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Study on Wax Injection Techniques for Steel Tendons of Monitoring Prestress States in the Third-Generation of Nuclear Power Plants

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Abstract. In the prestressing system of nuclear island containment structures, steel tendons with stress measurement devices are installed to monitor the prestress loss during the construction and operational phases of nuclear power plants. As the effective corrosion protection for monitoring tendons is vital, wax injection techniques for monitoring tendons were explored in this study. By analyzing the critical aspects and challenges therein, selecting anti-corrosion materials and injection devices, and conducting verification tests and on-site construction, the construction processes of wax injection were determined and the effectiveness of domestic equipment was verified. During the wax melting process, stirring can significantly shorten the time it takes for the wax to fully melt. During wax injection, the wax temperature should not be lower than 65°C and should not exceed 130°C. To achieve good injection effect, the injection time should not exceed 30 minutes, with 10 minutes being optimal. Several conclusive findings were proposed and might be useful for engineering practice.

Keywords. Monitoring tendons, wax injection, domestic

1. Introduction

In the construction of nuclear power plant safety shells, several prestressed steel tendons with stress measurement devices are typically utilized to measure prestress loss during the construction and operation phases. These tendons, known as monitoring tendons, have tension sensors installed at passive ends, which can be replaced in case of failure. After jacking of the monitoring tendons, a flexible injection material is used for corrosion protection of the steel wires. The monitoring tendons need continuous monitoring of stress states in steel wire throughout the 60-year service life of the nuclear power plant. Any damage or corrosive rust under the extremely high tension of 1200t can lead to wire breakage. Thus, effective corrosion protection for monitoring

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tendon is necessary and challenging, particularly in a humid and salt-laden environment near the coast [1-3].

A post-tensioned system with bonded prestressing was utilized in a domestic third-generation nuclear power plant. The prestressed tendons consist of 54 bundles of 1860MPa grade low-relaxation steel strands, with each strand composed of 7 steel wires, and a nominal area of 150mm². The inner diameter of prestressing duct is 160mm.

In this project, the selected monitoring tendon type is pure vertical, totaling 4 steel tendons, with a pipe length of approximately 65m. The primary construction area is in the circular prestressing corridor under the containment structure, with a corridor cross-section dimension of 3850mm in height and 2500mm in width. The limited space in the corridor is not conducive to large equipment construction. Additionally, the entrance for prestressing corridor equipment and materials is located within the nuclear auxiliary building, making it impossible to use conventional lifting equipment. Therefore, the choice of injection equipment is restricted.

The bottom of the monitoring tendons is located in the prestressing corridor, while the top is located in the dome ring beam. The overall height of the pipes is approximately 64m, with a large disparity in the injection height. The pipe diameter is 160mm, and the injection cross-section is large, with a injection volume of approximately 12L per meter. It is crucial to ensure that the anti-corrosion material flows out smoothly from the top of the pipe before it cools and solidifies. Any failure in the injection process requires a significant amount of hot water cleaning, which is time-consuming and presents strict environmental requirements. Therefore, this construction activity places high demands on the performance of the anti-corrosion materials, injection devices and construction processes [4][5].

2. Selection of Anti-corrosion Materials and Injection Equipment

2.1. Anti-Corrosion Materials

Considering the construction environment and challenges on-site, anti-corrosion materials that are solid at room temperature and become liquid when heated are suitable. Given the high safety and quality requirements of nuclear power plant construction and the need for stable and low drop point materials, the CP-THPF special wax is chosen for the corrosion protection of the monitoring tendons in this study. Compared to anti-corrosion grease used for stay cables in domestic bridges, the CP-THPF wax has a lower drop point, making it easier to melt. It also has lower penetration index, meaning it has high viscosity and better adhesion at normal room temperature [6-9]. Some of its properties are shown in table 1.

Table 1. Properties of CP-THPF Special Wax.

Index	Performance
Drop Point /°C	≥65°C
Penetration Index(25°C,1/10mm)	60～95
Oil Release Rate(7d,40°C)/%	≤0.5
Corrosion Test (No.45 Steel Plate,100°C,24h)	No Corrosion
Salt Spray Test (No.45 Steel Plate,30d)/Grade	Not Higher than B

2.2. Wax Melting Equipment

A domestic heating system with band-shaped heaters was utilized as wax melting equipment [10]. As shown in figure 1, the heating system has four heating sections, which are the base heater, lower heater, middle heater and upper heater. Each part can be independently controlled for temperature with a digital thermostat ranging from 30 to 280°C, operating on a 220V power supply.

Figure 1. Wax melting equipment with band-shaped heaters.

2.3. Wax Injection Equipment

Once the CP-THPF wax melts, it becomes a gel-like substance with a certain viscosity. Influence factors for wax injection equipment selection includes pressure range, conveying capacity, heat resistance, viscosity range and so forth. In previous nuclear power plant projects, wax injection equipment such as imported vane pumps and diaphragm pumps were commonly used. In this study, a domestic NYP series rotor pump is proposed as a replacement for imported equipment. A comparison of major parameters is shown in table 2.

Table 2. Comparison of major parameters for Imported and Domestic Pumps.

Scenario	A certain EPR project	A certain HPR project	This study
Equipment model	Mouvex P series sliding vane pump	Graco D200 series diaphragm pump	Domestic NYP series rotor pump
Place of production	French	USA	China
Mechanical type	Electric	Pneumatic	Electric
Power	4kw	/	7.5kw
Pressure range	≤1.0MPa	0.6MPa	≤1.0MPa
Conveying capacity	100 L/min	50 L/min	100 L/min
Heat resistance	250℃	/	200℃
Viscosity range	0-180000 cps	/	0-300000 cps

Based on the maximum injection height of about 65m and the wax density of approximately $0.88 \times 10^3 kg/m^3$, the maximum injection pressure needed is about 0.6MPa. Thus, the domestic NYP series rotor pump appear to fulfill the pressure requirement.

3. Material and Equipment Compatibility Verification

3.1. Heating Equipment and Material Compatibility Verification

The wax barrel is wrapped with the wax melting equipment and the heating temperature is set to 130°C. The time required for the wax to completely melt and reach the specified temperature is recorded for the conditions with and without stirring, respectively. The test results are presented in table 3.

Table 3. Wax Melting Test Results.

Test No.	Wax stirring state	Time required for complete melting (h)	Time required to reach 130°C (h)
1	Without stirring	11.8	13.9
	With stirring	5.5	7.3
2	Without stirring	10.9	13.0
	With stirring	4.6	6.8
3	Without stirring	10.5	12.8
	With stirring	4.3	6.5

According to the test results, the time required for complete melting is approximately between 10 and 12 hours when the wax is not stirred, and significantly shortens to about 4 to 6 hours when stirring is applied during the melting process. Once fully melted, the heating rate is not significantly affected by stirring.

The states of wax at different temperatures are illustrated in figure 2. Based on the test results, the wax reaches a state suitable for injection when its temperature is between 105°C and 110°C, where it turns into a clear deep blue liquid.

Figure 2. States of wax at 94°C (left) and 110°C (right).

3.2. Injection Equipment and Material Compatibility Verification

After the wax melting test, the heating equipment is maintained at a constant working temperature for the compatibility verification of injection equipment. As shown in figure 3, the injection pipes are connected to the injection pump with DN40 galvanized steel pipes installed at the inlet and outlet, and a pressure gauge is monitoring the pressure at the outlet.

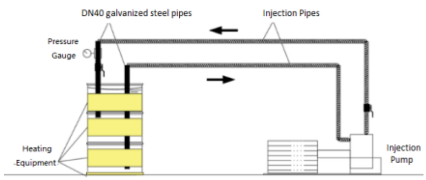

Figure 3. Schematic diagram of the wax injection equipment.

The injection pump is powered on after connecting the pipes, and once the wax flows out of the outlet, the outlet pipe is inserted into the wax. The wax is circulated for approximately 15 minutes, and then the outlet valve is gradually turned down while monitoring the pressure gauge. When the pressure reaches approximately 5 bar, the wax is circulated for another 15 minutes.

During this process, the following aspects need to be verified:

(1) Injection Pump: The continuous delivery capacity and operational stability with and without pressure, as well as the heat resistance, of the injection pump should be verified.

(2) Pipes and Valves: it needs to be verified whether the pipes become clogged when filling with wax at the specified temperature and whether the valve controls operate smoothly.

(3) Pressure Gauge: it needs to be verified whether the pressure is displayed accurately and if the high-temperature wax affects the rubber diaphragm inside the pressure gauge.

The test results indicate that the pump is suitable for wax injection work under different pressures, with stable performance and strong heat resistance. No blockage occurs in the pipes and valves when the wax temperature is greater than 60°C. When the wax temperature is less than 60°C, there is no impact on the wax outlet pipe, but blockage occurs in the wax inlet pipe. When the wax temperature is below 130°C, the pressure gauge operates normally and displays accurately.

3.3. Wax Cooling Validation Test

The cooling test of a cup of melted wax liquid was conducted at room temperature. As shown in figure 4 and table 4, the time and temperature of the wax state transition was tracked.

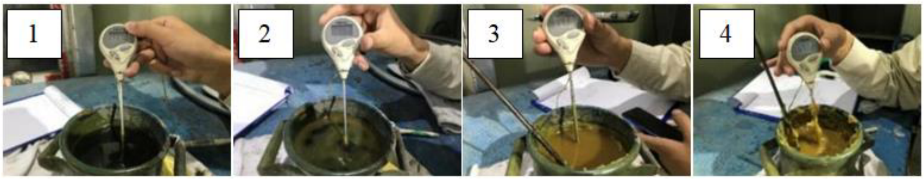

Figure 4. Wax cooling test process photos.

Table 4. Results of Wax Cooling Test.

Photo	Time	Wax State	Temperature /°C
1	Initial	Clear liquid	113.7
2	8 min	Appearance of floccules	108.6
3	27 min	Completely flocculent	94.3
4	44 min	Colloidal	64.7

From the wax cooling test, it is determined that when the initial wax temperature is 113.7°C, floccules start to appear after 8 minutes at a temperature of 108.6°C, at which point the wax liquid state is still good. After 27 minutes, it becomes entirely flocculent at a temperature of 94.3°C, and the wax liquid still exhibits some fluidity. It is inferred that the injection time should not exceed approximately 30 minutes, with 10 minutes being the optimal duration.

For a single monitoring tendon duct, the wax injection volume is approximately 850 L. To ensure the injection is completed within 10 minutes, the minimum delivery capacity of the wax injection pump should be 85 L/min. The domestic NYP series rotary wax injection pump has a delivery capacity of 100 L/min, which can fulfill the delivery capacity requirement.

4. Wax Injection Construction Process

4.1. Preparations before Wax Injection

Detailed geotechnical investigations and site improvements should be performed for the entire nuclear power plant site to fulfill the geophysical and engineering properties requirements of the subsurface layers [11]. Sealing inspection of the wax injection system should be passed and accepted. The numbering and condition of pipes, horn openings and wax to be used should be confirmed. The wax injection pump and wax heating equipment should be verified. Insulation should be provided for the exposed part of the injection pipe, upper wax barrel, and injection branch pipe. All pipes should be dry, and can be preheated with a warm air blower before wax injection if necessary. The communication equipment for the operators at the injection inlet and outlet should be ensured functioning properly.

4.2. Connection of Wax Injection Equipment

The wax injection pump is connected to the wax barrel using the suction and circulation pipes (two injection pipes), as shown in figure 5. All valves are closed initially. The wax heating equipment is turned on and stirring is applied during the melting process. When the wax reaches a temperature of 110°C to 130°C, the injection pump is started for a few minutes before closed. By the above steps, the pre-circulation of wax in the injection pump and wax barrel is completed.

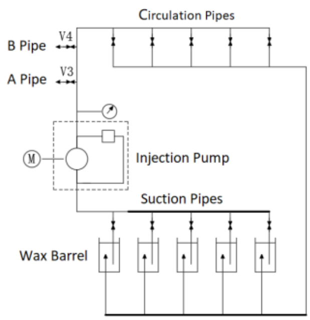

Figure 5. Schematic diagram of wax heating and pre-circulation.

4.3. Wax Injection Operation

The valve connections at the monitoring tendon duct during wax injection are shown in figure 6.

Figure 6. Schematic diagram of monitoring tendon duct connections during wax injection.

The lower part operation during the wax injection: The A pipe is connected to injection vent V2 at the bottom of duct and the B pipe is connected to the injection vent V2' on the upper part of grouting cap. All valves are closed initially. The intake valve of the first wax barrel is opened, followed by valves V2 and V2'. The injection pump is turned on while valve V3 is gradually opened to slowly inject wax into the grouting cap. The valve V4 is then opened to allow maximum flow through injection vents V2 and V2', and the start time is recorded.

During this operation stage, the upper valve V1 at the top of duct should be opened. When the wax level in the bucket is approximately 15cm from the bottom, the intake valve of the next barrel is opened and the valve of the previous barrel is closed, simultaneously, to continue wax pumping and prevent air from entering the injection system.

The upper part operation during the wax injection: When the wax flows out from the upper injection port, the arrival time is recorded and valve V1 is closed. The wax injection is continued until the upper gravity bucket contains at least 30 liters of wax, and the wax temperature is then measured and recorded. If the wax temperature (wax temperature above 65°C) is acceptable, the injection pump is notified to stop. After valves V2 and V2' at the lower end are closed, the pressure is released and all pipes are removed. When the wax hardens (after cooling), remove the upper gravity bucket and valves are removed, and injection vents are then sealed.

4.4. On-Site Wax Injection Effect

In the safety shell prestressing construction of this project, all four monitoring tendon ducts are fully grouted without blockage or leakage. During wax injection, the highest wax temperature at the inlet of duct was 126.9°C, and the lowest was 122.8°C. At the upper outlet, the highest wax temperature was 105°C, and the lowest was 103°C. The grouting time ranged from 11.2 minutes to 12.1 minutes.

5. Conclusion

The anti-corrosion materials, injection devices and construction processes for steel tendons of monitoring prestress states in the third-generation of nuclear power plants are explored in this study. The feasibility of utilizing domestic wax melting and injection equipment in the prestressed tendon wax injection construction of nuclear power plants is validated. Based on the research in this article, the following conclusions can be drawn:

(1) During the wax melting process using domestic heating equipment, stirring can significantly shorten the time it takes for the wax to fully melt, typically between 4 to 6 hours. Once completely melted, the wax heating rate is not significantly affected by stirring.

(2) During wax injection, the CP-THPF special wax should reach a temperature of 110°C or higher, at which point it becomes a deep blue clear liquid, achieving a good injection state.

(3) Domestic injection equipment and pressure gauges can withstand high-temperature wax. The wax temperature should not be lower than 65°C and should not exceed 130°C.

(4) To achieve good injection effect, the injection time should not exceed 30 minutes, with 10 minutes being optimal, and the delivery capacity of the domestic NYP series rotary wax injection pump can fulfill the requirements.

(5) The prestressed tendon wax injection construction process proposed in this article achieved excellent injection results in on-site safety shell construction of nuclear power plant project, worthy of further application in similar construction projects.

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