Cavitation characteristics analysis of a novel rotor-radial groove hydrodynamic cavitation reactor

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ABSTRACT

Hydrodynamic cavitation was widely used in sterilization, emulsion preparation and other industrial fields. Cavitation intensity is the key performance index of hydrodynamic cavitation reactor. In this study, a novel rotor-radial groove (RRG) hydrodynamic cavitation reactor was proposed with good cavitation intensity and energy utilization. The cavitation performances of RRG hydrodynamic cavitation reactor was analyzed by utilizing computational fluid dynamics method. The cavitation intensity and the cavitation energy efficiency were used as evaluation indicators for RRG hydrodynamic cavitation reactor with different internal structures. The amount of generated cavitation for various shapes of the CGU, interaction distances and rotor speed were analyzed. The evolution cycle of cavitation morphology is periodicity (0.46 ms) in the CGU of RRG hydrodynamic cavitation reactor. The main cavitation regions of CGU were the outflow and inflow separation zones. The cavitation performance of rectangular-shaped CGU was better than the cylindrical-shaped CGU. In addition, the cavitation performance could be improved more effectively by increasing the rotor speed and decreasing the interaction distance. The research results could provide theoretical support for the research of cavitation mechanism of cavitation equipment.

1. Introduction

Hydrodynamic cavitation is accompanied by formation, growth and subsequent collapse of cavitation bubbles. During the collapse process of cavitation bubbles, enormous energy could be released into the surrounding liquid which causes thermal effects [1], mechanical effects [2] and chemical effects [3]. Strongly oxidizing hydroxyl and hydrogen peroxide free radicals (chemical effects) [4], local hotspots with 2300 K ~ 4600 K (thermal effects) [5], shock waves and shear stress of 1000 bar (mechanical effects) [6] are generated by hydrodynamic cavitation. The special liquid environment created by hydrodynamic cavitation could be effectively used to strengthen certain processes, such as sewage treatment [7], emulsion preparation [8] and food processing [9].

During the application of hydrodynamic cavitation, the hydrodynamic cavitation reactor is the generating device of cavitation. An efficient hydrodynamic cavitation reactor could save the application cost and improve the application effect. However, the hydrodynamic cavitation reactors such as orifice plates and venturi tubes have the disadvantages of poor cavitation effect and low energy utilization rate [10]. Therefore, the design of practical and efficient hydrodynamic cavitation reactor is the most important issue of hydrodynamic cavitation technology. In recent years, a variety of new types of hydrodynamic cavitation reactors with good performance have appeared: vortex diodes [11], jet hydrodynamic cavitation reactors [12], self-excited hydrodynamic cavitation reactors [13] and rotary hydrodynamic cavitation reactors [14]. The structure of the reactor is an important factor for the cavitation performance. The pressure drop and flow field characteristics of the new hydrodynamic cavitation reactor are changed by its special internal structure, which affects the cavitation characteristics. The special structure where cavitation occurs is called a cavitation generating unit (CGU). For the cavitation mechanism of reactors, research methods such as experimental flow field visualization, computational fluid dynamics (CFD) simulation and experimental cavitation treatment were widely used. Martin Petkovsek et al. [15] studied the cavitation
effect of a rotary hydrodynamic cavitation reactor consisting of two rotors with opposite radial grooves. The results show that the mechanism of cavitation was the formation of cavitation inside the shear air pockets. Sun Xun [16,17] studied the cavitation flow characteristics of a representative interacting hydrodynamic cavitation reactor. The generation mechanism and development process of cavitation were analyzed through experimental flow field visualization and computational fluid dynamics (CFD) simulations methods. Mandar Badve et al. [18] proposed a new type of cavitation reactor, which consisted of a rotor with grooves and a stator. The strong shear cavitations occur at the grooves, when the liquid entered and exited the grooves with high rotating speeds. Although many studies on novel hydrodynamic cavitation reactors have been published, the basic research on the cavitation mechanism is still limited. The cavitation mechanism of some reactors is still unclear, and there is no suitable metric to quantify the overall cavitation performance of the reactor. These deficiencies affect the optimal design and application development of hydrodynamic cavitation reactor.

This paper is organized as follows. A novel Rotor-Radial Groove hydrodynamic cavitation reactor is proposed in Section 2. Section 3 describes the numerical method including meshing and solver. The transient unsteady cavitation flow field of the reactor under design conditions was simulated, and the generation and development process of cavitation were analyzed in Section 4. Finally, the conclusions are drawn in Section 5.

2. Modeling

2.1. Governing equations

The two-phase flow with turbulent effects is solved using a steady Reynolds-averaged Navier-Stokes (RANS) solver [19,20]. The continuity equations and momentum equations are as follows.

Continuity Equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]  
(1)

Momentum equation:
\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho u_i u_j \right)
\]  
(2)

where \( \rho \) is the density, kg/m\(^3\); \( P \) is the pressure, Pa; \( \mu \) is the dynamic viscosity, Ns/m\(^2\); \( u_i \) is the time-average velocity, m/s.

2.2. Cavitation model

The Zwart-Gerber-Belamri (Zwart) model based on the Rayleigh-Plesset equation was utilized to analyze the cavitation flow behavior [21,22]. Assuming the same bubble radius, when \( P<P_c \), the phase transition rate \( R_c \) of bubble expansion is expressed by Eq. (3) as follows:

\[
R_c = F_{\text{exp}} \frac{3\alpha v (1 - \alpha_v) P_c}{R_b^3} \frac{2(P - P_c)}{3\rho_t}
\]  
(3)

When \( P>P_c \), the phase transition rate \( R_c \) of bubble compression and collapse is expressed by Eq. (4) as follows:

\[
R_c = F_{\text{cond}} \frac{3\alpha v P}{R_b^3} \frac{2(P - P_c)}{3\rho_t}
\]  
(4)

where, \( F_{\text{exp}} \) and \( F_{\text{cond}} \) denote the empirical coefficients of evaporation and condensation (\( F_{\text{exp}} = 50, F_{\text{cond}}=0.01 \)). \( P \) is the flow field pressure, Pa; \( P_c \) is the saturated vapor pressure of the medium at the working temperature, Pa; \( \alpha_v \) is the volume fraction of nucleation points; \( \alpha_t \) is the volume fraction of steam; \( \rho_t \) is the flow field density, kg/m\(^3\); \( \rho_b \) is the vapor density, kg/m\(^3\); \( R_b \) is the bubble radius, m. The evaporation process is calculated by Eq. (3). \( F_{\text{exp}} \) is the evaporation empirical coefficient. The condensation process is calculated by Eq. (4). \( F_{\text{cond}} \) is the condensation empirical coefficient.

2.3. Turbulence model

The turbulent flow field has an important influence on the cavitation characteristics. The turbulence model is the most important issue in CFD numerical simulation. In this paper, the Realizable \( k-\epsilon \) turbulence model was used. The Realizable \( k-\epsilon \) model was more accurate than other models for the calculation of the blind hole’s jet process. There were multiple blind holes in the RRG cavitation reactor. The blind hole is a groove with a rectangular gap of 20 mm long and 2 mm wide. In the Realizable \( k-\epsilon \) model, for incompressible fluids, the equations for \( k \) and \( \epsilon \) are expressed by Eqs. (5) and (6) [23–25]:

\[
\frac{\partial k}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_k} \right] \frac{\partial k}{\partial x_j} + G_k - \rho \varepsilon
\]  
(5)

\[
\frac{\partial \epsilon}{\partial t} + \frac{\partial (\rho u_i \epsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_\epsilon} \right] \frac{\partial \epsilon}{\partial x_j} + \rho C_1 \varepsilon \frac{\partial k}{\partial x_i} + \rho C_2 \frac{\partial \varepsilon}{\partial x_i} - \frac{\varepsilon^2}{k + \sqrt{\varepsilon}}
\]  
(6)

where \( \varepsilon \) is the turbulent pulsation rate; \( C_1, C_2 \) are constants; \( \sigma_k \) and \( \sigma_\epsilon \) are the turbulent Prandtl numbers of the \( k \) equation and \( \epsilon \) equation; \( G_k \) is the turbulent kinetic energy term produced by buoyancy; \( v \) is the turbulent velocity, m/s; \( \mu \) is the fixed dynamic viscosity, Ns/m\(^2\); \( \mu_t \) is turbulent dynamic viscosity, Ns/m\(^2\); \( E \) is diffusivity; \( k \) is turbulent kinetic energy, m\(^2\)/s\(^2\); \( \rho \) is turbulent density, kg/m\(^3\).
2.4. Geometric model

The RRG hydrodynamic cavitation reactor consists of stator, rotor and casing, as shown in Fig. 1. The volute type structure is adopted in the casing. The rotor is a semi-open impeller structure, which has a good liquid conveying effect. The profile is a third-order Bezier curve. The rectangular-shaped CGUs are arranged on the stator. The center of the stator is hollow which was design for the fluid from the inlet. The fluid enters from the axial direction, and is thrown out radially by the rotor after the hydrodynamic cavitation reaction. It would be verified that there is high-strength cavitation in the area of impeller and blind hole inside the reactor.

In the present study, the effects of shapes, interaction distances of the CGU and rotor speed on the cavitation rate and cavitation energy efficiency were revealed i.e., shapes of the CGU (rectangle-shaped, cylinder-shaped), rotor speed ($v = 3600, 4320$ and $5760$ rpm), interaction distances ($s = 1, 1.5$ and $2$ mm). The detailed information on the factors could be found in Fig. 2.

2.5. Boundary condition

The Volume of Fluid (VOF) model was applied to predict multiphase flow in the reaction. The velocity inlet and pressure outlet boundary condition types were used for the model. The inlet velocity was specified as $0.97$ m/s, and the wall temperature was constant at $300$ K.

2.6. Cavitation rate and cavitation energy efficiency

In this study, the vapor volume fraction, cavitation rate and cavitation energy efficiency were used to evaluate the performance of the reactor. The cavitation rate is the ratio of the total vapor volume to the computational domain volume, which characterizes the generation efficiency of cavitation in space.

$$\alpha = \frac{V_{\text{vapor}}}{V_{\text{total}}} \quad (7)$$

where $\alpha$ is the cavitation rate. $V_{\text{vapor}}$ is the total vapor volume of the computational domain, m$^3$. $V_{\text{total}}$ is the total volume of the computational domain, m$^3$.

Torque and rotor speed were used to calculate input power [26].

$$P = \frac{n \times T}{9550} \quad (8)$$

where $P$ is the input power, kw. $n$ is the torque, n/m. $T$ is the rotor speed, rpm.

Cavitation energy efficiency $\eta$ is the ratio of total vapor volume to input power, which characterizes the generation efficiency of cavitation in energy.

$$\eta = \frac{V_{\text{vapor}}}{P} \quad (9)$$

In order to accurately characterize the difference of cavitation, various parameters are calculated under the optimal cavitation development time and different operating conditions.

3. Numerical method

3.1. Mesh of modeling

The polyhedral meshes were applied to mesh the reactor computational domain [27]. In order to improve the calculation accuracy and save the calculation time, a relatively large division scale (1 mm) was used for the peripheral fluid domain, and a relatively small mesh division scale (0.8 mm) was used for the area of cavitation inside the reactor. In order to improve the accuracy of numerical simulation, five boundary layers are set on the surfaces of stator and rotor. The mesh quality of the computational domain all reached above 0.35, which met the requirements of numerical calculation. The total number of meshes is...
2,875,107 in the computational domain. Fig. 3 showed the grid-independence verification results for different sizes. The monitored pressure in the Fig. 3 was the pressure at the monitoring point on the suction surface of the impeller. The types of Sliding walls and sliding grids were used for the rotor area. The computational domain of the stator and rotor are shown in Fig. 4.

3.2. Solver setup

In the present study, the double-precision finite volume method was used to discretize the N-S equation, and the PISO algorithm was used to couple the pressure mixing velocity [28]. The momentum, turbulent kinetic energy, and dissipation rate equations were discretized using the second-order upwind method. The pressure gradient was calculated using the PRESTO interpolation scheme [29]. In order to accurately calculate the development of cavitation in the reactor, the time for the rotor to turn through 1° was set as the time step (0.05787 ms). The convergence criterion was selected based on the residual value of the calculated variable gas volume fraction. For the simulation model, the numerical computation was convergent if the residuals for the different variables were reduced by five orders of magnitude.

4. Results and discussions

To compare the performance of various CGU structures, Table 1 summarized the effects of different shapes, interaction distances and rotor speed on cavitation bubble volume, cavitation rate and cavitation energy efficiency.

4.1. Cavitation characteristics

The cavitation of the RRG hydrodynamic cavitation reactor was generated by the high-speed rotation of the rotor and the interaction between stator and rotor. The evolution cycle of cavitation morphology is periodicity (0.46 ms). To analyze the cavitation characteristics of the RRG hydrodynamic cavitation reactor in one cycle, Fig. 5 depicted the development of cavitation in cavitation generation units (CGUs) under different pressure, vapor phase, velocity vector and vorticity. The location of the CGU profile is shown in Fig. 6.

At t = 0 ms, the rotor turns over CGU. A large number of cavitation bubbles flow into the flow channel near CGU. The fluid between the static rotors is divided into two parts. Specifically, a portion of the fluid (7 m/s) escaped from the main channel and entered the CGU at a lower velocity (4 m/s). This part of the fluid forms eddy currents in the CGU, occupying most of the volume of the CGU and forming a two-part separation zone as the fluid enters and exits the CGU. The Kelvin-Helmholtz instability leads to vortex cavitation which was created by this velocity gradient-based separation zone. Therefore, during the development of cavitation in CGU, the cavitation mainly occurs in the separation zone. The vorticity was used to evaluate the shear separation strength. The cavitation effect was the result of the combined effect of shear
separation and low pressure. As the rotor rotates, cavitation bubbles flowed along the flow channel and develop in the inflow separation zone where the low pressure caused by the rotor and the strong shearing action of the inflow separation zone. At the same time, the stable state of the outflow separation area was destroyed by the rotor. From 0 ms to 0.092 ms, the vorticity of the outflow separation zone decreased from $10000 \, \text{s}^{-1}$ to $6500 \, \text{s}^{-1}$, the shear separation effect decreased, and the cavitation bubbles originally existing in the outflow separation zone collapsed.

At $t = 0.092$ ms, the rotor passes through the outflow separation zone. Due to the influence of the rotor, the vorticity of the outflow separation zone increased, the pressure decreased, and the cavity in the outflow separation zone developed rapidly. From 0.092 ms to 0.276 ms, the shear cavitation in the inflow separation zone gradually separated from the cloud cavitation generated by the rotor, and the localized shear cavitation zone was formed.

From 0.276 ms to 0.368 ms, the static pressure in the inflow separation zone started to recover. The vorticity of the inflow separation zone decreased rapidly from $6500 \, \text{s}^{-1}$ to $2000 \, \text{s}^{-1}$, which caused the separation strength and instability decreased, and the cavity collapsed. On the contrary, the vortex in the center of the outflow separation zone was continuously compressed by the vortex in the center of the CGU, due to the effect of rotor suction surface. The vorticity increased along the transverse (CGU wall) and longitudinal (CGU inlet) directions. As a

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**Fig. 5.** The cavitation development in CGU in one cycle.
result, the area of the cavitation region increased along the two directions.

After $t = 0.368$ ms, the static pressure of the entire CGU gradually recovered. First, the shear strength of the separation zone decreased. The overall cavitation strength and the vorticity of the separation zone decreased. Then, due to further recovery of pressure, the cavity was compressed into an elongated region and most of the cavitation bubbles were suddenly crushed. Until 0.46 ms, the cavitation in the entire CUG collapsed completely, while a large number of new bubbles was produced by the rotor action, representing a new start of an interaction cycle.

### 4.2. Effect of shape

The interaction between the stator and the rotor was influenced by the structure of CGU, which affects the cavitation strength. In addition to rectangular-shaped CGU, cylindrical-shaped CGU was also analyzed. Due to the smaller cross-sectional area of the cylindrical CUG, the flow velocity in the CGU was faster. The cylindrical-shaped CUG facilitates the generation of vortex, allowing for smoother development of vortex cavitation. Fig. 7 indicated the effects of the corresponding structures on the distributions of pressure, vapor phase, velocity vector and vorticity.

![Fig. 6. The bird’s-eye view with the profile location.](image)

Similar to rectangular-shaped CUG, the cavitation of the cylindrical-shaped CGU occurred in the separation zone based on the velocity gradient. The difference was due to the vortex in the middle of the CGU, which limited the development of cavitation in the separation zone. The vortex also existed in the rectangular-shaped CGU, but its CGU cross-sectional area was so large that the vortex could not affect the entire CGU. The cavitation was less affected by the vortex. The cross-sectional area of the cylindrical-shaped CGU was small, and the vortex basically covered the entire CGU. Although the low pressure of the vortex center was beneficial to the generation of vortex cavitation, it also limited the further development of cavitation. Compared to the rectangular-shaped CGU, the flow velocity in the CGU decreased from 7 m/s to 2 m/s. The shear effect in the separation zone decreased, the local vorticity was reduced by 1000 s$^{-1}$ (from 4000 s$^{-1}$ to 3000 s$^{-1}$), and the total vapor volume decreased by 194.18 mm$^3$ (from 2305.98 mm$^3$ to 2111.80 mm$^3$). In addition, the energy dissipation of cylindrical CGU occurred due to its narrow cross-sectional area. Its energy consumption was 17.7% (from 9682.83 mm$^3$/kw to 8226.4 mm$^3$/kw), which lower than that of the rectangular-shaped type. In summary, the cavitation in cylindrical CGU was influenced by the vortex, which limited the development space of cavitation and lead to weaker interaction between rotor and stator. The cavitation performance of cylindrical CGU was lower than that of rectangular CGU. In terms of cavitation rate and cavitation energy efficiency, the application of cylindrical CGU was less effective than rectangular CGU.

### 4.3. Effect of rotor speed

The performance of the different shapes of CGUs at rotor speed (3600 rpm, 4320 rpm and 5760 rpm) were shown in Fig. 8 and Table 1. The speed increasing had partly the same effect on different shapes of CGU. Due to Bernoulli’s theorem, higher rotor speed led to lower local pressure. It was conducive to the occurrence of cavitation, and the shear separation effect in the separation zone also was stimulated. The vorticity of the rectangular-shaped CGU and the cylindrical-shaped CGU separation zone both had different increasing degrees of vorticity. As the speed increased, the cavitation volume increased rapidly. The increasing rate was faster than that of energy consumption, and the cavitation energy efficiency kept improving. Therefore, it is feasible to improve the cavitation efficiency by increasing the rotor speed. For the cavitation performance at different speeds, the rectangular-shaped CGU cavitation reactor was used as an example. As the speed increased from 3600 rpm

![Fig. 7. Effect of various CGU shapes on vapor phase, pressure, velocity vector and vorticity.](image)
to 4320 rpm, the cavitation rate increased by 1.6% (from 0.095% to 1.695%), and the cavitation energy efficiency increased by 8910.1 mm$^3$/kw (from 772.73 mm$^3$/kw to 9682.83 mm$^3$/kw). As the speed increased from 4320 rpm to 5760 rpm, the cavitation rate increased by 4.945% (from 1.695% to 6.64%), and the cavitation energy efficiency increased by 12410.52 mm$^3$/kw (from 9682.83 mm$^3$/kw to 22093.35 mm$^3$/kw). The growth rate gradually increased due to the formation of long-term cavitation in the center of the CGU.

With the speed increasing of rotor, the cavitation development of rectangular-shaped CGU and cylindrical-shaped CGU was partially different. Regarding the development of cavitation in rectangular-shaped CGU, the shear separation effect of the inflow and outflow separation zone was enhanced with the increasing of the rotor speed. The cavitation effect in separation zone region was enhanced. For the speed from 4320 rpm to 5760 rpm, the effect of the central vortex of CGUs was enhanced, and the vorticity increased with the increasing of rotor speed. Under the action of strong vortex, the cavitation is compressed and concentrated in the center of vortex, and a stable cavitation is formed.

Fig. 8. Effect of various rotor speed on vapor phase, pressure, velocity vector and vorticity.
this time, vortex cavitation was the type of cavitation in CGU, the cavitation area increased rapidly, and the cavitation in the outflow separation zone disappeared due to the low pressure in the center of the vortex.

Regarding the development of cavitation in cylindrical-shaped CGU, the initial development process was similar to that of rectangular-shaped CUG. With the speed increasing of rotor speed, the shear separation effect in the separation zone increased, and the intensity of the central vortex of CGUs increased continuously. However, due to the small cross-sectional area of the cylindrical CGU, the vortex affected the entire flow channel. When the cavitation developed to a certain extent, it could not continue to develop deep into the CGU. Therefore, during the speed increased from 4320 rpm to 5760 rpm, the cavitation intensity increased. The cavitation effect of the cylindrical-shaped CGU was lower than that of the rectangular-shaped CGU.

4.4. Effect of interaction distance

The effect of different interaction distances on the reactor flow and pressure fields was shown in Fig. 9. With the increase of the distance, the area of the separation zone is fully developed, the interaction between stator and rotor increases, and the vorticity of the separation zone (inflow and outflow) increases to varying degrees, which promotes the generation of cavitation. However, the pressure in the CGU increased rapidly with the increasing of the interaction distance. The pressure in the main flow area increased by 21000 Pa during the interaction distance increased from 1 mm to 1.5 mm. Pressure was an important factor affecting cavitation. Due to the high pressure generated by the large interaction distance, the cavitation was difficult to occur in the main stream region so the cavitation intensity and cavitation area decreased rapidly. As the interaction distance increased from 1 mm to 1.5 mm and 1.5 mm to 2 mm, the cavitation rate decreased by 0.726% (from 1.695% to 0.969%) and 0.499% (from 0.969% to 0.47%).

The interaction distance between rotor and stator is an important factor affecting the cavitation performance of the rotor-diameter gap hydrodynamic cavitation reactor. On the one hand, the larger interaction distance leads to lower flow rate and higher pressure, which suppressed the occurrence of cavitation. On the other hand, the development space of cavitation in the separation zone increases due to the farther interaction distance. The shear and interaction between rotor and stator in the separation zone is enhanced, which is conducive to the occurrence of cavitation. Due to the influence of two opposite effects, the cavitation intensity variation in CGU is not a simple positive or negative correlation variation. In the range of 1 mm ~ 2 mm, pressure plays a dominant role, the closer of interaction distance and the greater of cavitation efficiency. However, in practical applications, the distance should not be too small in order to maintain the stability of the rotor. Therefore, in the range of 1 mm ~ 2 mm, the reduction of the interaction distance between rotor and stator is beneficial to improve the cavitation performance.

5. Conclusions

In this paper, a novel rotor-radial groove (RRG) hydrodynamic cavitation reactor was proposed with good cavitation intensity and energy utilization. The effect of reactor structure and operating conditions on the cavitation flow characteristics in the RRG hydrodynamic cavitation reactor was investigated by computational fluid dynamics. The vorticities were used to quantify the shear separation effect in the separation zone. The following conclusions could be drawn from the present investigation.

- The development of cavitation in the rotor-diameter gap hydrodynamic cavitation reactor CGU presented an obvious periodicity (0.46 ms), and the main cavitation regions were the outflow and inflow separation zone.
- The cavitation performance in the cylindrical CGU was affected by the vortex which limited the development space of cavitation. The performance of cylindrical CGU was much lower than that of rectangle CGU.

![Fig. 9. Effect of various CGU interaction distances on vapor phase, pressure, velocity vector and vorticity.](image-url)
• The rotor speed increases the cavitation effect due to the low pressure effect. Stable cavitation bubbles are formed in the center of CGUs due to the influence of the central vortex of the CGUs at high rotor speed. The cavitation effect could be improved effectively by increasing the rotor speed in the range of 4320 rpm to 5760 rpm.

• The changes of the interaction distance between the stator and the rotor leads to pressure variations and cavitation development spatial variations. In the range of 1 mm to 2 mm, the pressure effect played a dominant role. As the interaction distance increased from 1 mm to 1.5 mm and 1.5 mm to 2 mm, the cavitation rate decreased by 0.726% (from 1.695% to 0.969%) and 0.499% (from 0.969% to 0.47%). The cavitation effect could be improved more effectively by decreasing the interaction distance in the range of 1 mm–1.5 mm.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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