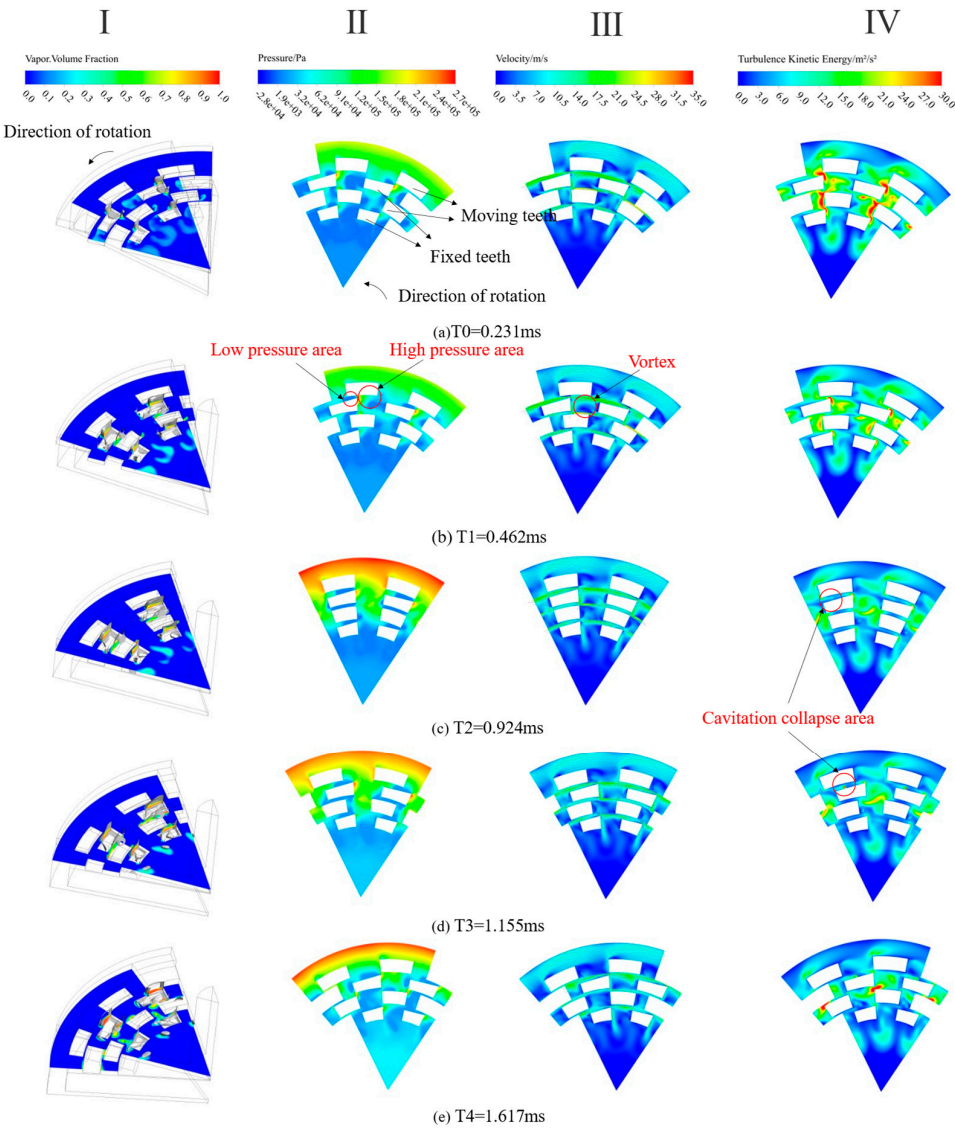


Figure 16: Cavitation generated in the radial flow field during one interaction cycle from 0.231 ms to 1.617 ms (a–e). (I) Cross-sectional gas-phase distribution diagram and gray equivalent surface indicating the gas-phase volume of 0.1; (II) pressure distribution diagram; (III) velocity vector diagram; (IV) turbulent kinetic energy distribution plot.

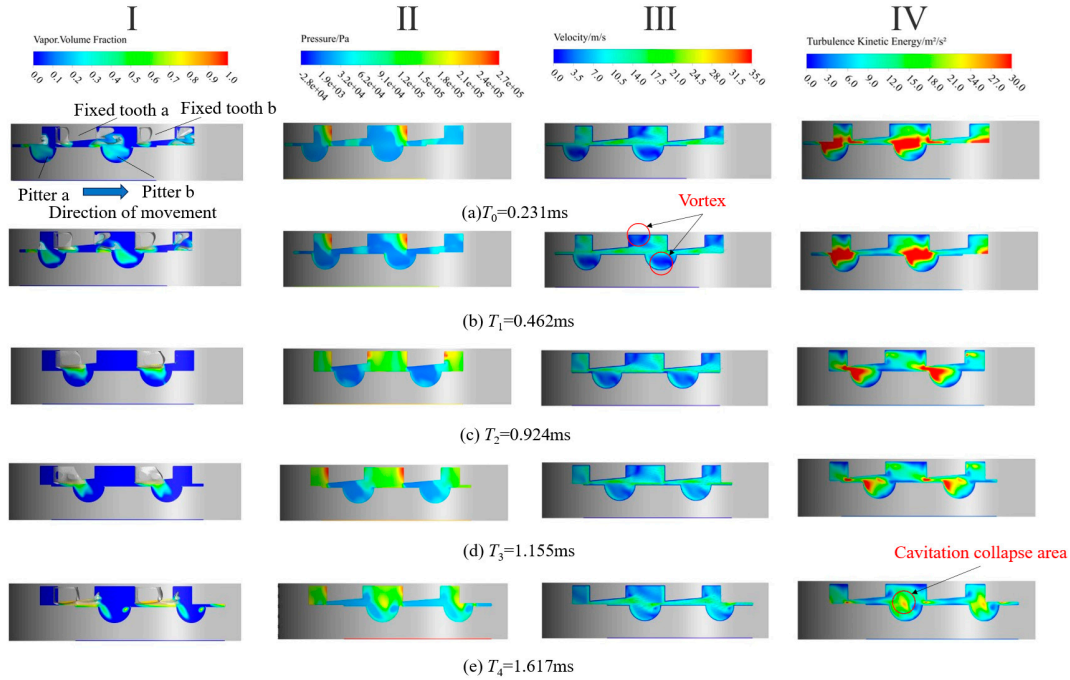


Figure 17: Cavitation generated in the flow field in the circumferential direction during one interaction period from 0.231 ms to 1.617 ms (a–e). (I) Cross-section gas-phase distribution and gray equivalent surface indicating gas-phase volume of 0.1; (II) pressure distribution; (III) velocity vector; (IV) turbulent kinetic energy distribution.

4.2.2 Response Surface Result Analysis

Design Expert 13.0 was used to analyze the data in Table 3. The quadratic regression equation for the model is as follows:

$$Y = -1269.08 + 0.70A + 47.09B + 0.65C - 6.01e^{-3}AB + 8.96e^{-4}AC - 0.025BC - 9.83e^{-5}A^2 - 11.87B^2 - 0.17C^2 \quad (22)$$

The response surface 3D maps of the interaction between the two of rotational speed, inlet flow and initial concentration were plotted by combining Design-Expert software with Origin software, as shown in Fig. 18.

As shown in Fig. 18a, under the influence of the intersection of rotational speed A and inlet velocity B, a fixed inlet velocity B was selected, and with the change of rotational speed in the range of 3300–3900 rpm, the decolorization rate of rhodamine B solution changed substantially, which made the steepness of the curved surface very obvious, and the decolorization rate showed a tendency of increasing and then decreasing. When the rotational speed A was fixed, and when the inlet velocity B was varied in the range of 0.5–1.5 m/s, the magnitude of the change in the 3D graph was weakened compared to the trend of the change in the decolorization rate of rhodamine B solution produced by fixing the inlet velocity B and using rotational speed A as the independent variable. In summary, the effect of rotational speed A on the decolorization rate of rhodamine B solution was more significant than that of inlet velocity B. As shown in Fig. 18b, the 3D plot of the reciprocal response of the inlet velocity B and the initial concentration C showed that, when the initial concentration C was fixed, and the inlet velocity B was used as the independent variable, and the decolorization rate of the rhodamine B solution was used as the dependent variable, the decolorization rate surface in the 3D plot showed the trend of first increasing and then decreasing. The

decolorization rate surface in the 3D graph showed a trend of first increasing and then decreasing. On the other hand, when looking at the image trend of the inlet velocity B alone, when the inlet velocity B varied within the range of 0.5–1.5 m/s, the 3D graph only showed a slight fluctuation, and the surface showed a relatively smooth fluctuation. This indicates that the influence of the factor of inlet velocity B on the decolorization rate is not very significant. As shown in Fig. 18c, under the influence of the intersection of rotational speed A and initial concentration C, choosing to fix the initial concentration C, with the change of rotational speed A in the range of 3300–3900 rpm, the decolorization rate of the rhodamine B solution changed substantially, which made the steepness of the surface very obvious, and the decolorization rate showed a tendency of increasing and then decrease. When the initial concentration C was varied in the range of 6–14 mg/L by fixing the rotational speed A, the magnitude of change in the 3D graph was weakened compared with that of the decolorization rate of rhodamine B solution by fixing the initial concentration C and using rotational speed A as the independent variable.

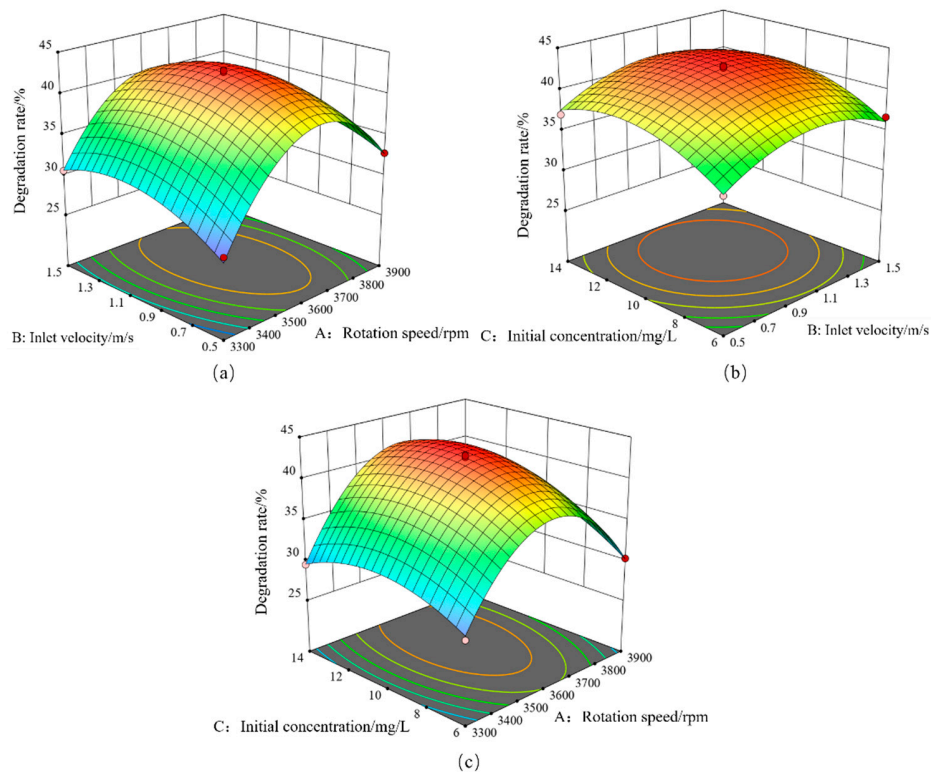


Figure 18: Three-dimensional response of rotational speed a, inlet velocity B, and initial concentration C to decolorization rate (a–c).

To maximize the predicted value of the response value decolorization rate and make the best results, the conditions were optimized using an effective regression model, and the optimal solution was obtained using the response surface software prediction module, and the optimized objective function and mathematical model are as follows:

$$\begin{cases} Y_1(\text{Degradation rate})(\text{Max}) \\ 3300 \leq A \leq 3900 \\ 0.5 \leq B \leq 1.5 \\ 6 \leq C \leq 14 \end{cases} \quad (23)$$

The actual values of the factors corresponding to the optimal conditions were obtained as follows: the rotational speed A was 3633.92 rpm, the inlet velocity B was 1.05 m/s, and the initial concentration C was 11.13 mg/L. The model predicted a decolorization rate of 42.9% with a confidence level of 0.994, and the predicted results of the optimal parameters are shown in Fig. 19. Considering the actual conditions and operability, the parameters were set to 3630 rpm for rotational speed A, 1.05 m/s for inlet velocity B, and 11.1 mg/L for initial concentration C. Three repetitions of the test were carried out to obtain the validation results using these conditions, resulting in an average cavitation rate of 42.6%, and the relative errors between the measured and predicted values were 1.39%, 2.33%, and 1.63%. The relative error between the predicted and measured values was less than 5%, and the specific test results are shown in Table 4. The response predicted values were basically consistent with the actual test values, which also verified the accuracy and reliability of the model, and the optimal process parameters were obtained and practically applied. Most existing rotary cavitation studies only discuss single-factor changing rules and cannot obtain the global optimal parameter combination under multi-factor coupling. The response surface optimization system adopted in this paper quantitatively distinguishes the significance order of different operating factors, and the verified prediction model can directly guide the matching of actual working conditions, forming a complete performance evaluation system different from previous single-factor experimental schemes.

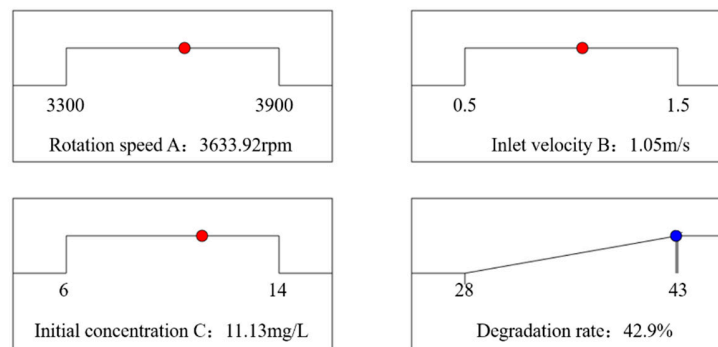


Figure 19: Optimal parameter prediction chart.

Table 4: Validation test results table.

No	Parameters			Decolorization Rate (%)
	Rotation Speed A	Inlet Velocity B	Initial Concentration C	
1				42.3
2	3630	1.05	11.13	41.9
3				43.6
Average value				42.6

To further verify the rationality of the experimental results and clarify the performance positioning of the proposed composite generator, the optimal operating parameters and degradation performance obtained in this work are compared with typical rotary hydrodynamic cavitation reactors in existing literature, as elaborated below.

In terms of optimal rotational speed, most conventional single-structure rotary cavitation devices (e.g., single-row toothed disc and single-pit rotor reactors) achieve the best cavitation degradation performance in the range of 3000–5000 rpm. The optimal rotational speed obtained in this study is 3633.92 rpm, which falls within the widely recognized reasonable interval. Benefiting from the composite design of double-row

stator teeth and cylindrical pits on the mover, the proposed reactor can trigger strong synergistic cavitation at a relatively lower rotational speed. Compared with some single-structure reactors that require speeds above 4000 rpm to reach similar cavitation intensity, this device has a lower effective speed threshold, which helps reduce operating energy consumption.

For inlet velocity, the optimal value of 1.05 m/s in this work is consistent with the typical operating range (0.8–2.0 m/s) of low-inlet-pressure rotary cavitation reactors. Unlike venturi or orifice plate cavitation devices that usually rely on high inlet velocity (3–10 m/s) to generate sufficient pressure drop, rotary cavitation reactors mainly depend on high-speed shear of rotating components to induce cavitation, thus imposing lower requirements on inlet pumping power. The inlet velocity range obtained in this study conforms to the inherent flow characteristics of rotary cavitation systems.

With regard to initial concentration and degradation rate, for Rhodamine B degradation, previous studies on single toothed-disc rotary cavitation reactors reported a decolorization rate of 60%–75% under an initial concentration of around 10 mg/L with 30 min treatment, while optimized pin-disc reactors achieved a decolorization rate of 70%–82% under similar conditions. It should be emphasized that decolorization efficiency is highly dependent on experimental parameters including treatment duration, reactor geometry and circulating-flow setup, so direct cross-comparison of decolorization percentage values from different studies is not rigorous. In this work, the composite reactor obtains a decolorization rate of 42.9% at the optimal initial concentration of 11.13 mg/L under 100 min operation. Rather than pursuing higher absolute decolorization percentage under identical test conditions, this result verifies that the dual-cavitation synergistic effect of flow-separation cavitation and vortex cavitation within the proposed composite structure can effectively enhance pollutant degradation capacity, and enables effective cavitation excitation at a relatively moderate rotational-speed threshold.

It should be noted that slight differences in absolute degradation rate across different studies are mainly attributed to variations in reactor volume, total treatment time and rotor-stator matching structure. On the whole, the variation trends of degradation performance with operating parameters are highly consistent with existing literature, and the performance improvement brought by the composite structure matches the expected design objectives.

The variation of degradation performance is essentially governed by the evolution of internal cavitation flow fields. Combined with CFD data of static pressure, vapor volume fraction, velocity and turbulent kinetic energy, the physical mechanisms are analyzed as follows:

Within a reasonable range, rising rotational speed increases the relative velocity between mover pits and stator teeth in radial and circumferential gaps, enhancing flow shear. This expands the low-pressure region below saturated vapor pressure, increases global vapor volume fraction, and elevates gap turbulent kinetic energy, strengthening radical-pollutant mixing and improving degradation rate. Beyond the optimal value (3633.92 rpm), excessive bubble agglomeration weakens collapse energy release, slowing down or slightly reducing degradation efficiency.

At the optimal inlet velocity (~1.05 m/s), moderate through-flow maintains sufficient shear for cavitation initiation, sustains low local static pressure for stable vapor generation, and promotes uniform circumferential distribution of turbulent kinetic energy. Excessively high inlet velocity raises overall cavity pressure, compresses the cavitation region and reduces vapor volume fraction; meanwhile, shortened fluid residence time in the cavitation zone impairs full radical-pollutant contact, lowering degradation performance.

Under fixed operating conditions, the total yield of oxidative free radicals is determined by cavitation intensity (vapor volume fraction, turbulent kinetic energy) and remains stable. As initial Rhodamine B concentration increases, free radicals allocated per pollutant molecule decrease, leading to a lower

degradation rate. CFD results confirm that cavitation distribution and intensity barely change with solution concentration, verifying that the concentration effect is dominated by radical-pollutant ratio rather than flow field variation.

The double-row teeth and cylindrical pit structure form dual cavitation modes (flow separation cavitation and vortex cavitation). CFD results show their alternating distribution in radial and circumferential directions, with superimposed high-shear and high-turbulent-kinetic-energy zones expanding the effective cavitation area, which accounts for the superior degradation performance over traditional single-structure devices.

5 Conclusions

This work designed a new composite rotating hydrodynamic cavitation generator and systematically investigated its cavitation evolution mechanism and organic pollutant degradation performance through coupled numerical simulation and experimental characterization. Distinct from traditional single-tooth or single-pit reactors that only produce one type of cavitation along a single flow direction, the proposed composite tooth-pit layout simultaneously induces flow separation cavitation and vortex cavitation within radial and circumferential gaps, forming abundant multi-cavitation zones to significantly boost energy utilization efficiency. A strong linear correlation $r = 0.947$ between simulated total cavitation volume and measured degradation rate fully verifies the reliability of the established numerical model. Among all tested operating variables, the influence priority is sorted as rotational speed > initial pollutant concentration > inlet flow velocity; the optimal matching parameters for maximum degradation performance are determined to be 3633.92 rpm, 1.05 m/s and 11.13 mg/L, respectively.

Structurally and analytically, this integrated composite design delivers differentiated research progress compared with conventional single-structure cavitation reactors: it realizes dual-directional, dual-mode synergistic cavitation, and adopts dual orthogonal cross-sections to conduct comprehensive flow field analysis, effectively making up for the one-sided unilateral analysis defects of previous literature. The established dual-dimensional cavitation coupling analysis framework and multi-factor collaborative optimization system jointly form the core original contributions of this paper, rather than simple minor structural adjustments based on existing rotor-stator devices, which can provide distinctive theoretical support for the structural upgrading of rotary cavitation equipment.

Corresponding targeted research directions are outlined for subsequent exploration: First, conduct high-speed visualization experiments to observe real-time cavitation flow fields, supplement gradient temperature and system pressure control tests, and complete systematic calculation of universal dimensionless parameters including cavitation number and rotational Reynolds number under multiple working conditions. Liquid temperature and static pressure have significant regulatory effects on cavitation regimes; adjusting system pressure can suppress supercavitation and expand the available stable rotational speed range for testing, while the calculated dimensionless indices will support direct horizontal comparison of cavitation intensity with diverse rotary cavitation reactors reported in existing literature. Second, investigate the impact of surface roughness and cavitation erosion on device performance with reference to existing reviews [30,31], and carry out numerical parameter sensitivity analysis. Third, perform experiments on actual industrial wastewater to verify the practical performance of the reactor. Fourth, optimize structural parameters combined with mature cavitation control methods [32] to further improve cavitation efficiency and service life.

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