# Structure Design Of ROV-Based MOPU Platform Pin Hole Spin Cleaning Device

Jianhua Hou *

School of mechanical science and Engineering, Northeast Petroleum University, Daqing, China

* Corresponding Author Email: 136071662@qq.com

**Abstract.** The pile legs of the MOPU platform have been submerged in seawater for a long time, and there are a large number of Marine organisms on the surface, which has a negative impact on the stability of the platform and needs to be cleaned regularly. Most of the existing jacket cleaning technologies are aimed at cleaning the outer surface, and there are few studies on cleaning the Marine organisms attached to the pin holes of the pile legs of MOPU platform. In order to solve the above problems, this paper firstly designs a spin-type pin hole cleaning device based on underwater wall-climbing robot by drawing lessons from domestic and foreign experience. At the same time, the Fluent simulation of three commonly used cavitation water jet nozzles is carried out, and the most suitable nozzle type for pin hole cleaning is selected from the organ pipe type, shear type and corner cavitation nozzles. In the actual operation, the water temperature and depth around the ROV are changing, so the simulation needs to consider the influence of temperature and depth changes. In this paper, a reasonable point is put forward for the structural design of the spin cavitation cleaning device. The simulation results show that the corner cavitation nozzle should be selected in the pinhole cleaning operation.

**Keywords:** MOPU platform; Pile leg pin hole; Underwater wall-climbing robot; Spin cavitation cleaning; Cavitation nozzle.

## 1. Introduction

With the continuous development of Offshore oil and gas resources, Mobile Offshore Production Unit (MOPU) has been widely used [1]. The near water area and inundation area of the pile legs of MOPU platform usually have a large number of parasitic Marine organisms, especially the parasitic layer thickness of the platform operating in the South China Sea area is more than 9 cm. Too thick attached Marine organisms will corrode the outer wall of the pile leg, interfere with the normal outflow field, change the mechanical structure of the platform, and bury serious hidden dangers to the production safety of offshore oil and gas[2][3]. Therefore, the research on cleaning the attached Marine organisms on the offshore platform is a hot topic in recent years.

Cavitation water jet cleaning technology uses local instantaneous pressure drop to form a cavitation bubble, which collapses when the jet impacts the surface of the object being cleaned and forms micro-impact and local high temperature on or near the surface of the attachment to enhance the cleaning effect [4]. Compared with the traditional cleaning method, the cavitation cleaning technology has the characteristics of high efficiency and no damage to the surface coating of the component. At present, cavitation water jet cleaning technology is mostly used for jacket, ship bottom, oil pipeline cleaning, etc., has not been applied to the pin holes of MOPU platform. Liu Fei-fei[5] designed a water jet jacket Marine biological wall cleaning device held by an ROV robot arm, and conducted a cleaning test. Yu F et al [6]. designed a cavitation jet cleaning system carried by ROV. The nozzle of the system can maintain a constant distance from the jacket wall to ensure the cleaning effect. Zhu Feng [7] proposed a rotating cavitation jet cleaning disk scheme which is applied to ship bottom cleaning and carried by underwater wall-climbing robot. Xing Xueyang et al [8]. designed a spin-type water jet tubing cleaning device and compared the experimental results of the influence of different speed and pump pressure on the cleaning effect.

Based on the MOPU platform, the author designed a spin-type cavitation cleaning device based on underwater wall-climbing robot based on the summary of previous studies. At the same time, considering the characteristics of the pinhole cleaning operation, the key component of the cleaning cavitation nozzle is simulated by FLUENT on the basis of temperature and depth changes. According to previous studies, axial gas content and axial velocity have a great influence on cavitation cleaning effect. Based on these two factors, this paper makes a comparison and selects the most suitable nozzle for pin hole cleaning from the three common cavitation nozzle types, namely shear nozzle, organ pipe nozzle and corner nozzle.

## 2. Design of cleaning process

### 2.1. Engineering Background

The spin-type cleaning device in this paper is designed to meet the needs of cleaning the pin holes of the pile legs of MOPU platform. The MOPU platform is usually a jack-up structure, which can be automatically installed against the wellhead. The platform pile legs are generally four cylindrical steel pile legs, equipped with hydraulic lifting system, in order to adapt to the needs of offshore oil production in different sea areas and sea conditions; In order to realize the hydraulic lifting function of the platform, each pile leg is equipped with a number of pin holes. The MOPU platform is shown in Figure 1.


**Fig. 1** Schematic diagram of MOPU platform

### 2.2. Work flow design

The pin hole cleaning device of the pile leg of the MOPU platform is carried by the magnetic adsorption crawler underwater wall climbing robot and installed on the electric slide through the special fixture; During operation, the underwater wall-climbing robot is attached to the wall of pile leg and dives vertically along the axis of pile leg. When the ROV approaches the pin hole, the binocular vision system of the robot body and the color pinion camera system determine the pin hole position, place the cleaning device directly above the pin hole, and align the device with the center point of the pin hole by means of automatic path adjustment of the robot and manual adjustment by the platform operator through monitoring by the upper computer. After confirming the correct position, the operator starts the pump, the cleaning device begins to rotate under the action of hydraulic power, and slowly probe into the pin hole under the drive of the electric slide for Marine life cleaning, to achieve the descent - cleaning process, which can be repeated many times until the pin hole is cleaned; When the operator confirms that the pin hole is cleaned through the video signal, the cleaning device is reset under the drive of the slide table to realize the rise-reset process; Then the wall-climbing robot moves down the axis of the pile leg and continues to clean the next pin hole until the pin hole on one side of the pile leg is completely cleaned. The MOPU platform pin hole cleaning process is shown in Figure 2:

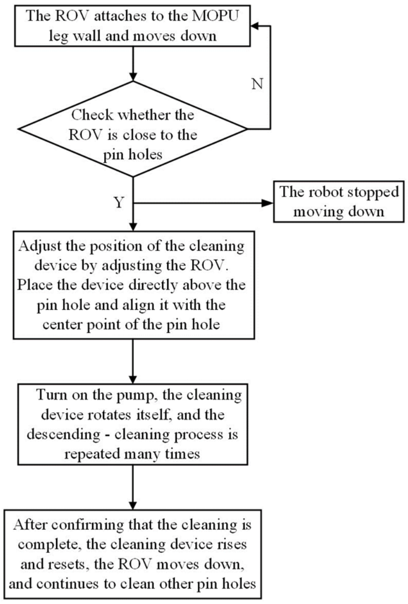


**Fig. 2** MOPU platform pin hole cleaning operation flow chart

## 3. Structure design of the cleaning device

The spin-type pin hole cavitation cleaning device is the execution part of the whole pin hole cleaning system, and its mechanical structure determines the cleaning effect of the pin holes of the pile legs of the MOPU platform. The author used Solidworks to establish a three-dimensional model of the cleaning device, determine the overall scheme of the device, and then complete the selection of important parts through mathematical calculation, and finally complete the detailed mechanical structure design. The overall layout of the spin-type cleaning device given in this section is reasonable and the mechanical structure is perfect, which can meet the needs of sea life cleaning in the pin holes of the platform.

### 3.1. Overall design of the cleaning device

The spin-type pin hole cavitation cleaning device is mainly composed of 1 upper end cover, 2 rotating water pipes, 3 special fixtures, 4 sealed end covers, 5 flange sleeves, 6 Angle contact ball bearings, 7 disc damping, 8 lower end cover, 9 water connector, 10 water manifold, 11 cavitation nozzle, 12 dynamic sealing ring a and 13 dynamic sealing ring b, wherein disc damping is connected with the lower end cover through the pin. The damping outer ring remains fixed, and the inner ring rotates with the rotating water pipe to achieve the purpose of increasing the resistance moment. The overall scheme and mechanical structure of the cleaning device are shown in FIG. 3 and FIG. 4:

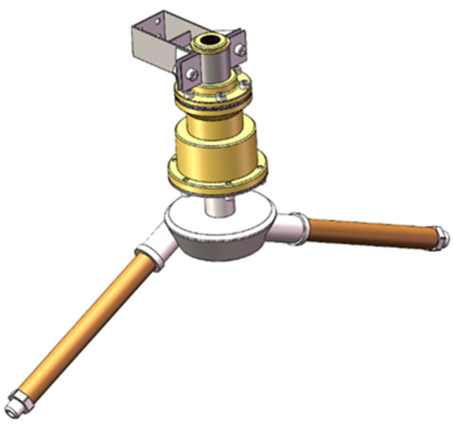

**Fig. 3** Overall scheme

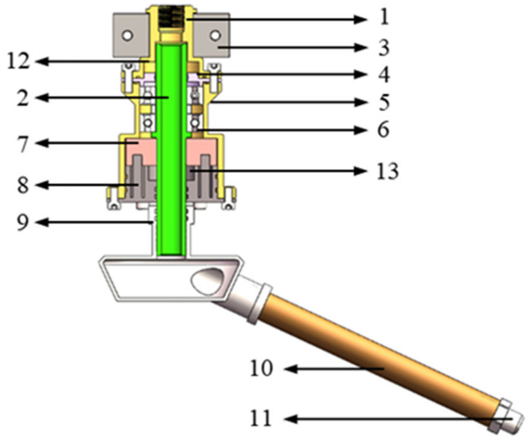


**Fig. 4** Mechanical structure drawing

### 3.2. The key design of mechanical structure

For the parts that have a greater impact on the mechanical structure rationality of the spin pin cavitation cleaning device, there are angular contact ball bearings, water joints, disc damping and dynamic seal ring, the design points are described as follows:

(1) Bearing selection

Whether the selection of bearings is reasonable determines whether the cleaning device can work normally, and the size of the bearing also has a huge impact on the overall size of the pin hole cleaning device, so the selection of bearings is a key point that must be paid attention to for the spin cleaning device. When the pinhole cleaning device is working, it mainly bears axial load, and occasionally it will bear slight or moderate impact caused by collision, water pressure fluctuation and other factors. The angular contact ball bearing can meet the operation needs of the cleaning device. According to the selected nozzle parameters, the equivalent load to be borne by the bearing under extreme conditions is 4981.46N. Referring to relevant data [9], it can be seen that the dynamic load of angular contact ball bearing 7003AC is 6300N, which meets the requirements of extreme working conditions, and the larger contact Angle is more suitable for bearing axial load.

(2) Waterway joint

The water joint is an important part to realize the self-rotating function of the cleaning device, and the rationality of its design has a great influence on the cleaning effect of the device. The water joint consists of a water inlet and two water outlets staggered at a certain distance in the vertical direction. The function is to make the spray gun produce a rotating torque under the action of the water jet reaction and realize the self-rotating cleaning function of the device. The two water outlets have a certain Angle with the axis of the waterway joint in the vertical direction, and the function is to take into account the cleaning of the attached Marine organisms on the wall and bottom of the pin hole. When the nozzle parameters are determined, the diameter of the waterway joint determines the reaction torque of the jet, and the torque size should be determined by combining the rated speed of the device and the reverse torque of the damping. The shape of the water structure inside the component has a great influence on the high-pressure water flow. Reasonable water structure can reduce the energy loss along the high-pressure water flow, improve the utilization efficiency of the pump and enhance the cleaning effect.

(3) Disc damping

The damping selected by the spin type pin hole cavitation cleaning device is disc damping, which is characterized by the damping inner ring that can rotate with the rotating axis, the outer ring and the lower end cover are relatively static through the fixed pin connection, and the high viscosity damping liquid is filled between the inner ring and the outer ring to provide the rotating reverse torque. The main function of damping is to slow down the vibration and impact of the device during cleaning, and at the same time, it can also control the speed of the device to avoid the energy of the pump becoming too much into the kinetic energy of rotation. Damping can increase the impact force of water jet, which has an important influence on the cleaning effect of the device.

(4) Dynamic sealing ring

The dynamic seal ring relies on the extrusion deformation of the seal to achieve the dynamic seal, which usually produces a lot of friction resistance, and the influence on the spin motion of the device cannot be ignored. The dynamic sealing ring selected by the cleaning device should be adapted to the water jet reverse torque and damping torque on the basis of ensuring the sealing effect and should not excessively hinder the spin motion of the cleaning device. Considering the above factors, the D-type sealing ring with small interference volume is selected as the dynamic sealing ring of the device, and the specific value of the interference volume needs to be determined by simulation calculation.

In addition, the mechanical structure design of the cleaning device should also fully consider the check of the threaded connection under extreme working conditions, the influence of the thickness of Marine organisms on the target distance, the influence of the tilt Angle of the spray gun on the cleaning effect and other factors. Considering that the cleaning device is carried by an underwater wall-climbing robot, it should also follow the criteria of small mass, so the high-performance 6061-T6 aluminum alloy is selected as the main component material of the device.

# 4. Finite element model of cavitation nozzle

Cavitation jet nozzle is a key component of a cleaning device, and its structural parameters have an important impact on the generation effect of cavitation jet [10]. As shown in Figure 1, the pin holes of the MOPU platform are distributed down along the pile legs, and the water depth is deepening, and the water temperature is gradually decreasing. The commonly used cavitation nozzles are different in such working environment, and the type of optimization needs to be carried out. The cavitation high pressure pump is expensive, and the construction of water jet test platform requires tedious work in the early stage. The simulation test of commercial software Fluent solves the above problems well, and the numerical simulation results can provide an important reference for the selection of cavitation nozzle [11]. For Fluent simulation, reasonable nozzle mesh division and mathematical model selection are very important to improve the calculation accuracy.

## 4.1. Geometry of cavitation nozzle

There are three types of nozzles commonly used in cavitation cleaning operations, namely organ pipe nozzles, shear nozzles and corner nozzles, whose structures are shown in FIG. 5, FIG. 6 and FIG. 7. By referring to previous research data [12][14], it is determined that the shear nozzle performs best when the length *D* and width *D* of the outlet mouth are equal. The organ pipe nozzle performs best when the diffusion Angle of the diffusion chamber is $\theta_1$=25°. The angular nozzle performs best when the diffusion Angle of the diffusion chamber is $\theta_2$=60° and the contraction Angle of the contraction chamber is $\theta_3$=13.5°. In order to ensure the power consistency of the cavitation nozzles mentioned in the paper and reduce the influence of size factors, the cylinder length *l*, nozzle diameter *d* and inlet diameter $D_s$ of the three cavitation nozzles are the same.

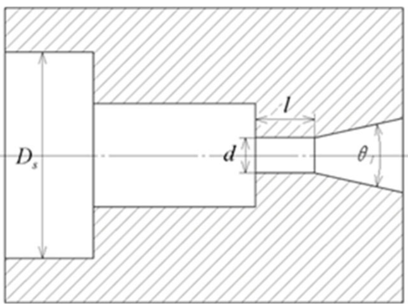


**Fig. 5** Organ pipe nozzle

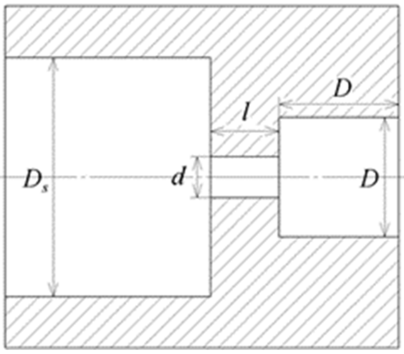


**Fig. 6** Shear nozzle

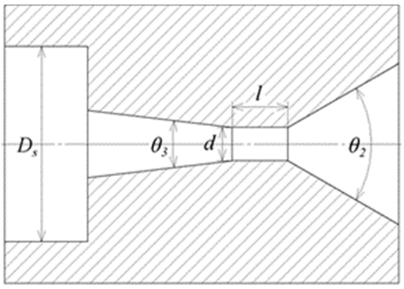


**Fig. 7** Corner nozzle

### 4.2. Grid division and boundary condition setting

(1) Grid finite element model of three cavitation nozzles

Since all types of cavitation nozzles selected in this paper have the characteristics of rotational symmetry, the three-dimensional model can be simplified into a two-dimensional model for simulation analysis, so as to save computing power and improve simulation efficiency [15]. The author used Solidworks software to establish a two-dimensional axismetrical model of the nozzle, and then used Meshing module in Workbench to carry out structural grid division and boundary setting for the two-dimensional model, and finally imported Fluent module for simulation, and obtained the calculation results. Through calculation and verification, there is little difference between the nozzle outlet velocity value of the simulation model and the theoretical calculation result [16], which proves the accuracy of the test. The mesh finite element model of the three nozzles is shown in Figure 8:

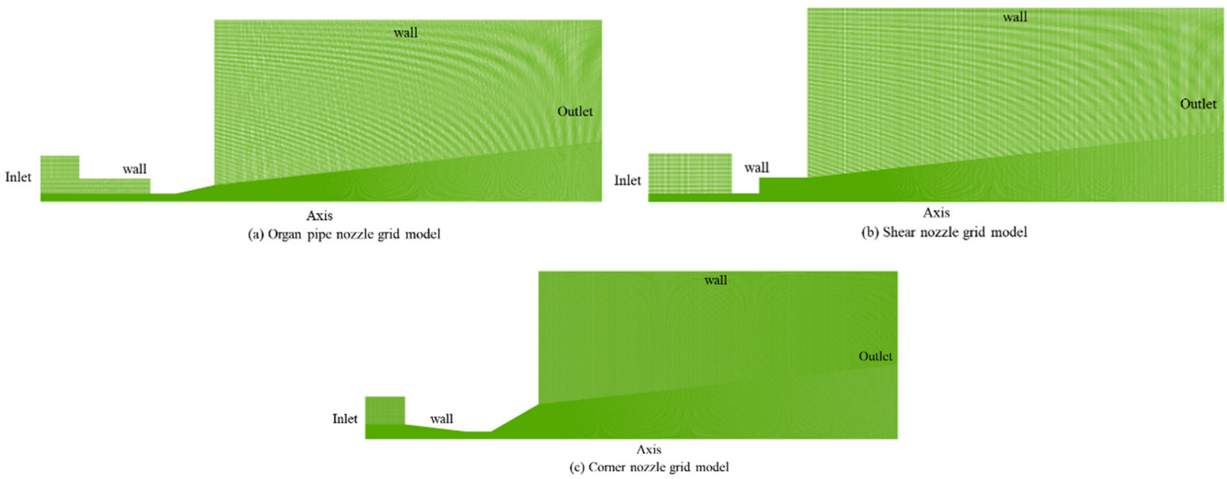


**Fig. 8** Grid finite element model of three cavitation nozzles

(2) Boundary condition setting

The Inlet boundary of the mesh finite element model is set as pressure-inlet, and the inlet pressure is set as 22MPa according to the project requirements. The temperature simulation requires opening the energy equation and setting the inlet temperature and water vapor saturation pressure according to Table 1. The Outlet boundary condition is set to pressure-outlet, and the outlet gauge pressure is set according to Table 2 in the deep simulation. The near-wall area is set as a standard wall function, and no slip speed is checked, regardless of the influence of gravity.

**Table 1.** Saturation pressure gauge for water vapor

| TEMP(°C) | 0 | 18 | 36 |
|---|---|---|---|
| Vapor pressure(Pa) | 935.4 | 2064.4 | 5945.3 |

**Table 2.** Water pressure comparison table

| Depth(m) | 0 | 40 | 80 |
|---|---|---|---|
| Gauge pressure(KPa) | 0 | 392 | 784 |

### 4.3. Mathematical Modeling

The numerical simulation in this paper is based on Fluent 2021r1. Due to the characteristics of high velocity and negative pressure vortex at the nozzle exit of cavitation water jet, RNG k-ε turbulence model with high accuracy for solving such problems is selected in this paper. In terms of the multiphase flow model, this paper selected a Mixture of multiphase flow models that are easy to converge, and selected the Schnerr-Sauer cavitation model that is more accurate in describing the cavitation process in Phase Interactions [17].

(1) RNG *k-ε* transport equation

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\alpha_k\mu_{eff}\right)\frac{\partial k}{\partial x_i}\right]+G_k+G_b-\rho\varepsilon-Y_M \tag{1}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\alpha_\varepsilon\mu_{eff}\right)\frac{\partial\varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon \tag{2}$$

There: $G_k$ is the Turbulent kinetic energy caused by velocity gradient; $G_b$ is the turbulent kinetic energy caused by buoyancy; $Y_M$ is the effect of turbulent pulse expansion on the total dissipation rate; $\alpha_k$ and $\alpha_\varepsilon$ are turbulent Prandtl numbers; $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are empirical constants.

(2) Phase transition equation of Schnerr-Sauer cavitation model

$$\frac{\partial}{\partial t}\left(\alpha\rho_v\right)+\nabla\cdot\left(\alpha\rho_v\vec{v}_v\right)=\frac{P_v\rho_1}{\rho_1}\frac{D\alpha}{Dt} \tag{3}$$

There: $\alpha$ is the gas phase volume fraction; $\rho_v$ is the gas phase density; $\vec{v}_v$ is the gas phase velocity; $\rho_1$ is the density of the liquid.

## 5. Optimization of cavitation jet nozzle types

Due to the continuous diving of ROV attached to the pile leg wall during ROV operation, the water depth and temperature of the seawater environment where the cleaning device is located are constantly changing, so it is necessary to select the nozzle type that is most suitable for the pile leg cleaning operation from the commonly used cavitation nozzle configuration. In this section, based on the actual situation of the pin hole cleaning operation, Fluent simulation is carried out on the organ pipe nozzle, shear nozzle and Angle nozzle respectively from two aspects of temperature and depth, and the nozzle type that is most suitable for the MOPU leg pin hole cleaning operation is selected. In order to accurately reflect the efficiency of the cavitation nozzles, the axial gas content and axial velocity, which have the greatest influence on the cleaning effect, are selected as evaluation indexes in this paper. Due to the continuous diving of ROV attached to the pile leg wall during ROV operation, the water depth and temperature of the seawater environment where the cleaning device is located are constantly changing, so it is necessary to select the nozzle type that is most suitable for the pile leg cleaning operation from the commonly used cavitation nozzle configuration. In this section, based on the actual situation of the pin hole cleaning operation, Fluent simulation is carried out on the organ pipe nozzle, shear nozzle and Angle nozzle respectively from two aspects of temperature and depth, and the nozzle type that is most suitable for the MOPU leg pin hole cleaning operation is selected. In order to accurately reflect the efficiency ofthe cavitation nozzes, the axial gas content and axial velocity, which have the greatest influence on the cleaning effect, are selected as evaluation indexes in this paper.

### 5.1. Temperature influence

The MOPU platform is widely used in the South China Sea area of China. Based on relevant data, the average surface water temperature in tropical regions of China during summer exceeds 34℃[18]. Considering the impact of global warming trends, the maximum seawater temperature reaches 36℃. During pin hole cleaning operations, ROV must continuously dive along the pile leg. Given that ambient sea water temperatures are subject to constant fluctuations and seasonal changes, three temperature settings are employed: 0℃, 18℃, and 36℃.

As can be seen from FIG. 9, in the case of simulated temperature change, the closer the three cavitation nozzles are to the nozzle, the higher the gas content of the nozzle, while the gas content decreases to different degrees when the nozzle is far away from the nozzle. Compared with the data, it can be found that the angular nozzle has the highest axial gas content, which is much higher than the other two types of nozzles. The axial gas content of the organ nozzle is the second, and there is a small fluctuation at the nozzle. The shear nozzle has the lowest axial gas content, and there is almost no change. When the distance from the nozzle is about 15mm, the axial gas content of the three cavitation nozzles is close to the minimum value.

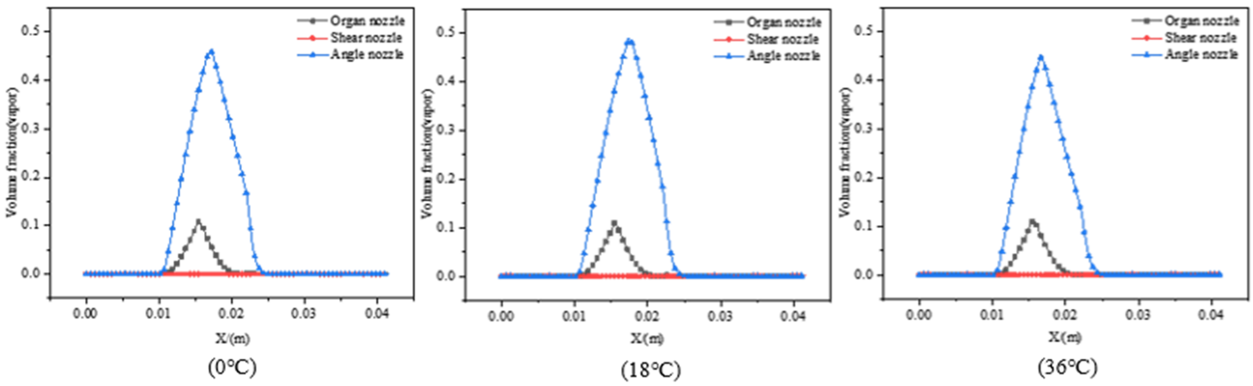


**Fig. 9** Axial gas content of three cavitation nozzles at different temperatures

As can be seen from FIG. 10, under different temperature conditions, the isokinetic core length of the water jet from the corner nozzle and the organ nozzle after leaving the nozzle is the longest, and the length is similar. The shear nozzle has the shortest isokinetic core length and the fastest velocity attenuation, which indicates that under similar environmental conditions, the impact energy of the shear nozzle is smaller than that of the other two nozzles. Compared with the angular nozzle and the organ nozzle, it can be found that the angular nozzle has a slightly slower jet velocity attenuation, and the water jet has a higher energy utilization efficiency.

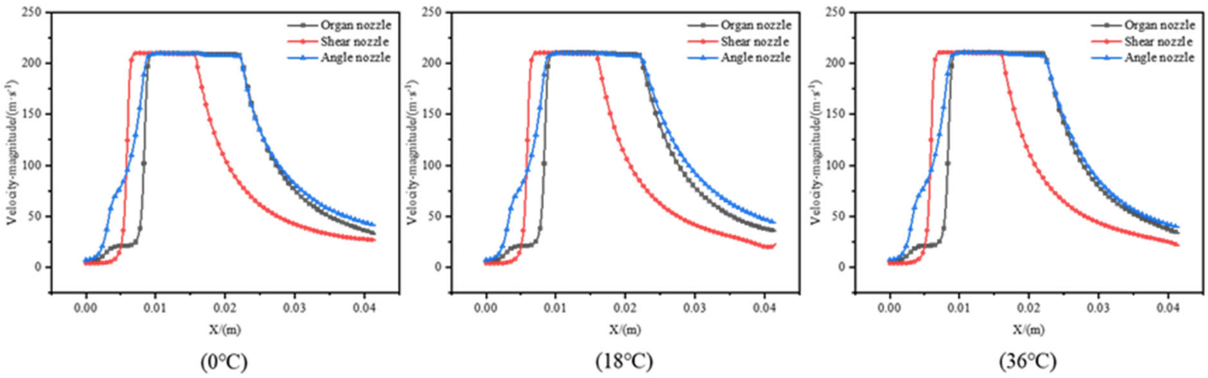


**Fig. 10** Axial velocities of three cavitation nozzles at different temperatures

## 5.2. Depth effect

As the ROV dives, the water depth around it will increase, so it is necessary to consider the impact of the depth of the environment on the cavitation nozzle. The MOPU platform is generally used in shallow sea, and the maximum depth of the pile leg into the water is more than 40m. Considering the possible limit working conditions and future promotion and application, the depth factor is determined to be 0m, 40m, 80m.

As can be seen from FIG. 11, under the simulated water depth change, the angular nozzle has the highest axial gas content, which is much higher than the other two cavitation nozzles, followed by the organ pipe nozze, and the shear nozzle is the worst. The simulation results show that with the increase of depth, the axial gas content of both the angular nozzle and the organ nozzle decreases significantly, but the angular nozzle is better than the organ nozzle in numerical terms. Obviously, the water depth pressure factor has a great influence on the cavitation bubble formation ability of the cavitation nozzle, which is also consistent with the actual operation experience.

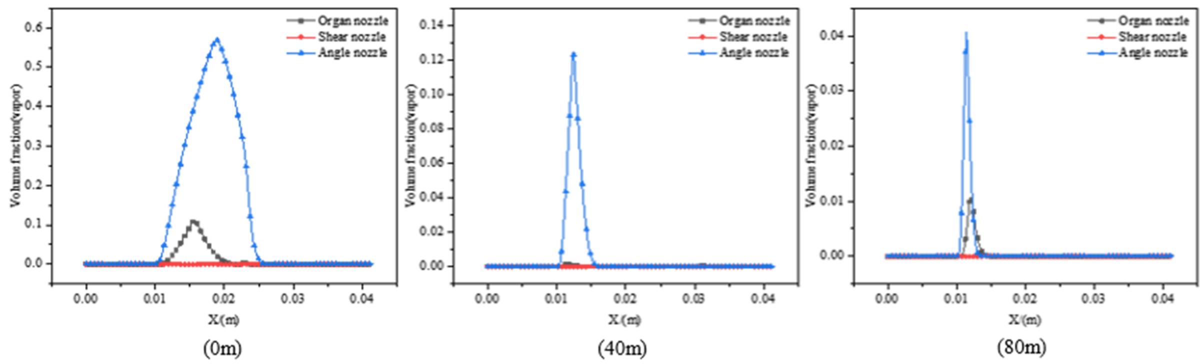


**Fig. 11** Axial gas content of three cavitation nozzles at different depths

As can be seen from FIG. 12, with the increase of water depth, the maximum axial velocity of the three nozzles decreases, which indicates that the ambient back pressure at the nozzle mouth dissipates part of the water jet energy. By observing the axial velocity curves of the three types of cavitation nozzles, it can be found that, within a reasonable range, even with the increase of water depth, the angular nozzle still has the slowest axial velocity attenuation, and the length ofthe isokinetic core changes the least. This indicates that among the commonly used cavitation nozzles, the angular nozzle water jet has the strongest resistance to environmental back pressure and is most suitable for continuous ROV dives.

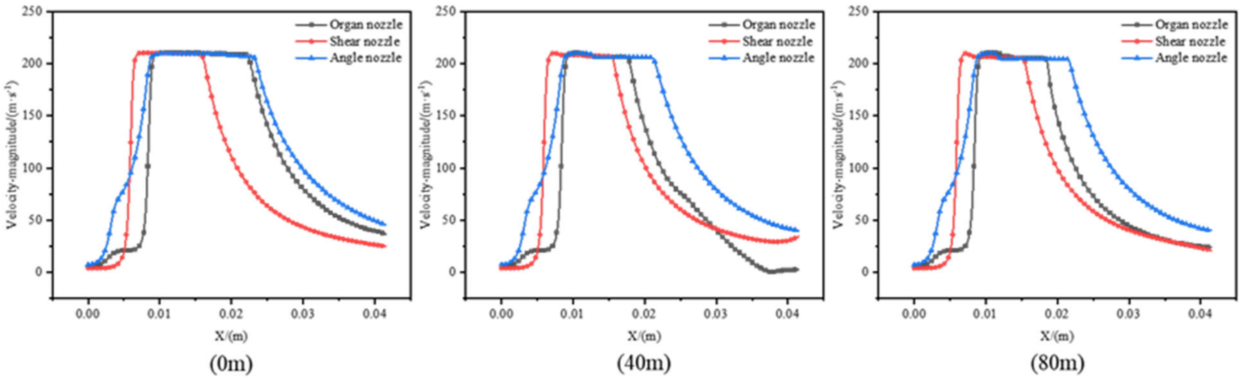


**Fig. 12** Axial velocities of three cavitation nozzles at different depths

In this section, based on the comparison of Fluent simulation results of axial gas content and axial velocity of three commonly used cavitation nozzles from two aspects of temperature and depth change, it can be seen that the angular cavitation nozzles perform best compared with the other two types of nozzles. Therefore, the angular nozzle is selected as the executing element of the cavitation water jet in the MOPU platform leg pin hole spin cleaning device designed in this paper.

## 6. Conclusions

(1) According to the structural design of the spin-type cavitation cleaning device of the pin hole of MOPU platform, it can be concluded that the key point of the design of the waterway joint is that the shape of the internal waterway should be reasonable, so as to reduce the loss of the pump along the way and increase the energy of the water jet itself.

(2) The spin cavitation cleaning device is driven by waterpower, and the internal need to install disc damping to ensure that the speed of the cleaning device is within a reasonable range and prevent the energy of the water jet from being dissipated too much due to the hydraulic. spin speed.

(3) The sealing system of the spin cavitation cleaning device should consider the influence of interference when selecting the dynamic seal ring. The key point of design is to minimize the friction resistance moment of the seal ring while ensuring the dynamic seal effect and reduce the interference with the spin motion of the cleaning device.

(4) Based on the characteristics of ROV pin hole cleaning operations, this paper compared the Fluent simulation results of three different cavitation nozzles and found that the angular nozzle performed better than the other two cavitation nozzles in terms of axial gas content and axial velocity, indicating that the angular nozzle is more suitable for the pinhole cleaning device.

## References

[1] Jiang Chunqi, Hu Meng, Zhang Mingxiang et al. Application of MOPU intelligent management system for shifting operation [J]. Marine Engineering, 2023, 52 (02): 35-38.

[2] Zhang Qijun, Wu Gongguo. Research on the thickness of attached organisms on the surface of underwater components of offshore platforms in Wenchang Area of the South China Sea [J]. Guangdong Chemical Industry, 2021, 48 (08): 122-123+111.

[3] Yu Zhikai, Lu Yue. Analysis of influence of Marine organisms on Environmental Load of jacket platform [J]. Ocean Engineering, 2020, 49 (03): 132-135.

[4] Liu H, Cao Z, Xie C, et al. Research on erosion characteristics of a novel cavitation nozzle under nonsubmerged condition[J]. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2021, 235(6): 988-998.

[5] Liu Fei-Fei. Design and optimization analysis of ROV based high-pressure water jet Marine biological cleaning system [D]. Beijing Institute of Petrochemical Engineering,2021.

[6] Yu F, Li Q, Wang Y, et al. Optimization of tool orientation for improving the cleaning efficiency of offshore jacket-cleaning systems [J]. Applied Ocean Research, 2021, 112: 102687.

[7] Zhu Feng. Hydrodynamic Analysis and Cleaning System Characteristics of Underwater Boat Brushing Robot [D]. Shanghai Ocean University,2021.

[8] Xing Xue-Yang, Zhao Jian, Guo Gongpu et al. Design and research of high-pressure rotary jet cleaning tubing device [J]. Cleaning World, 2016, 32 (01): 17-21.

[9] Cheng Daxian, WANG Defu, Ji Kuisheng et al., Mechanical Design Manual [M]. 6th Ed. Beijing: Chemical Industry Press, 2016, 8-320.

[10] Zhao W, Li Z, Deng J, et al. Experimental and numerical study on the effects of nozzle geometry features on the nozzle internal flow and cavitation characteristics [J]. Atomization and Sprays, 2021, 31(6).

[11] Li Yong, Gao Hui, Liu Fei-Fei. Simulation and optimization of high-pressure water jet Gun based on Fluent [J]. Journal of Marine Technology, 2021, 40 (06): 80-88.

[12] Zhao Wenliang. Underwater Cavitation Jet Erosion Technology and Experimental Research [D]. Zhejiang University,2016.

[13] Yu Haitao, Xu Yan, Wang Jiaxiang, LIU Shui-hai, Zhang Jinglong, Wang Zunce. Numerical simulation of cavitation jet characteristics of organ pipe nozzles [J]. Contemporary Chemical Industry, 2022, 51 (08): 1991-1995.

[14] Dong W, Yao L, Luo W. Numerical Simulation of Flow Field of Submerged Angular Cavitation Nozzle[J]. Applied Sciences, 2023, 13(1): 613.

[15] Cui Cong, Zhang Gongxue, He Kai et al. Analysis of Effect of Nozzle Structure on cavitation jet [J]. Modern Machinery, 2021, (05): 64-67.

[16] GE Anliang, Li Yanlong, Wang Xinbao et al. Simulation test of net washing cavitation jet nozzle [J]. Fishery Modernization, 2022, 49 (02): 18-24.

[17] Schnerr G H, Sauer J. Physical and numerical modeling of unsteady cavitation dynamics [C]. Fourth international conference on multiphase flow. New Orleans, LO, USA: ICMF New Orleans, 2001, 1.

[18] Xiu Linpeng, Chang Yufei, Zhou Zhi et al. Study on the degradation of FRP bars in seawater sand concrete under real seawater environment [J]. Journal of Hainan University (Natural Science Edition), 2022, 40 (03): 300-308.