MODELING OF HYDRODYNAMIC CAVITATION REACTORS BASED ON VORTEX DIODE

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Water cavitation is a complex process, which is affected by the working environment, the parameters of the instrument and the state of the liquid.Vortex diode is a new type of hydraulic cavitation reactor, its cavitation capacity is 3~8 times higher than that of conventional reactor.Based on hydraulic cavitation related principle and the characteristics of vortex diode, this research about the structure of vortex diode (cavity diameter (D), the ratio of the shaft tube diameter and the diameter of cavity (D/dc), cavity diameter and height of cavity ratio (D/H)) numerical orthogonal experiment, get the rule of the influence of various factors and optimized conditions, determined the best cavitation effect of cavitation,It provides a good theoretical basis and reference for the practical application of similar cavitators.

Key Words:*hydrodynamic cavitation, Vortex diode, K-wmodel*

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(~1,000atm)[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].

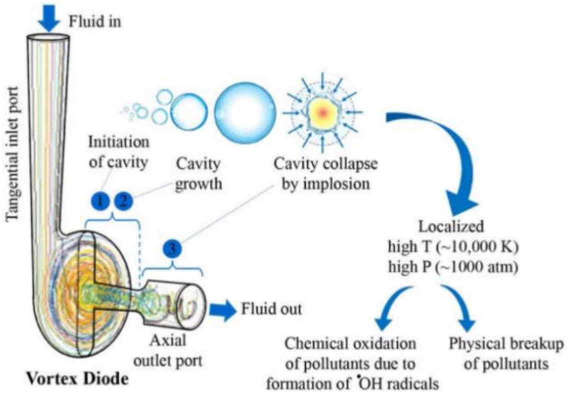


Figure 1. Cavitation effect of vortex diode.

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

$$\frac{\Delta P}{\rho g}=\zeta_F\frac{v^2}{2g}=\zeta_F\frac{1}{2g}(\frac{Q}{A})^2 \tag{1}$$

where ΔP is the pressure drop, Q is the flow rate, v is the velocity of the outlet, ζ_F is the forward resistance coefficient, A is the area of the outlet.

Define

$$S_F=\zeta_F\frac{1}{2gA^2} \tag{2}$$

Then

$$\frac{\Delta P}{\rho g}=S_F Q^2 \tag{3}$$

In a similar way,

$$\frac{\Delta P}{\rho g}=\zeta_R\frac{v^2}{2g}=\zeta_R\frac{1}{2g}(\frac{Q}{A})^2 \tag{4}$$

Where ζ_R is the reverse resistance coefficient. Then we have

$$S_R=\zeta_R\frac{1}{2gA^2} \tag{5}$$

$$\frac{\Delta P}{\rho g}=S_R Q^2 \tag{6}$$

Define

$$E=\zeta_R/\zeta_F \tag{7}$$

$$E^{'}=S_R/S_F \tag{8}$$

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:

$D=117mm$, $H=16mm$, $d_c=19mm$, $d_t=16mm$.

The forward flow operating conditions:

$P_c=0.239MPa$, $P_t=0.224MPa$ (P_c :the pressure of axial tube, P_t :the pressure of tangential tube).

The flow rate of outlet was 0.69 kg/s. The reverse flow operating conditions:

$P_c=0.172MPa$, $P_t=0.262MPa$

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 Table1.

From the comparation in Table1 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.

Table 1. Comparison of different computational model.

Flow Direction	Grid settings	Turbulence model	Algorithm schemes	Discretization	Flow rate of outlet(kg/s)	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

(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 a 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=80mm is bigger than that of D=120mm under the same other structure parameters.

(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.

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.

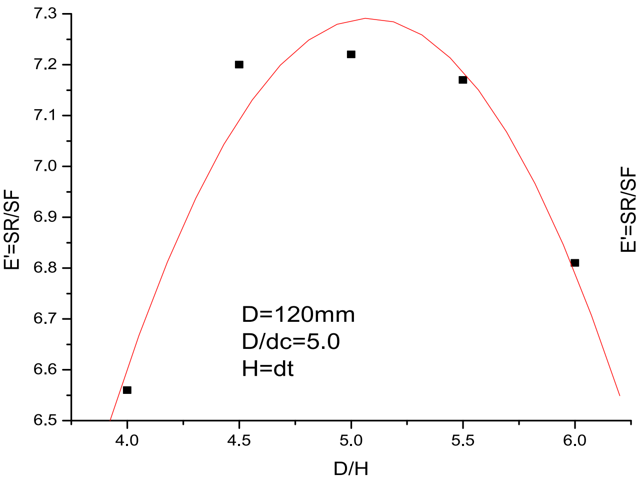


Figure 2. The resistance ratio at different D/H.

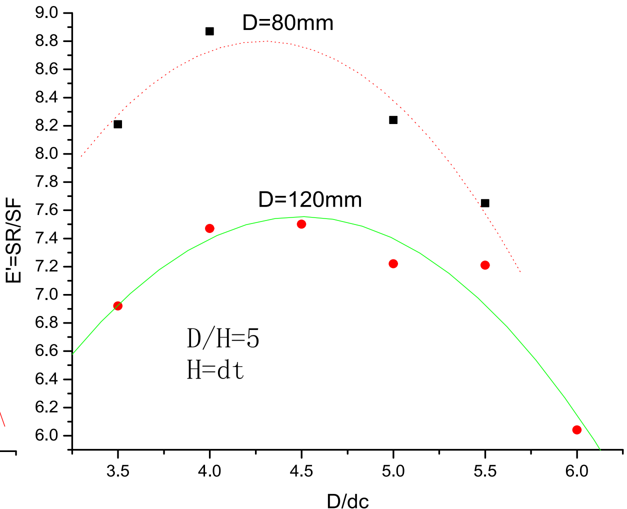
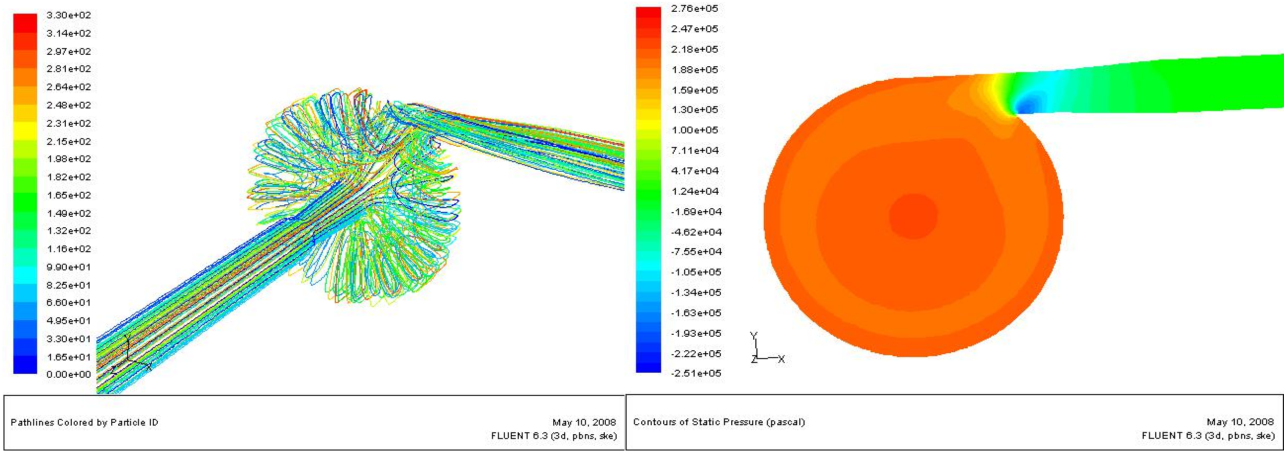
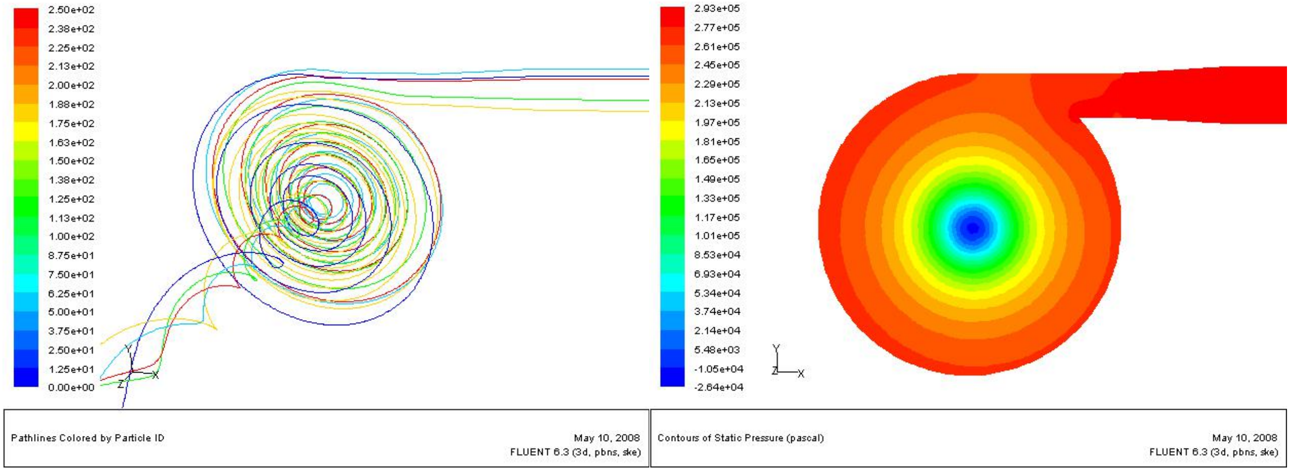


Figure 3. The resistance ratio at different D/dc.



（a） pathlines　　（b）contours of static pressure

Figure 4. Forward flow.



（a）pathlines　　（b） contours of static pressure

Figure 5. Reverse flow.

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 $L_9(3^4)$.

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	5.73
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=120mm；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	∑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	μ=∑E’/9=6.1
$\overline{K_3}$	6.82	5.88	5.65	
R	1.28	0.71	0.91	

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=120mm；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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