Numerical and experimental investigation on flow field characteristics of organ pipe nozzle

Z L Fang¹,², Y Kang¹,², X C Wang¹,², D Li¹,², Y Hu¹,², M Huang¹,² and X Y Wang¹,²

¹School of Power and Mechanical Engineering, Wuhan University, No.8 Donghu South Road, Wuhan, 430072, China
²Key Laboratory of Hubei Province For Water Jet Theory & New Technology, No.8 Donghu South Road, Wuhan, 430072, China

E-mail: kangyong@whu.edu.cn

Abstract: As a new technology that is developed rapidly in recent decades, water jet technology is widely applied in coal, petroleum, chemical industry, aviation, construction, etc. Self-resonant cavitating jet, by playing cavitation, is capable of great destruction. As a typical kind of self-resonant cavitating nozzle, organ pipe nozzle has its special application. In this paper, the flow field of organ pipe nozzle was numerical simulated. Nozzles with different structures were manufactured according to simulation results; their performances were tested on different driving pressure under the condition of submerging. The results showed that working pressure, cavity length and cavity diameter had influence on the characteristics of organ pipe nozzle and it exited optimum parameters.

Key Words: organ pipe nozzle; numerical simulation; experimental investigation; flow field characteristics

1. Introduction

High pressure water jet is a new technology developed in recent decades, which is widely used for industrial cutting, rock drivage, surface cleaning, material crushing, etc in coal, petroleum, chemical industry and other fields. Comparing to traditioanal methods, high pressure water jet has four main advantages: (1) Since water is the working medium and coolant, most of heat generated during cutting process is taken away. This will prevent thermal damage to materials. (2) The nozzle can be moved flexibly in any direction under numerical controlling. (3) Combining with mechanical technology, it has a high efficiency in rock breaking.

Organ pipe is a typical kind of self-resonating nozzle. Using oscillation cavity as the oscillator amplifier, it can generate pressure-feedback oscillation by sending the changing
initial pressure of necked-down section back to oscillation cavity. When the frequency of pressure vibration is match with inherent frequency of oscillation cavity, the feedback oscillation will be expanded and resonance will be generated in oscillation cavity. And large separated circular vortex will be appeared in the shear layer of jet, which increase the cavitation and improve the cleaning effect and erosion ability.

With the development of water jet, many scholars investigate self-resonating cavitating jet by theoretical analysis, numerical simulation, erosion experiments, force experiments. Barden C and Cholet H showed that deep well confining pressure will generate cavitation and confining pressure play a promoting role in cavitation through indoor simulation drilling test. Shen studied on experimental pressure characteristics and erosion effect of self-resonating cavitating jet, and concluded optimal spraying distance. Liao used self-resonating cavitating jet in rock drilling, and improved the drilling speed. Li and coworkers got the highest surge pressure peak and pressure pulsation amplitude by experimental investigation on pressure pulsation characteristics of different structure organ pipe. Wang investigated the frequency of self-resonating cavitating jet, and results showed radio-frequency component in vibration frequency domain graph is caused by cavitation bubble bursting in resonant cavity. Previous research has obtained certain achievements, but the occurrence mechanism and the internal flow characteristics of self-resonating cavitation is insufficient.

This paper investigated occurrence mechanism and flow characteristics of self-resonating cavitation by numerical simulation and experiments.

2. Numerical Simulation

2.1. Calculation Model

The structure diagram of organ pipe is shown in Fig.1. A cavity resonator made up of organ pipe whose length is \( L \), diameter is \( D \) as a monofier. Cavity entrance is connected with incoming flow pipe whose diameter is \( D_s \) and \( (Ds/D)^2 \) constitute the entrance of the cavity contraction section. The underpart of cavity is connected with the exit section with diameter \( d \) and \( (D/d)^2 \) constitute the exit of the cavity contraction section which is both the self-excitation mechanism and feedback mechanism. When the steady flow gets through, the contraction section can not only cause initial pressure exciting, but also feed pressure exciting back to cavity chamber which can form feedback pressure oscillations.

![Figure1. Structure diagram of organ pipe nozzle](image-url)
Computational domain is shown in Fig.2. Water sprayed out from the organ pipe nozzle and entered into a cylindrical flow field, $L_c=50d$, $D_c=20d$, to ensure that the flow field was in fully development. However, in order to save computing resources and computing time, 2d axisymmetric model was chosen to simulate the model.

![Figure 2. Schematic diagram of calculation domain](image)

The structure parameters of designed organ pipe nozzles were shown in Table 1 which were numbered 1~7. There were 4 variables nozzle diameter $d$, entrance diameter $D_s$, chamber diameter $D$, chamber length $L$ and 3 dimensionless structural relationships $(D_s/D)^2$, $(D/d)^2$, $L/d$.

| No. | $d$ (mm) | $D_s$ (mm) | $D$ (mm) | $L$ (mm) | $(D_s/D)^2$ | $(D/d)^2$ | $L/d$ |
|-----|----------|------------|----------|----------|-------------|------------|-------|
| 1   | 2.0      | 13.0       | 5.0      | 21.0     | 6.76        | 6.25       | 10.50 |
| 2   | 2.0      | 13.0       | 4.0      | 21.0     | 10.56       | 4.00       | 10.50 |
| 3   | 2.0      | 13.0       | 6.0      | 21.0     | 4.69        | 9.00       | 10.50 |
| 4   | 2.0      | 13.0       | 7.0      | 21.0     | 3.45        | 12.25      | 10.50 |
| 5   | 2.0      | 13.0       | 5.0      | 15.0     | 6.76        | 6.25       | 7.50  |
| 6   | 2.0      | 13.0       | 5.0      | 16.5     | 6.76        | 6.25       | 8.25  |
| 7   | 2.0      | 13.0       | 5.0      | 28.0     | 6.76        | 6.25       | 14.00 |

2.2. Mesh and boundary condition

The whole flow field of models was meshed by ICEM CFD. Schematic diagram of local mesh was shown in Fig.3. Mesh near nozzle exit and wall were increased to guarantee the precision while the whole quantity of mesh was 300 thousands.
The flow inside the nozzle was assumed to be unsteady, controlled by the RANS equations together with the continuity equation. Realizable $k-\varepsilon$ models were contrastively adopted to govern the turbulence characteristics and the near-wall treatment was left as the “standard wall functions”. Pressure boundary conditions were applied on the inlets and pressure outlet for outlet boundaries. Fluent was employed in the whole simulation works. The governing equations were discreted by the finite volume method and the 2nd order upwind scheme was adopted for spatial discretization of the convection terms. The Coupled algorithm was employed to couple the pressure and velocity. In order to capture the cavitation phenomenon, Mixture and Cavitation model were employed. Time step was $10^{-7}$s and it was considered convergence while the residual was lower than $10^{-5}$s and export flux tended to be stable.

2.3 Calculating results analysis
The phase volume fraction of No.1 nozzle from \( t=10^{-4}s \sim 7 \times 10^{-4}s \) was shown in Fig.4 which could clarify cavitation development process near the nozzle exit. Part of cavitation occurred inside the nozzle near the wall and they would increase gradually and transport out of nozzle. High-speed flow inside the cavity by feedback amplifier, strongly entrained environmental fluid. Then cavitation could develop and expand unceasingly until impacting the target.

The effects of the different pressure on the cavitation of No.1 nozzle are shown in Figure.5, with the increase of pressure, the cavitation effect became obviously, and the degree of gasification and the cavity volume were increased. The higher the pressure was, the greater the chance of cavitation induced in the chamber was. As the development of the cavitation in the environment, the effect of cavitation was more and more obvious.

The influence of cavity diameter on axis velocity attenuation

---

**Figure 4.** Organ cavitation development process

**Figure 5.** The influence of different pressure on the cavitation effect

**Figure 6.** The influence of cavity diameter on axis velocity attenuation
Fig. 7. The influence of cavity length on axis velocity attenuation

Fig.6 and Fig.7 show the influence of cavity length and diameter on axis velocity attenuation of organ pipe nozzle, which can be observed that the greater the diameter was, the slower the attenuation of the axis velocity was, and there was an optimal cavity length ($L = 21$ mm), which could keep the axial speed characteristic good. Thus it could be seen that large diameter increase the feedback of interior vortex ring, which was helpful for self-resonating. The cavity length effected the pulse period, so it existed an optimal value.

3. Experiment

3.1. Experimental apparatus

Fig.8 shows the connections of this experimental system powered by a piston pump, whose maximum pressure and flux can reach 60MPa and 120L/min, respectively. There was an accumulator between the nozzle and pump to eliminate the influence of flow fluctuation of the pump on the pressure pulsation. The pressure was controlled by a frequency transformer and the quantity of flow was acquired by a turbine flowmeter. The back-end of the drill pipe was sealed by the sealing unit while the front-end was installed the organ-pipe nozzle. The stand-off distance could be adjusted by the sliding motor. The target whose center was collinear with
the jet was fixed on the specimen plate and there was an orifice on the target, then the dynamic pressure could reach to the pressure sensor which was fixed on the target. The data acquired was then transmitted to the computer.

3.2. Experimental methods

Water jet impacting on target plate where there was a tiny hole at a certain stand-off distance was utilized to conduct pressure test. The jet impact pressure acted on the tiny hole and passed to the pressure sensor so that change rule of impacting pressure could be obtained. The impact pressure on the target plate of each nozzle was tested under the pressure of 10MPa, 15MPa, 20MPa, 25MPa by HBM MX840A dynamic data acquisition system for data collection and analysis.

3.3. Experimental results and analysis

Figure 9. Plot of pressure fluctuation time-domain and frequency spectrum

Fig.9 provides the plot of pressure fluctuation time-domain and frequency spectrum of the organ-pipe nozzle. Figure 9 illustrates that the dynamic pressure fluctuated periodically and the amplitude varied from 6Mpa to 10Mpa while oscillation frequency was about 5000Hz. The amplitude was influenced by oscillation period of the chamber and the vibrations caused by impact of vacuoles collapse.
Figure 10. Peak pressure under different working condition

Fig.10 shows how the stagnation pressure of jet axis varied along length changes of the chamber under different pressure of 10MPa, 15MPa, 20MPa, 25MPa. When L=12mm, the maximum pressure reached the peak and with the increase of length of the chamber the maximum almost stayed the same. Energy loss in the pipe increased with the pressure rising and the feedback period increased correspondingly, however, the amplitude was not affected.

Figure 11. pressure fluctuation of jet axis under different pressure

Fig.11 shows the pressure fluctuation of jet axis under different pressure. It can be seen that the fluctuation amplitude varied irregularly with the increase of L. when L=13mm and 15mm, the amplitude reached minimum and L=16.5mm, the amplitude reached maximum. The jet can be affected by ambient temperature, nozzle size and many other factors, and any change of the factor can induce a slight variation in the jet characteristics, therefore, lots remained to be studied.

4. Conclusions

(1) As the working pressure increased, the cavitation effect became obviously and the cavity volume was larger;

(2) The greater the diameter was, the slower the attenuation of the axis velocity was, and there was an optimal cavity length \((L = 21 \text{ mm})\), which could keep the axial speed characteristic good;

(3) With the increase of length of the chamber the maximum almost stayed the same; when L=13mm and 15mm, the amplitude reached minimum and L=16.5mm, the amplitude reached maximum.

Acknowledgement

This work was supported by National Key Basic Research Program of China (NO. 2014CB239203), Program for New Century Excellent Talents in University (NCET-12-0424), Natural Science Funds of Hubei Province for Distinguished Young Scholar (2012FFA020), Scientific Research Foundation for Returned Scholars, Ministry of Education of China.
References

[1] X.H. Li, Y.Y. Lu and W.Y. Xiang 2007 Water Jet Theory and the Application in the Mining Project (Chongqing: Chongqing University Press)

[2] Morel T 1979 Experimental study of a jet driven Helmholtz oscillator. Trans ASME J. Fluids Eng., 101 383-390.

[3] Rockwell D and Naudascher E. 1978 Review: self-sustaining oscillations of flow past cavities Trans ASME J. Fluids Eng. 100 152-165.

[4] Crow S C and Champagne F H. 1971 Orderly structure in jet turbulence J. Fluid Mech. 48(3) 547-591.

[5] Tang C L, Hu D, Pei J H. 2006 Experimental research on dynamic characteristic of the self-excited oscillation pulsed water jet Water Res. and Hydropower Eng. 37(12) 71-74.

[6] Wang P H. 2008 Impact Force Experimental Research of Self-Resonating Cavitation Water Jet. Mach. Design and Res. 24(6) 102-108.

[7] Wang P H and Ma F. 2009 Vibration Analysis Experiment of Self-resonating Cavitating Water Jet J. Mech. Eng. 45(10) 89-95.

[8] Li G S, Shen Z H, Zhou C S, et al. 2003 An experimental study on impact pressure characteristic of self-resonant cavitating jets J. Hydrodyn. 18(5) 570-575.

[9] Liao Z F, Tang C L 2002 Theory of the Self-excited Oscillation Pulsed Jet Nozzle J Chongqing University( Natural Science Edition) 25 (2) 24-27.

[10] Tang C L, Zhang F H, Yang L 2001 The Simulation and Analysis and Experimental Study on the Interaction of a Discrete Vortex with an Impinging Edge in Oscillation Cavity of High Velocity Oscillation Pulse Jet J Vib. and Shock 20(4) 25-28.