Numerical optimization design of vortex diode hydrodynamic cavitation reactor

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Abstract. Vortex diode is a novel hydrodynamic cavitation reactor, whose cavitation energy yield can be about 3~8 times higher than the conventional ones. In this study, the numerical orthogonal experiment of the structure(Diameter of the chamber(D), Ratio of the diameter of the chamber to the diameter of axial tube(D/dc), and Ratio of the Diameter of the chamber to the height of the chamber(D/H) ) of vortex diode was carried out and the importance of the impedance ratio influence factor is: D>D/dc>D/H. The best performance was achieved when D=120mm; D/dc=5.0; D/H=5.0.Under the same conditions, the optimal value of D/H is in the range 5~5.5 and the D/dc is in the range 4.0~4.5. The impedance ratio was increased lightly and the flowrate was improved distinctly when we contracted the inlet and outlet of the axial and tangential tube.

1. Introduction
With the rapid development of our society, there are a lot of industrial wastewater containing refractory organic pollutants discharging into the environment. The organic pollutants can exist in the environment for long periods as they are chemically stable and not easy for biodegradation, not only destroying the ecological balance, but also harming the health of the human beings. While the traditional treatment methods such as physical, chemical or biological treatment are not effective enough for their low treatment efficiency, poor remove results or secondary pollution.

Hydrodynamic cavitation is a novel method for water treatment, the enormous power of cavitation provides special environment for physical and chemical reactions which are difficult or impossible to occur under general conditions, which provides a new way to remove refractory organics in wastewater [1-4]. While the traditional hydrodynamic cavitation can’t be used in industrial production individually for its low treatment efficiency.

2. Principle
Vortex diode is a novel hydrodynamic cavitation device which consists of three parts: the chamber, the axial tube and the tangential tube. The water flows into the chamber through the tangential tube and comes across the pressure drop when forming the strong vortex flow in the chamber. The cavitation occurs when the local pressure falls below the vapor pressure of the water. The cavity is growing when it moves to the outlet, when it reaches the axial tube, the pressure recovers and cavity collapse by implosion happens which can provide the environment with high temperature(~10,000K) and
pressure (~1000 atm) [5,6]. As a result, the carbon-carbon bond of some kinds of organic pollutants can be broken down and macromolecules can be decomposed into micromolecules. Moreover, the highly reactive free radical • OH is generated which can oxidize the pollutants unselectively [7,8].

Consider the vortex diode as a resistance element, according to the energy conservation equation,

\[ \frac{\Delta P}{\rho g} = \zeta_f \frac{v^2}{2g} = \zeta_f \frac{1}{2g} \frac{Q^2}{A^2} \]  

(1)

Where \( \Delta P \) is the pressure drop, \( Q \) is the flow rate, \( v \) is the velocity of the outlet, \( \zeta_f \) is the forward resistance coefficient, \( A \) is the area of the outlet.

Define

\[ S_f = \zeta_f \frac{1}{2gA^2} \]

(2)

Then

\[ \frac{\Delta P}{\rho g} = S_f Q^2 \]

(3)

In a similar way,

\[ \frac{\Delta P}{\rho g} = \zeta_r \frac{v^2}{2g} = \zeta_r \frac{1}{2g} \frac{Q^2}{A^2} \]

(4)

Where \( \zeta_r \) is the reverse resistance coefficient. Then we have

\[ S_r = \zeta_r \frac{1}{2gA^2} \]

(5)

\[ \frac{\Delta P}{\rho g} = S_r Q^2 \]

(6)
Define

\[ E = \frac{\zeta_R}{\zeta_F} \]  
\[ E' = \frac{S_R}{S_F} \]  

The resistance ratio \( E' \) can represent the cavitation potential because the higher the \( E' \), the more pressure drop, and the more pressure drop, the more cavitation yield.

3. Numerical simulation scheme

We chose the commercial computational fluid dynamics (CFD) software FLUENT 6.3 to do the simulation. \( k-\varepsilon \) and \( k-\omega \) turbulence model can be used to simulate the pathline with strong curve and vortex.

In our previous experiments, the structure parameters of the Vortex Diode are: \( D=117 \text{mm}, H=16\text{mm}, d_e=19\text{mm}, d_i=16\text{mm} \). The forward flow operating conditions: \( P_a=0.239\text{MPa}, P_r=0.224\text{MPa} \) (\( P_r \) : the pressure of axial tube, \( P_r \) : the pressure of tangential tube). The flow rate of outlet was 0.69 kg/s. The reverse flow operating conditions: \( P_a=0.172\text{MPa}, P_r=0.262\text{MPa} \). The flow rate of outlet was 0.53 kg/s. These results can be used to verify the accuracy of our numerical simulation models and the comparison is listed in Table 1.

From the comparison in Table 1 we can conclude that the \( k-\omega \) model has more deviation and cost more computational time than \( k-\varepsilon \) model; The results of SIMPLE and PISO algorithm are close but the converging time of PISO algorithm is longer than that of SIMPLE algorithm; If we refined the grids of the tube and use first order discretization scheme, the results were acceptable and the cost less time than using second order discretization scheme. As a result, we preferred \( k-\varepsilon \) model, SIMPLE algorithm, first order discretization scheme, and refined the grids of the tube.

| Flow Deviation Direction | Grid settings | Turbulence model | Algorithm | Discretization | Flow rate of outlet (kg/s) | (% of deviation) |
|--------------------------|---------------|------------------|-----------|----------------|---------------------------|-----------------|
| Forward                  | Uniform       | \( k-\varepsilon \) | PISO      | Second order   | 0.514                     | 25.51           |
| Forward                  | Uniform       | \( k-\varepsilon \) | PISO      | Second order   | 0.509                     | 26.23           |
| Forward                  | Uniform       | \( k-\omega \)   | PISO      | Second order   | 0.513                     | 25.65           |
| Forward                  | Refinement    | \( k-\varepsilon \) | SIMPLE    | First order    | 0.516                     | 25.21           |
| Forward                  | Refinement    | \( k-\varepsilon \) | PISO      | First order    | 0.516                     | 25.21           |
| Forward                  | Refinement    | \( k-\omega \)   | SIMPLE    | First order    | 0.501                     | 27.39           |
| Reverse                  | Refinement    | \( k-\varepsilon \) | SIMPLE    | First order    | 0.601                     | 13.4            |
| Reverse                  | Refinement    | \( k-\varepsilon \) | PISO      | First order    | 0.608                     | 14.7            |

4. Results and discussion

4.1. Vortex diode with general tube

We used commercial software origin to fit the \( E' \) with different \( D/H \) and \( D/dc \), the results are in Fig.2 and Fig.3. The vortex diode with larger chamber diameter allows more flow rate to pass but requires longer pathline, so there is an optimal value of the \( D/H \). The optimal value for \( D/H \) is in the range 5.0~5.5 and for \( D/dc \) is in the range 4.0~4.5. The resistance ratio of vortex diode with \( D=80\text{mm} \) is bigger than that of \( D=120\text{mm} \) under the same other structure parameters.
4.2. **Orthogonal experiment for vortex diode with contracted tube**

In order to refine the flow field and get the optimal structure parameters, we contracted the inlet and outlet tube and designed the orthogonal simulation experiment.

4.2.1. **Flow field analysis.** In forward flow Fig. 4, the fluid flows into the chamber from the axial tube and out through the tangential tube, the pathlines are short and the resistance is low. The maximum pressure of forward flow is in the middle of the chamber and the minimum pressure is in the throat of the tangential tube. While in reverse flow Fig. 5, the fluid flows into the chamber from the tangential tube, the pathlines are longer and the resistance is higher than that of the forward flow. The maximum pressure is on the edge of the chamber and the minimum pressure is in the middle of the chamber. As is mentioned above, if the pressure falls below the vapor pressure, cavitation occurs.
4.2.2. Analysis for resistance ratio. In order to verify the importance of the influence factors of the resistance ratio, we design the orthogonal simulation experiment, the factors and levels are in Table 2, the orthogonal simulation experiment schemes are in Table 3.

Table 2. Factors and levels of the orthogonal simulation experiment.

| Factor  | 1     | 2     | 3     |
|---------|-------|-------|-------|
| Matter  | D(mm) | D/H   | D/dc  |
| Level   | 1, 2, 3 | 1, 2, 3 | 1, 2, 3 |
| Value   | 80, 100, 120 | 5.0, 5.3, 6.0 | 5.0, 5.3, 6.0 |

Table 3. Orthogonal simulation experiment schemes $L_0(3^4)$.

| Experiment No. | D(mm) | D/H | D/dc |
|---------------|-------|-----|------|
| 1             | 80    | 5.0 | 5.0  |
| 2             | 80    | 5.3 | 5.3  |
| 3             | 80    | 6.0 | 6.0  |
| 4             | 100   | 5.0 | 5.3  |
| 5             | 100   | 5.3 | 6.0  |
| 6             | 100   | 6.0 | 5.0  |
| 7             | 120   | 5.0 | 6.0  |
| 8             | 120   | 5.3 | 5.0  |
| 9             | 120   | 6.0 | 5.3  |

We calculated the resistance ratio according to the simulation schemes mentioned above and got the results listed in Table 4.

Table 4. Resistance ratio of the simulations.

| D   | D/H | D/dc | E'  |
|-----|-----|------|-----|
| 80  | 5.0 | 5.0  | 6.90 |
| 80  | 5.3 | 5.3  | 4.89 |
| 80  | 6.0 | 6.0  | 4.82 |
| 100 | 5.0 | 5.3  | 6.47 |
| 100 | 5.3 | 6.0  | 6.73 |
| 100 | 6.0 | 5.0  | 5.78 |
| 120 | 5.0 | 6.0  | 6.39 |
| 120 | 5.3 | 5.0  | 7.01 |
| 120 | 6.0 | 5.3  | 7.04 |
Input the simulation results and calculated the $K$, $\overline{K}$ and range $R$. From the range $R$ in Table 5, we can conclude that the importance of the factors is: $D > D/dc > D/H$. From the average value of the levels we can conclude that the optimal condition is: $D=120$mm; $D/dc=5.0$; $D/H=5.0$.

**Table 5. Results analysis of Orthogonal simulation experiment**

| Experiment No. | D(mm) | D/H | D/dc | $E'$ |
|----------------|-------|-----|------|------|
| 1              | 80    | 5.0 | 5.0  | 6.9  |
| 2              | 80    | 5.3 | 5.3  | 4.89 |
| 3              | 80    | 6.0 | 6.0  | 4.82 |
| 4              | 100   | 5.0 | 5.3  | 6.47 |
| 5              | 100   | 5.3 | 6.0  | 5.73 |
| 6              | 100   | 6.0 | 5.0  | 5.78 |
| 7              | 120   | 5.0 | 6.0  | 6.39 |
| 8              | 120   | 5.3 | 5.0  | 7.01 |
| 9              | 120   | 6.0 | 5.3  | 7.04 |
| K1             | 16.61 | 19.76 | 19.69 |
| K2             | 17.98 | 17.63 | 18.40 | $\sum E'=55.04$ |
| K3             | 20.45 | 17.65 | 16.95 |

$\overline{K}_1$ 5.54 6.59 6.56

$\overline{K}_2$ 5.99 5.88 6.13 $\mu = \sum E'/9=6.12$

$\overline{K}_3$ 6.82 5.88 5.65

R 1.28 0.71 0.91

4.2.3. **Comparation of the tube with or without the contraction.** Compared the vortex diode with tube contracted or not in Table 6, we can get that the $E'$ was increased when we contracted the tube of vortex diode with smaller chamber diameter. While for larger one, the contraction has almost no influence on the resistance ratio $E'$.

**Table 6. Comparation of the tube with or without the contraction.**

| D(mm) | D/H | D/dc | $E'$ (with contraction) | $E'$ (without contraction) |
|-------|-----|------|-------------------------|-----------------------------|
| 80mm  | 5   | 5    | 8.24                    | 6.90                        |
| 120mm | 5   | 6    | 6.04                    | 6.39                        |
| 120mm | 5.5 | 5    | 7.17                    | 7.01                        |

5. **Conclusion**

According to the orthogonal simulation experiment results, the importance of the factors is: $D > D/dc > D/H$, the optimal condition is: $D=120$mm; $D/dc=5.0$; $D/H=5.0$.

Under the same conditions, the best value for $D/H$ is in the range 5~5.5 and the best value for $D/dc$ is in the range 4.0~4.5. For the model without contracted tube, the resistance ratio of vortex diode(D=80mm) is higher than that of vortex diode(D=120mm).

For vortex diode with smaller size, contracted the tube can increase the resistance value obviously.

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