Research on Automatic Cleaning Equipment with High Pressure Water Jet for Optical Pipelines

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Abstract. In order to solve the problems of high labor intensity, low efficiency, and unstable cleaning quality when cleaning optical pipelines with traditional manual high-pressure spray, automatic cleaning equipment with high pressure water jet for optical pipelines is designed. The working principle and the design points are introduced. The movement rule of the nozzle under self-propelled drive is analyzed by ANSYS, the results show that the self-propelled drive cannot meet the cleaning speed requirements. Therefore, the wire rope driving method is proposed to realize the control of the nozzle speed. Subsequently, the speed of the simulated water jet is analyzed by the STARCCM, it is inferred that the water jet is still in the basic section at the maximum target distance of the pipeline, which can be used for cleaning. For verifying the cleaning effect, the prototype is applied to the cleaning of the actual optical pipelines. The verification results show that the cleaning equipment can meet the requirements of 100 / class clean, and the efficiency is increased by 70% compared with the traditional manual high-pressure spray.

1. Introduction
There are a lot of optical pipelines in large laser equipment, which provides 100 / class clean and high vacuum working environment for beam transmission. Therefore, the cleaning technology of optical pipelines is particularly important.

At present, the mainstream technologies in the field of high cleanliness precision industrial cleaning are ultrasonic [1], steam cleaning [2] and high pressure spray [3]. It is not easy to produce air bubbles on optical pipelines with thickness over 5mm by ultrasonic cleaning, and the paint surface is damaged seriously. The cleaning efficiency of steam washing is low and the process is complex. High pressure water jet cleaning is more and more widely used in pipeline cleaning due to its efficient and fast cleaning speed, as well as the advantages of no metal corrosion, no environmental pollution, low cost and high cleaning quality [4].

Many scholars have also carried out research on high pressure water jet pipe cleaning truck [5], automatic oil pipe cleaning jet gun [6], and high pressure water jet cleaning machine [7]. However, the existing mature pipeline automatic cleaning equipment are mainly used for cleaning the sewage pipe, oil pipe, etc., which cannot be applied to optical pipeline with 100 / class cleaning requirements.

The traditional cleaning method of optical pipelines in laser devices is manual high-pressure spraying. Due to the narrow and long pipeline, it is necessary to use sponge, clean cloth and other self-made tooling to clean the pipeline where it is difficult to reach. The manual high-pressure spraying has high labor intensity, unstable cleaning quality, and low cleaning efficiency, which cannot meet the
large-scale cleaning requirements of subsequent projects. Therefore, there is an urgent need to design optical pipes automatic cleaning equipment.

2. Working principle

The working principle of the automatic cleaning equipment is shown in figure 1. The pure water provided by the water supply device is pressurized by the high-pressure water pump, and then delivered to the spray head through the hose reel. The nozzle sprays high-pressure fluid backward, and the high-pressure jet breaks, shears and peels the pollutants away from the attached surface. In this process, the nozzle moves along the pipe under the action of high pressure jet thrust.

![Figure 1. Schematic diagram of working principle](image)

The diameter of the optical pipelines in the laser device is 300-500mm, and the length is less than 6m. According to NIF [8], the cleaning parameters are set as follows:

| Parameter | Working pressure | Flow rate | Cleaning speed | Target distance |
|-----------|------------------|-----------|----------------|----------------|
| Value     | 5-17MPa          | 300L/min  | 0.4-2.5m/min   | ≤ 450mm        |

3. Design points

Nozzle, bracket, hose reel, and drive components are the core components of high pressure jet pipe cleaning equipment. The design of these parts is introduced in detail.

3.1. Nozzle and bracket

Twelve nozzles are arranged along the circumference, the spray angle of the nozzle is 25°, and the nozzle installation angle γ is 35°. The water cone sprayed by the nozzle intersects the inner wall of the optical pipeline. When the diameter of the optical pipeline is the minimum value of 300mm, the angle along the optical pipeline's radial direction is 31.6°, and the coverage range is 31.6°×12=379°>360°. Radial full coverage of the pipeline can be achieved.

The jet recoil evenly arranged along the circumference can suspend the nozzle, but the stability is poor. Under the gravity of the water supply hose, the nozzle deflects and breaks the balance. The nozzle collides with the inner wall of the optical pipeline. Therefore, the design of the bracket allows the nozzle to run smoothly along the center of the optical pipeline during cleaning. As shown in figure 2, the bracket is mainly composed of connecting pipe, feet, front and rear pulleys, feet sliders, set screws and so on.
3. The connecting pipe plays the role of water supply and fixing feet. The stress analysis is shown in figure 3. The pressure in the optical pipeline is calculated at 20MPa. The stress at the point of action of the wrench is the largest, with the value of 144MPa. The material is 0Cr18Ni9, $\sigma_{0.2}=205$MPa, the safety factor is 1.3, and the allowable stress is $157$MPa>144MPa, which meets the strength condition.

3.2. Hose reel

The hose reel is used to wind and retract the water supply hose to keep it clean and the production site tidy. The hose reel is mainly composed of slewing frame, water supply hose, slewing bearing, rotary joint, support frame, etc., as shown in figure 4.

During the rotation process, the water pipe joint rotates with the slewing frame, and the rigid water pipe is stationary. The water pipe joint and the rigid water pipe are connected by the rotary joint, which has the function of dynamic sealing connection. The water supply hose and the high-pressure water in it are unevenly distributed, and the radius of gyration is large, which causes overturning moment. Therefore, the slewing bearing is used to bear the overturning torque to avoid overturning.
3.3. Drive components

3.3.1. Analysis of self-propelled motion law. In order to meet the cleaning requirements of the optical pipeline, the moving speed of the nozzle needs to be controlled within 0.4m/min-2.5m/min. Therefore, it is necessary to analyze the movement law of the nozzle under the self-propelled drive:

The equation for driving force to drive the movement of self-propelled cleaning equipment is:

\[ F_{\text{axial}} - f_1 - f_2 = (M + mL)a \]  \hspace{1cm} (1)

In the formula: \( M \)—the total mass of the nozzle and bracket; \( a \)—the acceleration of movement; \( L \)—the length of the water supply hose put in the pipeline.

The movement of the cleaning equipment is simulated by ANSYS, it is calculated that the relationship between the acceleration and speed of the nozzle with the time at the minimum working pressure of 5MPa is shown in figure 5 and figure 6, respectively. It can be seen from the calculation results that when the pressure of the cleaning equipment is only the minimum working pressure, the equipment only needs 1.75s to complete the 6m pipeline, the maximum acceleration is 4.98m/s\(^2\), and the maximum speed is 5.28m/s, which cannot meet the speed requirements in the range of 0.4m/min ~ 2.5m/min.

![Figure 5. acceleration of self-propelled nozzle (pressure at 5MPa)](image1)

![Figure 6. speed of self-propelled nozzle (pressure at 5MPa)](image2)

In order to achieve a better cleaning effect, the high-pressure jet needs to stay on the surface of the pollutant for a certain time to break, shear, and peel, but the impact of the residence time on the cleaning effect after a certain limit is negligible, only causing energy waste. Therefore, the speed of
the spray head must be controlled so that the optical pipeline is cleaned at a uniform speed by the high-pressure jet, and the speed needs to be adjusted according to the type of contaminants.

3.3.2. Speed-controllable drive components design. At present, the friction drive and the reel drive are the main methods for controlling the speed of the self-propelled high-pressure jet pipe cleaning equipment, as shown in figure 7 and figure 8. The first one is to use the friction between the pressure wheel and the water supply hose to control the movement of the nozzle. It has the advantages of simple structure and low cost, but it has slip phenomenon and poor reliability. At the same time, the water supply hose is also subject to axial force, and the steel wire mesh needs to be wrapped around the outer layer of the pipe; The second method is to use the motor to drive the reel to rotate to control the feed and retreat of the water supply hose to achieve a uniform speed of the nozzle. The mechanical structure is reliable, but there are deviations in the stroke control, which needs to be corrected regularly, and the water supply hose is also subject to axial force, which causes additional safety risks to the water pipe sealing structure.

Neither of the above two methods can be well applied to the speed control of the optical pipeline high-pressure water jet automatic cleaning equipment. Therefore, a new water-electric hybrid driving method is designed: the forward of the nozzle is powered by the jet reaction force, and the motor rotates forward to release the steel wire rope. The wire rope provides the tension matching with the jet reaction force, so that the nozzle can move forward at a uniform speed at the release speed of the steel wire rope, thus completing the first cleaning of the pipeline. When the nozzle needs to return, the motor reverses to recover the wire rope, and the nozzle to is dragged to return at a constant speed to complete the second cleaning of the pipeline. The specific structure of the driver components is shown in figure 9.
Among them, waterproof stepping motor is used to meet the wet working environment. By controlling the speed of the stepper motor, the stepless speed regulation of the wire rope during the release and recovery process can be achieved to meet the needs of the cleaning process. At the same time, the turbine reducer is used to prevent the nozzle from rushing out of the pipeline at high speed when the control system fails.

In the course of work, only the nozzle, bracket, the wire rope and water supply hose enter the inside of the pipe. These parts have been cleaned before, and the wire rope is tight and does not produce abrasive debris caused by friction. The moving parts are only the pulleys of the bracket, and the pulleys material is PTFE with self-lubricating property, without adding lubricating grease. Therefore, the drive components do not produce secondary pollution.

Under the action of the drive components, the motor can automatically control the positive and negative rotation of the drum, thereby providing different forces for the movement of the nozzle inside the optical pipeline. At the same time, it can manually control the positive and negative running of the nozzle, and realize the start and stop under the program running mode. The drive components have the advantages of low cost and small footprint, which also avoids the axial force of the water supply hose and improves the sealing safety.

4. The simulation analysis of water jet velocity

After the water jet leaves the nozzle, there is a great speed difference in the boundary layer formed between the water jet and the environmental medium, which generates a force perpendicular to the jet axis. There are also great turbulent fluctuations inside the water jet. The combined action of these forces causes the mass and momentum exchange between the jet fluid and the air. In this way, there is a continuous flow of air into the incident flow, and the jet continues to diffuse from the boundary layer to the axis. Obviously, the width of the boundary layer continues to expand as the target distance from the exit increases. When the jet and air are completely mixed, the cross section of the jet is separated into droplets by the air, and the jet becomes a mixture of water droplets and air. The velocity distribution cloud image of the water jet sprayed to the test board at a distance of 450mm was simulated by STARCCM, as shown in figure 10.

Figure 9. drive components
Figure 10. distribution of jet velocity

After jetting out, it is divided into three stages: core section, basic section and dissipation section. The pressure concentration in the core section is very short, it can be used for jet cutting, etc.; the dissipation section can only be used for dust suppression. The basic jet has a certain impact force and can be used for cleaning. The simulated water jet axis velocity curve is shown in figure 11. It can be seen that the velocity attenuation of the jet within 20mm is obvious, but it is very small within the target distance of 20mm-450mm. It means it is still in the basic section within the maximum target distance of 450mm, which can be used for cleaning.

Figure 11. curve of jet velocity

5. 4 experimental verification
The inner surfaces of the five pipelines contaminated by waste oil are stored outdoors for one month, and then transported to a 100 grade clean cleaning site. After that, they are cleaned with pipeline cleaning equipment under the working pressure of 5MPa, 7MPa, 10MPa, 15MPa and 17MPa at the maximum operating speed (2.5m/min). After cleaning, it is verified that the drive components can meet the design requirements. The comparison before and after optical pipeline cleaning under 5MPa pressure is shown in figure 12.

Figure 12. comparison before and after optical pipeline cleaning
Based on the "water film rupture method" commonly used in the engineering practice of laser equipment, whether the optical pipeline has been cleaned to 100/class is judged as follows: Pure water is sprayed on the surface of the cleaned optical pipe to form a water film on the surface. If the measured water film rupture time is greater than the design requirement of 15s, it means that the cleaning equipment has the ability to clean the pipeline to 100/class clean. According to the experiment, the water film breaking time is 20 seconds at the minimum working pressure of 5MPa, which is more than 15 seconds required by the design, which indicates that the device can clean the pipeline to 100/class. The cleaning results are shown in table 2. Due to the good cleaning effect, no test is carried out under the pressure above 10MPa.

### Table 2. Cleaning test results

| Serial number | Pressure (MPa) | Water film rupture time (s) |
|---------------|----------------|-----------------------------|
| 1             | 5              | 20                          |
| 2             | 7              | 40                          |
| 3             | 10             | 60                          |

During the cleaning process, the timing starts from the pipeline in place. Firstly, the equipment is installed to the first optical pipeline and clean the optical pipeline twice, then the equipment is dismantled and moved to the next optical pipeline until the cleaning of the five optical pipelines is completed. Finally, the equipment is removed. The process takes about 50 minutes, and the disassembly time of the equipment is about 10 minutes. The efficiency is more than 70% higher than that of manual cleaning.

### 6. Conclusion

This paper introduces the high pressure water jet automatic cleaning equipment for optical pipelines. The equipment provides full coverage and high strike force to ensure clean cleaning effect, while providing uniform speed cleaning to ensure cleaning quality. It has the advantages of low cost, small footprint, uniform and controllable cleaning speed, high sealing safety, and no secondary pollution, which can be used for the cleaning of optical pipelines in laser devices and similar pipelines with high cleanliness requirements.

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