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Multifunctional robot to maintain boiler water-cooling tubes

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SUMMARY
A robot has been developed to maintain boiler water-cooling tubes. This robot has a double tracked moving mechanism, an ash cleaning device, a slag purging device, a tubes' thickness measurement device, a marking device, and a control system. This robot can climb up and down the tube wall. A method for the robot to complete many tasks for boiler maintenance in one process cycle is presented. The mechanism of the robot is described. Especially, a kind of special magnetic block structure is designed to obtain strong adhering force using permanent magnets. Experiments in laboratory and real thermal power station have verified that the robot cannot only climb on the surface of the tube wall smoothly, but also take heavy payloads for boiler maintenance operation.

KEYWORDS: Mobile robot; Climbing robot; Boiler water-cooling tube; Boiler maintenance.

1. Introduction

Boiler is a key equipment of thermal power stations. Usually, steam generated by the boiler drives the turbine, and the turbine drives the generator to produce electric energy. With the advent of large-capacity boilers as well as the improvement of welding technology, almost all the thermal power stations in the electric industry adopt calandria water-cooling tube structure.[1] The strong steam generated from the heated water in the boiler pass through many tubes called steaming tubes to drive the steam turbine. If the steaming tubes cover the partial or the whole inner surface of the boiler, the water-cooling tube wall is formed. With boiler running, there are quantities of ash on the surface of the tube wall facing the flame. Also some inorganic salts appear as slag after sintering on the tube wall and segments of some tubes become corrosive and erosive. All these factors can cause serious damage to boilers or even give rise to disastrous accidents.

So the general solutions are to maintain the boilers regularly, such as slag purging, ash cleaning, and tube thickness measurement. A tube must be replaced to prevent it from bursting if it has become too thick. Usually, ash on the heated surface of the tubes is blown off by workers using compressed air, and slag on heated tubes should be removed by scraper, wire-brush, wire-cloth, or other tools. To clean slag upside the tubes, a ladder or hanging basket is necessary. Sometimes even a scaffold is needed to be set up. In the water-cooling tube wall inspection, the workers find out the locations where the tubes become thick and bulgy by their hands or eyes traditionally. Moreover, for cleaning the tubes properly, the work needs to be done in high-temperature environment, otherwise the ash will adhere back to the wall. Therefore, the cleaning work has to be started when the temperature is about 60°C after the boiler is shut down.[2,3] In addition, high pressure water is usually used to remove the slag when the sediments are rigid. Hence a special robot designed for this purpose will not only do a good job and save a lot of time but also expand the service life of the tubes.

As the tubes are inevitably subjected to erosion, corrosion, and pollution, it is important to maintain them regularly and thoroughly to ensure proper delivery of gas or liquid over long time. In recent years, various kinds of pipeline maintenance robots[4–7] working inside or outside the pipes have been developed. These robots for pipeline tasks are mostly equipped with ultrasonic sensors, cameras, or single operating tool such as a cleaning brush. The robot that can complete multi-operations in one process cycle appears rarely, so we have developed a robot with two magnetic crawlers that can perform all the maintenance tasks such as thickness measurement, slag purging, cleaning, and marking in one process cycle while climbing. Especially, a new type of magnetic circuit structure has been adopted for developing adhering magnetic blocks fixed on the robot crawlers. Hence the robot has a compact size and can easily carry operational devices to work. The paper is organized as follows: The current situation of power stations, design scheme of the robot, and its functions are described in Section 2. In Section 3, the structure of the robot is presented. The special magnetic block and its design are discussed in Section 4. Experiments and discussion are described in Section 5. Conclusions and future works are discussed in Section 6.

2. Situation of Power Stations and Design Scheme of the Robot in Functions

2.1. Water-cooling tube wall in thermal power station

The water-cooling tube wall is a closed structure around the inner burning chamber of the boiler, which is shown in Fig. 1.

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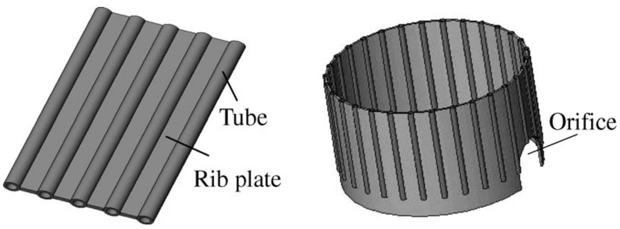


Fig. 1. Structure of the boiler water-cooling tube wall.

It is made up of many tubes (diameter is about 60 mm) and rib plates.

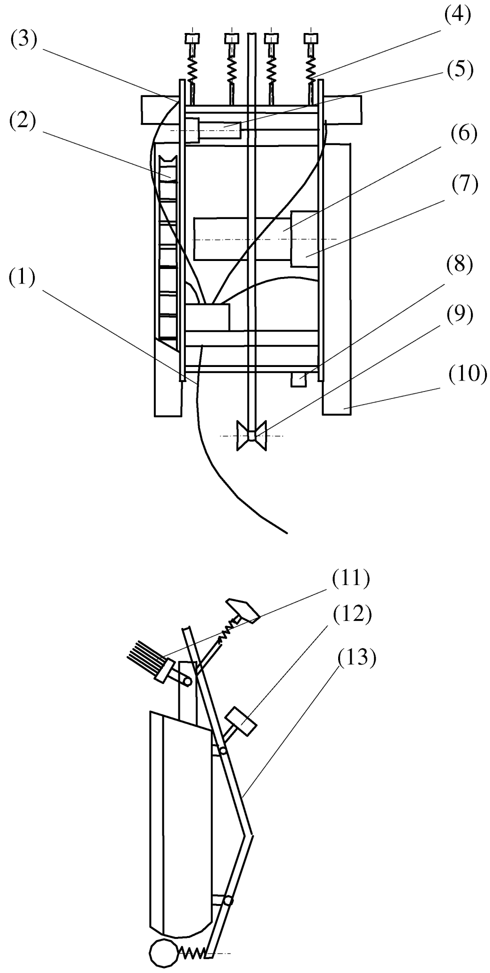
For a 200-MW thermal power station, the total dimension of its water-cooling tube wall can reach to 1000 m^2, and the width of its welding seam between pipe and rib plate is 3–5 mm. Besides, there is an orifice in the lower part of tube wall for convenient maintenance. Water-cooling tubes tend to get covered with thick ash and rigid slag after certain times of use. Some parts of tubes may even suffer from corrosion or rust. Such conditions are quiet severe for manual maintenance. So it is necessary to automate the manual work by robots.

2.2. *Basic functions of the robot*

The following technical requirements are considered necessary for the robot designed for maintenance operation of water-cooling tubes.

(1) Small size and payload capacity. Small-sized structure of the robot is necessary to guarantee the robot through the orifice whose diameter is 450 mm. The size of the robot should not be larger than the orifice. Also, the robot is equipped with operating devices and a cable, so the robot must have movable capability when adhering to the wall.
(2) Capability of preventing motion deviation and overturn. Commonly, there are about 5–15-mm thick ash and 5-mm thick slag on the external surface of the tubes. In addition, the volume of the boiler is huge and the height can reach up to tens of meters, so the robot should not only maintain on the vertical surface but also prevent itself from falling down when it meets a large slag.
(3) Hermetic unit. There are some ferromagnetic substances in the ash which can be adsorbed to the magnetic blocks of the robot tracks and will reduce the magnetic force.
(4) Slag purging ability. The robot should be equipped with slag purging devices mainly to peel off the hard massive objects outside the water-cooling tubes.
(5) Cleaning capability. Cleaning mechanism is used primarily to remove the residues after ash cleaning and slag purging processes.
(6) Thickness measurement. Water-cooling tubes may get eroded or corroded inevitably after a long-term running, so some parts of the tubes may get thinner. Therefore, it is necessary to measure the thickness of the tubes to find the damaged parts of the tubes.
(7) Marking function. The tubes which are found thinned should be marked for timely processing or replacing.

The above factors should be considered as much as possible during the design process of this kind of robot.



(1) Tube of compressed air (2) Magnetic track (3) Slag purging mechanism (4) Flexible hammer (5) Motor for cleaning (6) Motor for tracks driving (7) Reducer (8) Chain wheel (9) Supporting wheel (10) Hermetic unit (11) Cleaning brush (12) Observing camera (13) Anti-overturn lever

Fig. 2. Structure of the robot.

3. Structure of the Robot

As a mobile carrier, this robot consists of double-tracked moving mechanism, operating mechanism with multifunction and aiding mechanisms such as anti-overturn device, motion guiding device, and an observing camera.[8,9] Especially, every track has 30 permanent magnetic blocks. Every block is designed using a multiloop magnetic circuit structure. Its geometry shape is arced to match the shape of the tubes for an adherent working face. Besides, the purpose of an anti-overturn mechanism and the moving guide mechanism is to guarantee the balance of the robot when an overturning force occurs, to ensure that the robot keeps moving in vertical direction and to avoid the deviation. The structure of the robot is shown in Fig. 2.

When the wall climbing robot climbs along the tube wall, there are three major risks which are, first, rolling around the bottom contact point of the crawler and the wall, second, sliding along the wall, and third, rolling down along the wall. In any of the case, the robot will not stay on the wall safely, hence it is necessary to analyze these three situations specially.

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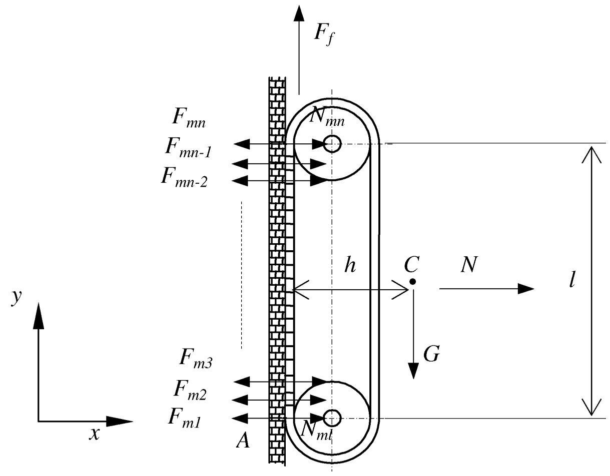

Fig. 3. Mechanic diagram of the track mechanism.

3.1. Rolling around the bottom contact point of the crawler and the wall

As shown in Fig. 3, suppose that center of robot gravity is point C, the gravity is G, the distance between gravity center and the wall is h, and the rolling around point is point A.

The force balance equation in x-direction is

$$\sum_{i=1}^{n} F_{mi} = \sum_{i=1}^{n} N_i = N, \tag{1}$$

where F_{mi}: adhering force between the magnetic block i and the wall, $i = 1, 2, \ldots, n$; N_i: counterforce of the wall against the magnetic block i; N: composition counterforce against all the magnetic blocks.

In addition, the robot's track chain structure is composed of a number of chain knots with the pitch P, the tracks therefore do not transmit torque. At the point A of Fig. 3, the torque balance equation for one track is

$$M_A = (F_{mn} - N_n)l - \frac{Gh}{2} = 0, \tag{2}$$

where F_{mn}: force between the uppermost magnetic block and the wall; N_n: counterforce against the uppermost magnetic block by the wall; l: distance from the uppermost magnetic block to point A. Equation (2) can be rewritten as

$$F_{mn} = N_n + \frac{Gh}{2l}. \tag{3}$$

If the robot is not to overturn, there is a force between the wall and the uppermost magnetic block, and the counterforce of the wall should be greater than zero at the same time. So F_{mn} in Eq. (3) could be expressed as

$$F_{mn} \geq \frac{Gh}{2l}. \tag{4}$$

Therefore, if the adhering force between the contact magnetic blocks of tracks and the tube wall can satisfy Eq. (4), the robot will not overturn from the wall during climbing.

3.2. Sliding along the wall

As shown in Fig. 3, the robot has a tendency of sliding down along the wall because of its gravity. Condition for its staying on the wall without sliding is

$$G \leq \mu \sum_{i=1}^{n} N_i, \tag{5}$$

where μ is the friction coefficient between each magnetic block and the tube wall. Based on Eq. (1), Eq. (5) can be rewritten as

$$F_f = \mu \sum_{i=1}^{n} F_{mi} \geq G, \tag{6}$$

where F_f is friction force between the track and the wall.

The value of the friction force equals to the multiplication of the friction coefficient and the sum of adhering forces between the magnetic blocks of one track and the tube wall, so the total friction force on the robot is two times of F_f. As long as the robot can fulfill the above requirements, it will not slide down along the tube wall.

3.3. Rolling downward along the tube wall

To the robot, there is also another tendency to roll down along the tube wall without sliding or overturning. It is therefore essential to analyze the condition as shown in Fig. 4.

M_1 is the output torque of reducer, and M_2 *is* the resistance torque generated by rotational components. If the robot is going to roll down, and assuming that the top magnetic block disengages from the wall at the moment, the adhering force and the counterforce between the magnetic blocks and the wall produce an anticlockwise torque. The composition torques M_1 and M_2 and the anticlockwise torque will prevent the robot from rolling down, so,

$$M_1 + M_2 + 2F_{mn} \times l' - Gh = 0. \tag{7}$$

Namely

$$M_1 + M_2 = Gh - 2F_{mn} \times l', \tag{8}$$

where l' is the length of one magnetic block.

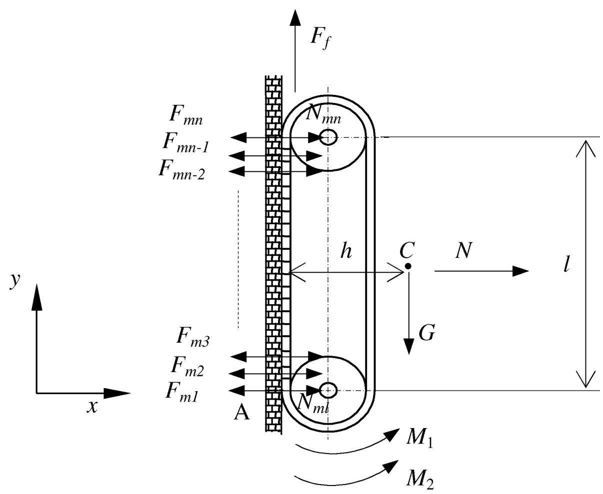

Fig. 4. Mechanic analysis while robot rolling.

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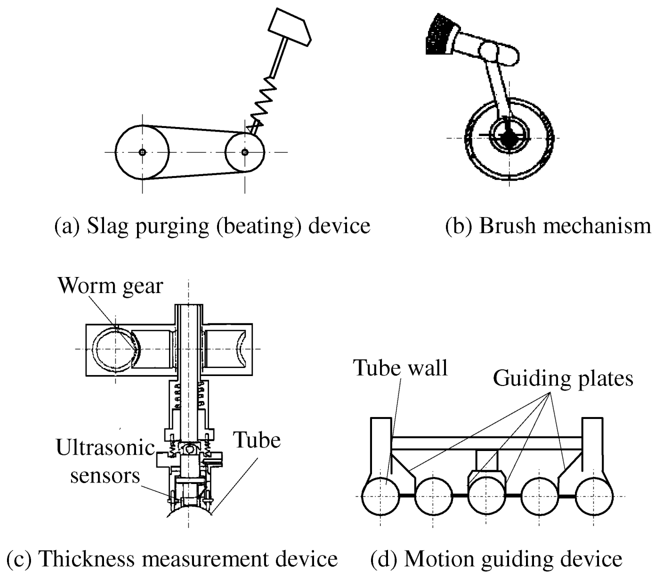

Fig. 5. Main operational devices and an aiding device.

The three basic conditions should be considered while designing the climbing robot. As long as the three conditions are satisfied, the robot can make itself adhere reliably on the tube wall.

3.4. Descriptions of main mechanisms and devices

The sprocket wheels of the two tracks are driven by one servo motor, and each track is equipped with certain magnetic blocks, so the robot can climb up and down on the tube wall. In addition, the robot also has operational devices and an aiding device as shown in Fig. 5. The slag purging device is a chain-drive mechanism in Fig. 5(a), the brush mechanism is a crank-drive mechanism in Fig. 5(b), and these two mechanisms are driven by the same motor.

The thickness measurement device is driven by a worm gear mechanism in Fig. 5(c), and this transmission mechanism can make the ultrasonic sensors touch or leave the tubes. In order to guarantee the moving direction of the robot along the tubes during its working, a guiding device in Fig. 5(d) is designed which is installed in the rear part of the robot body. The aiding mechanism includes several guiding plates which can fit the shape of the tubes.

4. Structure of the Magnetic Block with Multiloop Magnetic Circuit

The magnetic block sets in the tracks are the key parts of the mobile robot crawlers. Because of the characteristics of this robot, we choose an efficient magnet N_dF_eB which is a permanent magnet and has good magnetic capabilities, such as great coercivity, good magnetic properties consistency, and a lower temperature coefficient. Especially due to its exceptional intrinsic coercivity, magnetic flux leakage can be prevented in the magnetic circuit. The material has good application in open loop, pressure, anti-magnetic, and dynamic conditions.[10]

The block structure is shown in Fig. 6, yoke iron and the magnet are both rectangular in shape. As shown in the Fig. 7,

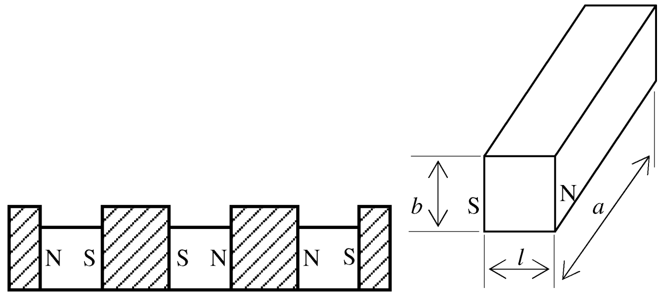

Fig. 6. Multiloop magnets structure and magnet bar.

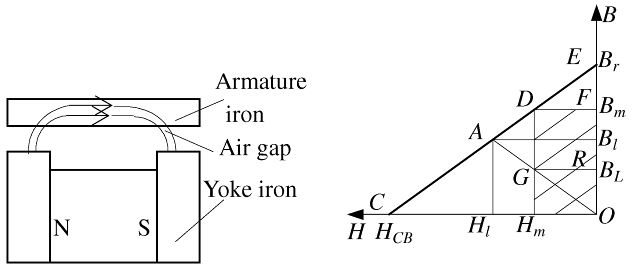

Fig. 7. Schema of the magnetic circuit and demagnetization curve of $N_{d15}F_{e77}B_8$.

when one magnetic block picks up the armature iron, small flux units will be created in it.

While the robot climbs along the tube wall, the magnetic block set in the chain track has three possible states (relative to the tubes): the magnetic block is gradually out of contact with the tubes, the magnetic block adheres to the tubes, and the magnetic block picks up the tubes gradually. Because only the foremost and backmost blocks get the tendency to pick up or deviate from the tubes gradually, the magnetic absorption force can be analyzed by applying the parameters and formulas of the static magnetic circuit.

The force depends upon the area of the magnetic gap, the magnetic induction intensity in the gap, and the magnetic field intensity.

Referring to Fig. 7, the static adhering force and dynamic force[11–16] can be expressed by the following formulas:

$$F_{\text{astatic}} = \frac{B_g H_g}{2} A_g = \frac{B_g^2}{2\mu_0} A_g \tag{9}$$

$$F_{\text{adynamic}} = \frac{B_g^2 A_g}{\mu_0} = \frac{A_g}{\mu_0}\left[\frac{B_r}{2A_g/A_m + (\mu_0\mu_{\text{rec}} + B_1/H_1) f L_g/\mu_0 L_m}\right]^2, \tag{10}$$

where F_a: magnetic suction (N); B_g: magnetic intensity in gap (T); B_r: residual magnetic induction intensity of the magnetic material (T); H_g: magnetic density in gap (KA/m); μ_{rec}: recoil magnetic conductivity (Tm/A); $\mu_0 - 4\pi \times 10^{-7}$ Tm/A,[11] vacuum magnet conductivity; *f*: coefficient of hysteresis, $1.1 \leq f \leq 1.5$; A_g: gap area (m^2), it is proportional

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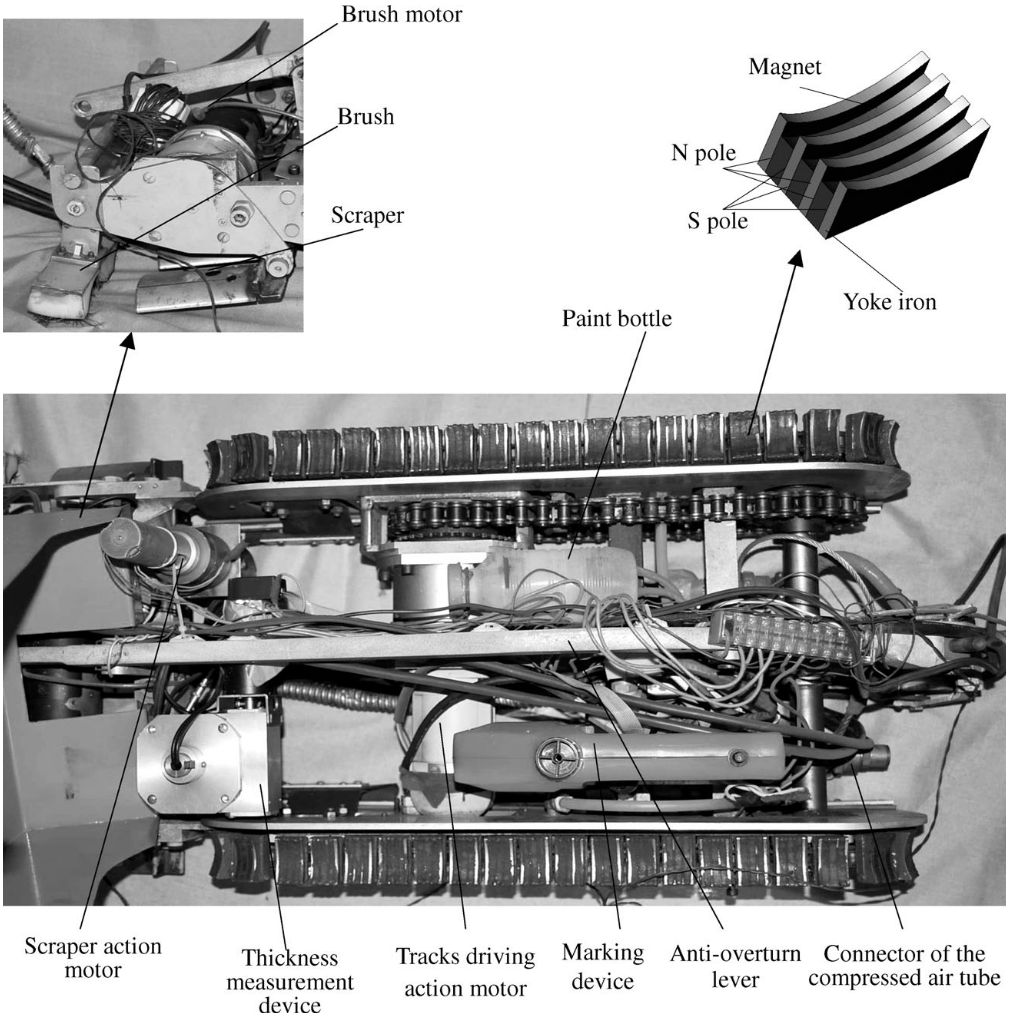

Fig. 8. Close-up of a magnetic block with multiloop circuit.

to the sizes of the air gap; A_m: area of the magnet bar (m^2); $A_m = n \times a \times 1$, n is amount of the magnet bar.

The selection of magnetic material depends upon the parameters of the material. We can see from Eqs. (9) and (10) that the adhering force is relevant to the gap area. Therefore, to ensure a sufficient adhering force, the height of the air gap is to be confirmed according to the degree of coarseness of the outer tube surface and the geometric dimensions of the magnetic block.

According to the calculation of the magnetic circuit, two magnet sheets are connected by a lamellar yoke. The same magnetic poles of the two magnets are face to face. This kind of arrangement not only realizes the maximum flux utilization ratio between the magnetic iron and the tube (equal to armature iron), but also divides one magnet block into several magnet units, so the suction chamber between one block and the tube is divided into many small suction chambers.

The advantage of this method is of a relatively short magnetic circuit. When a magnetic iron departs slightly from the tube centerline, the gap of only one side will be wider, but the adaptability and absorption capability of the magnetic blocks upon the tube wall will not decrease. This means that a large gap will adversely affect the magnetic flux, but the entire magnetic block will keep certain absorption.

In order to properly grasp the tube, both the magnet sheet and the yoke iron have to have convex faces whose radii are the same as the outer radius of the water-cooling tube. The yoke iron is designed to be higher than magnet sheet, because its magnetic material is relatively crisp. While the robot crawls along the outer face of tubes, yoke iron will touch the outer face to protect the magnet sheet. The size of each magnet bar in magnetic blocks is chosen to be 30 mm $\times$ 20 mm $\times$ 10 mm. The two chain tracks have a number of such magnetic blocks. The close-up of the blocks structure is shown in Fig. 8.

5. Experiments and Discussion

The multifunctional robot for the maintenance of the water-cooling tube wall has the dimensions of 550 mm $\times$ 400 mm $\times$ 260 mm, and it weighs 30 kg. The designed load capacity is 35 kg. The climbing speed is 2–8 m/min which can be adjusted. The experimental test and the technical parameters have been validated in the laboratory and the practical field of thermal power station separately.

5.1. Laboratory experiments

In our laboratory, a 4-m high tube wall is constructed to simulate the water-cooling tube wall of the boiler,

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Fig. 9. Test of motion speed.

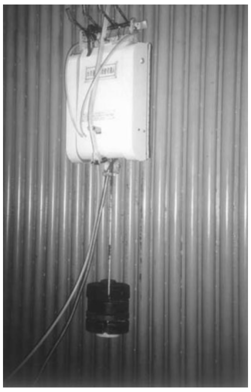

Fig. 10. Test of payload capacity.

as shown in Figs. 9 and 10. The main objectives of testing included validation of climbing speed, payload capacity, obstacle performance, motion guiding function, and thickness measurement with the ultrasonic sensor.

5.1.1. Climbing speed testing. The climbing distance of the robot is set to be 2 m. The robot is tested in two modes: low-speed and high-speed modes. In each mode, the speed is tested three times. In the low-speed mode, it is between 1.84 and 1.97 m/min with an average of 1.90 m/min. In the high-speed mode, the speed is between 7.86 and 8.15 m/min with an average of 8.03 m/min.

5.1.2. Payload capacity. At the beginning of the experiment, the robot is placed on the water-cooling tube wall with no payload. During climbing, it can be loaded with the weights of 5 or 10 kg continuously. When the payload is more than 40 kg, it is shown that the robot has a tendency of falling down. Namely, the payload capacity of the robot can reach to 40 kg. Figure 10 shows the payload testing process.

5.1.3. Obstacle performance. To check the characteristics of magnetic circuit of the magnetic blocks, many strips made of nonmetal material are stuck on the surface of the simulated tube wall. By adjusting the thickness of the strips and moving the robot up and down, we observe the suction influence caused by the difference of air gap. The result shows that the robot can pass over the 10-mm high obstacles.

5.1.4. Automatic motion guiding testing. When the robot is on the water-cooling tube wall, it is connected to a lead sinker at its tail. The angle between the lead sinker and the centerline of the tube is 1.5°. When the robot climbs 2.5 m along the tubes for five times, the angles of deviation are recorded. During climbing, due to the action of the motion guiding mechanism, the robot can correct its deviation obviously. After the robot climbs 2.5 m, the angle of deviation is found to be less than 0.5°.

Table I. Data of the tube thickness measurement (mm).

No.	Set 1	Set 2	Set 3
1	4.45	4.37	4.40
2	3.50	3.39	3.43
3	3.35	3.26	3.33
4	3.47	3.51	3.42
5	4.03	4.01	3.98
6	3.85	3.98	3.82
7	4.54	4.43	4.56
8	4.31	4.35	4.46
9	4.32	4.34	4.40
10	4.85	4.79	4.90
Average	4.06	4.04	4.07

5.1.5. Thickness measurement with ultrasonic sensor. For the simulated tube wall, the thickness of each tube is 3.5 mm. Based on the comprehensive analysis of the thickness measurement system, the relative measurement error is set to be ±0.20. Three sets of thickness measurement sensors are installed on the robot. The thickness measurement by the ultrasonic sensors is taken and the data is recorded 10 times.

The average value of the thickness is found to be 4.07 mm, therefore the relative error of the tubes is 0.16 less than 0.20. The precision is maintained and the obtained results are repeatable. Hence the thickness measurement is validated with a relative error of 16%. The data is listed in Table I.

5.2. Experiment in thermal power station

To prove the performance and practicability of the robot, the experiment in the power station is carried out. We chose the Thermal Power Station in Changchun, Jilin province. The experiment was done in the boiler no. 2. The height of the boiler tube wall is 50 m. The experiment objectives were to validate, the moving performance of the robot, the effectiveness of cleaning and slag purging, the rationality and reliability of robot mechanism, and its control system. The evaluated results of the robot in power station are summarized in Table II.

The relative precision of thickness measurement in power station is about 82%. There is 2% difference from the

Table II. Evaluation of the robot in power station.

Speed (m/min)	0–8 (Adjustable)
Mobility	Good
Ash cleaning performance	Good
Slag purging performance	
Hard slag	Not good
Loose slag	Good
Precision of thickness measurement and marking	82%

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Fig. 11. Experiments in thermal power station.

precision measured in laboratory, and the reason causing this difference is that there exists dust in the boiler and the surface quality of these tubes is no better than that of the tubes in laboratory.

Figure 11 shows the robot working in the power station. The results of the experiment in the power station show that the robot can move smoothly without any disturbances, and the motion guiding mechanism plays a distinct and effective role. The ash and the loose slag adhering to the tube wall are cleaned up by brush device. The slag purging mechanism made up of hammers or scrapers produces good results, without harming the tube. The hammer mechanism is driven by the motor with the brush mechanism (the brush mechanism can be seen in Fig. 9), and the scraper device is made up of a motor, a gear box, and a lever mechanism (the device can be seen in Fig. 8). In the real cleaning process, the hammer mechanism and the scraper mechanism can replace each other freely according to the dirty level of the tube wall. The thickness measurement system worked normally, and the data is acceptable. Moreover, the compressed air pipe is able to blow off the slag and ash effectively, and ensure the cleanness of the magnetic blocks.

At the same time, some problems are also observed in the experiment, for example, the hard massive slag is difficult to be cleaned, and the camera lens and the ultrasonic sensors are smeared easily.

6. Conclusions and Future Works

A multifunctional climbing robot with two magnetic absorption tracks has been developed for maintenance operation of water-cooling tubes in the thermal power station. It is an integrated multitask robot with the capabilities of ash cleaning, slag purging, tube thickness measurement, and marking. With its small structure and heavy payload capacity, the experiments proved that this robot can be used as a kind of automatic equipment for boiler maintenance in power stations. One distinct feature of this robot is its advanced capability to perform multitasks in one process cycle, which is better than the former same kind of robots.

The development of robot has been comprehensively described. The technical details about the robot mechanism, the operational devices, and the control system have been given in this paper. Especially, the theory and the technical method used in the design of the magnetic block with multiloop circuit have been presented and analyzed. Through the experiments in our laboratory and the power station, it has been proved that this robot can perform effectively and reliably.

Further work needs to be done to improve the stabilization of the robot system in an environment which is full of ash and magnetic conductive particles, and to improve the slag purging mechanism so that it can thoroughly clean up the hard massive slag.

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