Simulation and Experimental Study on Cavitating Water Jet Nozzle

Wei Zhou¹,³, Kai He*¹,², Jiannan Cai¹,³, Shaojie Hu¹,⁴, Jiuhua Li³ and Ruxu Du⁵

¹ Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China
² Shenzhen Key Laboratory of Precision Engineering, Shenzhen, China
³ China University of Petroleum, Beijing, China
⁴ University of South China, Hengyang, China
⁵ The Chinese University of Hong Kong, Hong Kong, China

*Email: kai.he@siat.ac.cn

Abstract. Cavitating water jet technology is a new kind of water jet technology with many advantages, such as energy-saving, efficient, environmentally-friendly and so on. Based on the numerical simulation and experimental verification in this paper, the research on cavitating nozzle has been carried out, which includes comparison of the cleaning ability of the cavitating jet and the ordinary jet, and comparison of cavitation effects of different structures of cavitating nozzles.

1. Introduction

The cavitating jet is a kind of water jet technology promoting the rapid evaporation of water and gas evolution in the water jet flow artificially by changing structure of the nozzle, reducing local pressure below the saturating vapor pressure of the liquid [1]. The effect of the jet is enhanced by the strong impact force generated by the bubble burst, shown in Figure 1. At present, the erosion mechanism of the cavitation jet is generally regarded as the theory of the mechanical action. According to the mechanical action theory, cavitation erosion is caused by the strong shock of the micro jet and microwave generated by bubble collapse [2].

Hammit [3] concluded by calculation and experimental measurement that when the cavitation bubble collapses, micro jet velocity near the wall reaches 70~180m/s, the pressure at the surface can up to 140MPa, the frequency of impact at surface from micro jet is about 100~1000 / (s·cm²).

Figure 1. Schematic diagram of cavitating jet (1 is nozzle. L is target distance. 2 is target surface).
Therefore, the cavitating jet has superior cleaning ability without very high pressure, and also can avoid damage to the surface covering expensive paint or anticorrosive coating. In addition, it can be used under water, not like high pressure water jet weakening dramatically by environmental media. To the same cleaning efficiency, the pressure of cavitating jet is only 1/4 of the high pressure water jet, and the maximum does not exceed 16MPa [4].

The current cavitating jet is mainly divided into two types: artificial submerged jet created by Vijav [5] and the self-resonance cavitating jet proposed by Johnson V E [6] and Conn A F [7]. The former improves on the basis of submerged jet, under which cavitating water jet can work better [5]. The latter generates cavitating jet by resonant cavity. This paper focuses on the self-resonance cavitating jet under the submerged condition. The organ pipe nozzle (shown in Figure 2) and Helmholtz nozzle are the most common two kinds of structures. With the further research on cavitation, Liao Z F [8] invented a new nozzle with better cavitation effect on the basis of the Helmholtz nozzle, a self-resonance pulsed nozzle (shown in Figure 3). This paper gives the comparison research on the two kinds of nozzles through experiment and simulation based on the application of underwater fouling organism cleaning.

2. Structure of nozzle and mesh generation
As shown in Figure 2, the main structural parameters of Nozzle 1 include diameter \( D_s \) and length \( h \) of inlet, diameter \( D \) and length \( L \) of resonant cavity, diameter \( D_w \) and length \( H \) of outlet. The main structural parameters of Nozzle 2 include diameter \( d_1 \) of upstream nozzle, diameter \( d_2 \) of downstream nozzle, diameter \( D_c \) of self-resonance cavity, length \( L_c \), collision angle \( \alpha \) as shown in Figure 3.

![Figure 2. Nozzle 1: organ pipe nozzle.](image1)
![Figure 3. Nozzle 2: self-resonance pulsed nozzle.](image2)

By using SolidWorks software, CAD models of Nozzle 1&2 are established, then are meshed by ICEM. Grid model of Nozzle 1&2 as shown in Figure 4 and Figure 5. Mesh quality is above 0.7. Grid numbers are 889602 and 213948, absolutely ensuring the accuracy of the simulation.

![Figure 4. Grid model of Nozzle 1.](image3)
![Figure 5. Grid model of Nozzle 2.](image4)

3. Numerical simulation and model selection
As water is incompressible viscous fluid, its motion law is controlled by Navier-Stokes equations, as in Equation (1) and Equation (2):

\[
\frac{\partial u_i}{\partial x_i} = 0
\]  

(1)

\[
\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_j}{\partial x_j} \right)
\]  

(2)

Where \( u \) is the velocity of fluid, \( P \) is the pressure of fluid, \( \rho \) is the density of fluid and \( \nu \) is the kinematic viscosity.

By using FLUENT software, choosing the mixture model as multiphase model, flow model is established on the basis of Navier-Stokes equations. Turbulent model uses RNG k-\( \varepsilon \) model [9]. Compared with standard k-\( \varepsilon \) model, it is usually considered as turbulence vortex, so it has higher accuracy and reliability. Cavitation model uses Schnerr-Sauer model [10]. Parameter of flowing medium uses fluent database parameters. In the computation, the inlet of the mixing flow uses the inlet pressure boundary condition with 15MPa, and the outlet of the mixing flow uses the pressure boundary condition with one bar.

4. Simulation Results & Analysis

4.1. Simulation Results of nozzle 1

As shown in Figure 6, the cavitating region of Nozzle 1 is mainly concentrated in small areas on both sides of the outlet. The vorticity figure also shows that there are more intense vortexes, so it is easy for cavitation to occur. From the pressure diagrams, cavitation occurs because of the pressure which is lower than the saturated water vapor pressure. The highest gas fraction of the cavitation region is 0.216.

![Figure 6. Contours of nozzle 1.](image)

4.2. Simulation Results of nozzle 2

It can be seen from the simulation results in Figure 7 that the cavitation area of Nozzle 2 is larger and low pressure area is also larger and cavitation phenomenon is stronger. In the middle of a resonant
cavity, the most volume fraction of vapor ups to 0.9. Certainly, the average gas fraction at the outlet is also above 0.286, larger than Nozzle 1. So, Nozzle 2 is more suitable for cavitation.

5. Experiments

5.1. Experimental device
Experimental device is shown in Figure 8 and Figure 9. The water supply system is composed of a water tank and a water pump. In order to reach the submerged condition, the cleaning experiment was carried out in the sealed chamber. The nozzles clean the sample vertically, keeping target distance 20mm. The structure of various nozzles are shown from Figure 10 to Figure 12 respectively.

Figure 7. Contours of nozzle 2.

Figure 8. Schematic diagram of experimental device.
Figure 9. Experimental device.
Figure 10. Common nozzle.
Figure 11. Nozzle 1.
Figure 12. Nozzle 2.
5.2. Derusting experiment
In order to compare the difference of striking forces caused by cavitating jet and ordinary jet, we use the nozzle 1 and conventional nozzle to do rust experiment. The pressure of inlet water is 15MPa. The cleaning effect is shown in Figure 13. The experiment result indicates that under a water pressure of 15MPa, cavitating jet can remove rust but conventional jet cannot. We can conclude that the striking force of cavitation jet is larger than conventional jet under the same pressure.

![Figure 13. The contrast diagram of derusting.](image)

5.3. Fouling organism cleaning experiment
Fouling organism mainly includes barnacles, shellfish and so on. We used the stones covered with mussels, barnacle as experimental sample to verify the feasibility of cavitating jet in the cleaning application and to compare the effect of the two kinds of cavitating nozzles. In this comparative experiments between the nozzle 1 and nozzle 2, the inlet pressure is 12.5MPa, and the target distance is 20mm and the cleaning time is 10s. Shown in Figure 14 and Figure 15, the cleaning area of Nozzle 1 is 10cm × 2cm and that of Nozzle 2 is 14cm × 2.5cm.

![Figure 14. The cleaning effect of Nozzle 1.](image)

![Figure 15. The cleaning effect of Nozzle 2.](image)
From the figure, it can be seen clearly that both the nozzle 1&2 have a good cleaning effect. But, the cleaning area of jet of Nozzle 2 is wider than that of Nozzle 1. So the cleaning efficiency of the Nozzle 2 is higher than that of the Nozzle 1.

6. Conclusions
This paper has studied the cavitating water jet nozzle by simulation and experiment. We believe that cavitating water jet, especially generated by self-resonance pulsed nozzle will has broad application prospects in the field of cleaning. The conclusions obtained are as follows.

- According to the simulation results, in the organ pipe nozzle, cavitation occurred mainly in the mutational cross-section of the position, especially in the outlet which is the narrow area with the lower pressure, so vapor is more. In the self-resonance pulsed nozzle, cavitation occurred not only in the same regions above, but also in resonant cavity, due to more vortex flow where absolute pressure is lower.
- Based on the simulation results, the cavitation in the self-resonance nozzle is more serious than that in the organ pipe nozzle. The gas fraction is higher and the cavitation zone is larger.
- The experimental results verify the hitting force of cavitating jet is greater than the ordinary in same pressure, and the former is even effective to remove rust in 15MPa. In addition, the cleaning effect of the self-resonance nozzle is better than that of the organ pipe nozzle.

Acknowledgments
This work was accomplished under the financial support provided by Shenzhen Technology Development project (CXZZ20140904104336050).

References
[1] Peng Guoyi, Shimizu Seiji 2013 Progress in numerical simulation of cavitating water jets. *Journal of Hydrodynamics*, 04:502-509.
[2] Yang Chunming 2014 The Experimental Research of Metal Surface Strengthening of Jet Cavitation Peening. China University of Mining and Technology.
[3] Hammit F G 1980 *Cavitation and multiphases flow phenomena*. New York: Mc Graw-Hill Book Co.
[4] Zhang Lixia 2006 Sea biological fouling prevention technology. *Rubber & Plastics Resources Utilization*, 02:7-11+14.
[5] Vijay M M, et al 1992 A study of the practicality of cavitating water jets. proc, 11th Int. Symp. On jet cutting technology. St. Andrews, Scotland.
[6] Johnson V E, et al 1982 Self-resonating cavitating jets. Proc.6th Int. Symp. On water jet technology, England.
[7] Conn A F, Johnson V E. 1982 *Fluid dynamics of submerged cavitating jet cutting jet for deep hole bits*. SPE11060.
[8] Liao Z F, Tang C L 2003 Theory and experimental study of the self-excited oscillation pulsed jet nozzle. *Chinese Journal of Mechanical Engineering*, 04:379-383.
[9] Yakhot V, Orzag S A 1986 Renormalization group analysis of turbulence:basic theory. *Journal of Scientific Computing*, 1:3-11.
[10] Schnerr G H, Sauer J. 2001 *Physical and Numerical Modeling of Unsteady Cavitation Dynamics*. In Fourth International Conference on Multiphase Flow, New Orelanas, USA.