Design of Automatic TV Inspection Equipment for CPR1000 Steam Generator 9th Tube Support Plate

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Abstract. With steam generator running more and more years, sludge will accumulate on the surface of 9th tube support plate, causing broached holes clogging and heat transfer efficiency decreasing. In order to know the situation of sludge deposit and provide evidence of judging whether soft chemical cleaning is necessary, the 9th tube support plate automatic TV inspection equipment is required and needs to be developed based on the upper structure of CPR1000 steam generator. In this paper, the application surroundings and requirements were analyzed. The inspection method, general design, magnetic crawler, probe characteristics and mockup tests were described, especially how to insert the probe into bundles to achieve inspection scope was introduced.

1. Introduction
Steam generator is the vital component of the primary loop in NPP (abbreviation of “nuclear power plant”), which has the role of preventing radiation leaking between the primary loop and the secondary loop[1-3]. As steam generator running for longer time, sludge accumulates more on the tubesheet, TSPs (abbreviation of “tube support plate”) and tube walls. If sludge is not removed on time, it can affect heat transfer efficiency and main gas pressure. Considering CPR1000 (abbreviation of “China Pressurized Reactor 1000 unit”) steam generator inspection access, only tubesheet, TSP1 and TSP9 can be carried out TV inspection. By far, tubesheet inspection has already been done during every outage[4] and TSP1 inspection needs to be done if necessary; however, TSP9 TV inspection has never been performed because it is much more difficult to design and apply such an equipment. According to operation feedback from EDF, TSP9 is much more likely to deposit sludge than others except tubesheet[5-6]. Whether TSP9 needs to be cleaned by high pressure water or soft chemical lancing is determined based on TSP9 broached holes clogging. If clogging is over 30 percent, high pressure lancing or chemical lancing is necessary[7]. To obtain clogging information, TSP9 TV inspection is becoming more and more important for steam generator running more than 15 years, which means automatic TV inspection equipment needs to be developed for the purpose above.

In Europe, the TSP9 inspection job is mainly done by a French specialized company using one magnetic crawler inside upper wrapper to climb up and down. The crawler carries a probe that is used for capturing clogging video and travels along wrapper circumference to find the inspected bundle for probe going in and out of bundle. The probe movement is done manually by operator outside of manhole, which is shown in figure 1[8].
Figure 1. TSP9 inspection crawler used in Europe

For CPR1000 steam generator, there has been no such an automatic TV inspection equipment because of developing difficulties, especially with all automatic function which can have more operation convenience and less radiation doses. It is proven to be feasible by enough investigations and performance tests. Therefore, it is worthy to develop it. In this paper, working surroundings were introduced and design difficulties were analyzed. The inspection method, equipment components and properties were mainly focused.

2. Application Analysis

Before developing the automatic equipment, it is necessary to summarize performance parameters and analyze the difficulties based on inspection object and structure surroundings.

2.1. Inspection Object

The main aim of TSP9 inspection is to check clogging of broached holes which number is 8948 in total with square arrangement in the pitch of 27.43mm. The sample inspection view is shown in figure 2, and the result obtained by the newly designed automatic equipment should be as clear as that.

Figure 2. Sample inspection view

2.2. Inspection Surroundings

In order to make sure the designed equipment can be applied on site successfully, it is very important to know every structural detail inside steam generator above TSP9, which is shown in figure 3.

Figure 3. Structure drawing of steam generator inside above TSP9 with half tubes
In order to make probe reach the upper surface, the crawler needs to enter inside wrapper through camera hole which is the only access. There are 3 camera holes in total on the platform where the operator places crawler inside. Through the drawing, it can be seen that another 3 characteristics which will bring new challenges to design work. Firstly, there are 12 gas pipes around the wrapper, and the biggest width between next inner holes for crawler passing through is only 207mm. Secondly, there is an edgefold with 130°on the wrapper side wall, which increases risk of falling down when crawler crossing the corner. Thirdly, the distance between wrapper inner wall and its nearest tube wall is only 40mm in the height of within 388mm over TSP9, which is impossible for a crawler carrying probe to travel around. Therefore, crawler must stay where the height is over 388mm. Moreover, in order to make operator receive less radiation, the water level inside steam generator must be over the top of the bend tubes, which means inspection work should be done under water.

3. Equipment Design

3.1. General Design

To achieve the inspection work and satisfy the above requirements, general equipment design is shown in figure 4.

![Figure 4. Schematic drawing of TSP9 automatic TV inspection equipment](image)

The equipment is composed of the following parts:

- Crawler. It travels around wrapper wall inside with 4 magnetic wheels, with adjusting probe head position to enter bundles easily and driving probe in and out of the inspected bundle. It also has 2 side cameras, 1 front camera and 1 position sensor to assist crawler movement and inspection work.
- Push-Puller Device. It has function of pushing or pulling crawler cable based on crawler position and it is working automatically with the order from monitoring system. It plays an important role of making no cable twisting with anti-vibration bar ends and crawler passing through the space between gas pipe holes.
- Surveillance Camera. It is used to check water level and assists in driving crawler. It is installed on another camera hole.
- Site Control Box. It is placed outside steam generator. It is used to receive orders to control all motors movement, acquire and process signals of encoders or sensors.
- Monitoring System. It has communication with site control box. Operator uses it to move crawler and probe, supervise crawler position, check inspection video and so on.
- Composite Cable. It is used to connect among crawler, push-puller device, site control box and monitoring system. It is used to transfer power, signal, audio, video between linked components.
3.2. Crawler
Crawler is the key component of the whole equipment. It is composed of body, flexible nose, front camera, side camera and 4 wheels. Its length is 350mm, its width is 160mm, its thickness is 120mm and its weight is 6.5kg. The body is divided into two layers vertically and its material is aluminum. The upper layer places probe roller, probe driving mechanism and front camera. The lower layer places 8 motors, control board, and 2 side cameras. There are 4 motors for driving wheels independently and the other 4 motors for driving flexible nose in 4 directions through stretching molybdenum wires inside flexible nose. The crawler structure is shown in figure 5 and lower layer arrangement is shown in figure 6.

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F = (1.6 \times F_n - 54) \times \cos 50^\circ - 2 \times F_2 + 1.6 \times F_n \tag{1}
\]

In Equation(1), \( F \) is required driving force, \( F_n \) is normal pressure of magnetic wheel, \( F_2 \) is the magnetic force in the negative X axis. Wheel diameter is 70mm and friction factor between wheels and wrapper wall is 0.8.

On the other side, software ANSYS is adopted to calculate \( F_2 \). It can be calculated that every wheel needs driving torque with 0.907N·m and every chosen motor type is Maxon DCX22S GBKL12V+GPX26A 172:1 which can provide 1.646N·m, which is 1.81 times of required torque. It means that crawler has enough power to climb wrapper wall and cross 130° corner with no risk of falling down. The force diagram is shown in figure 7.
Concerning the probe, it should have required balance between enough rigidity to move in the bundle and softness to be rolled into the roller. After enough experiments, the chosen body is 6mm in diameter and has a specially designed head, which is shown in figure 8.

The probe is moving inside flexible nose which can adjust bending angle through stretching molybdenum wires by motors. There are 4 wires inside flexible nose at the location 0°, 90°, 180°, 270° to control 4 directions respectively. The flexible nose is made of several articulations with one rotating free degree. Articulations are connected one by one through special links. The wires are placed in plastic tubes for protection and easy movement and the outside surface of flexible nose is made by knitted mesh grid. Flexible nose plays an important role in guarantee of inserting probe into the bundles successfully, which structure is shown in figure 9.

![Figure 8. Picture of probe head](image1)

![Figure 9. Schematic drawing of flexible nose](image2)

### 3.3. Monitoring System

The monitoring system is developed based on ROS framework under Linux system. It is displayed by industrial computer with the latest Intel Core processor. As is shown in figure 10, the computer has double screens. The left screen is showing information of probe video, clogging record, map for marking the inspected area; the right screen is showing information of crawler cameras, surveillance camera, crawler position, and crawler driving interface.

![Figure 10. Picture of monitoring system](image3)

### 4. Mockup Test

Before application on site, the equipment needs to be done a lot of tests on mockup to make sure it is coincident with steam generator and it can achieve the required inspection work. The tests include crawler climbing, probe head adjusting, probe going in and out of bundles, probe articulation, water proof and so on. The equipment is proven to be qualified by passing such tests. It can move to the destination with no falling down, drive the probe into bundles, record video when probe taking back by operating monitoring system. It has a good performance of sealing and video quality, which is shown in figure 11.
5. Conclusion
In this paper, the importance and application of TSP9 automatic TV inspection equipment was introduced and application surroundings and requirements were summed up to guide design work. Finally, inspection method and design scheme were given priority to describe, especially crawler structure. Generally speaking, there are mainly 4 following points about equipment development:
1. The scheme of TSP9 inspection equipment with all automatic function is proven to be achievable by enough tests and design.
2. The general design is suitable for TSP9 automatic inspection with no blind spots. The crawler with 4 magnetic wheels and 1 flexible nose can cross the edgefold with 130° easily and safely, adjust probe head to aim at the inspected bundle. The crawler movement for switching inspected bundles is done automatically based on arithmetic.
3. The probe is supportive for integrating into the crawler and performing outstanding inspection effect.
4. Such an equipment has already passed mockup test and will be applied on site, which will provide design and operation feedback for similar designs and applications.

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