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Analysis of Hardware Implementation of Far-field Static Magnetic Detection Technology for Oxide Scale Blockage

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Abstract:

This paper describes that when the accumulation of oxide scale in boiler tubes reaches a certain level under long-term exposure to high temperature, high pressure, and steam, it can lead to partial blockage of the tubes and cause tube explosion accidents. A field-applicable oxide scale detection instrument based on the far-field magnetostatic method has been developed to address the difficulty of quantitatively detecting oxide scales in weakly ferromagnetic boiler tubes using existing magnetic non-destructive testing methods. This paper introduces the instrument's composition, the implementation of software functions, and the operation mode, and conducts field experimental verification.

Keywords:

Oxide scale
Magnetism
Non-destructive testing
Far-field magnetostatic method

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1. Introduction

The supercritical (and ultra-supercritical) units are gradually becoming the mainstream of coal-fired power plants in China. As the core equipment of supercritical (and ultra-supercritical) thermal power plants, most boiler steel pipes are primarily stainless steel, exhibiting good high-temperature corrosion resistance and oxidation resistance [1]. However, under long-term high-temperature, high-pressure, and steam conditions, as well as due to unit startup and shutdown, the oxide scale on the inner wall of the pipes is prone to peeling off, leading to the formation of oxide scale on the inner wall [2,3]. The bends of the boiler steel pipes often accumulate peeled oxide scale, and the bends themselves, which are formed through cold working, are weakly ferromagnetic. Additionally, the long-term exposure of the boiler steel pipes to high temperature and high pressure also induces a certain degree of magnetism. Under these two conditions, the weak ferromagnetic characteristics of the boiler steel pipes greatly affect the current magnetic particle inspection methods. To address the difficulty of quantitatively analyzing the oxide scale in weakly ferromagnetic boiler pipes using magnetic inspection techniques, this paper proposes an oxide scale detection instrument based on the far-field magnetostatic method. This instrument is developed by amplifying the magnetic circuit based on existing magnetic inspection techniques and is suitable for field applications. The instrument's composition and the operation of its software functions are introduced, and experimental verification is conducted.

2. Research background

TP347H ($1Cr_{19}Ni_{11}N$) belongs to high-carbon niobium-containing Cr-Ni austenitic stainless steel. It contains the stabilizing element Nb and exhibits good oxidation resistance and high-temperature performance. It is widely used in the manufacture of superheater and reheater tubes for thermal power generation boilers, as shown in **Figure 1**.

Figure 1. Austenitic heat-resistant stainless steel pipe diagram.

During the operation of generator sets, blockages and accumulations of oxide scale can lead to overtemperature tube rupture accidents, resulting in significant economic losses and casualties. In this context, researchers worldwide have continuously studied methods for detecting oxide scale blockages. Several common non-destructive testing methods applied to oxide scale blockages include radiographic testing, ultrasonic testing, eddy current testing, acoustic vibration testing, and magnetic testing. However, these methods face difficulties in the quantitative detection of oxide scale.

To address the challenge of quantitative detection of oxide scale in weakly ferromagnetic boiler pipes using existing magnetic non-destructive testing methods, this paper improves upon the existing magnetic detection methods by expanding the magnetic circuit. It proposes a magnetic detection method based on the far-field magnetostatic method as the theoretical foundation. Through the development of software and hardware systems, a correlation between the detected signal value and the oxide scale blockage area ratio is discovered. Experiments are conducted on field pipes with different blockage area ratios of oxide scale, and the effectiveness of the system is verified through practical application.

3. Design of oxide scale blockage detection equipment

3.1. Experimental platform

The required instrumentation, as shown in **Figure 2**, mainly consists of a detection probe, a DC-stabilized power supply, and a computer. The DC-stabilized power supply, model WYL-5010, is used to provide a specified DC current to the entire oxide scale detection platform. It has an input voltage of 220V AC and a maximum output voltage of 50V. When powering the detection platform, the output voltage does not need to be too high and is set to 5V.

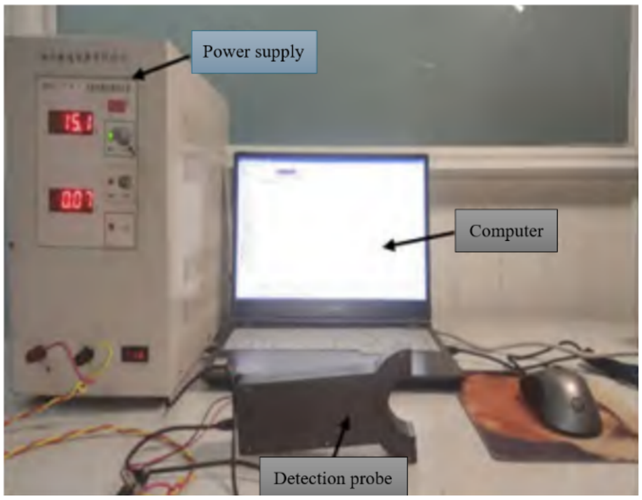


Figure 2. Experimental system platform diagram.

3.2. Design of oxide scale detection probe

(1) Internal structure design of the detection probe: The detection probe is a sensitive device used to detect

magnetized oxide scales within stainless steel. As shown in **Figure 3**, the three-dimensional exploded view of the detection probe structure reveals its main components: a magnetizer, internal circuit board, outer shell, and magnetic sensor element.

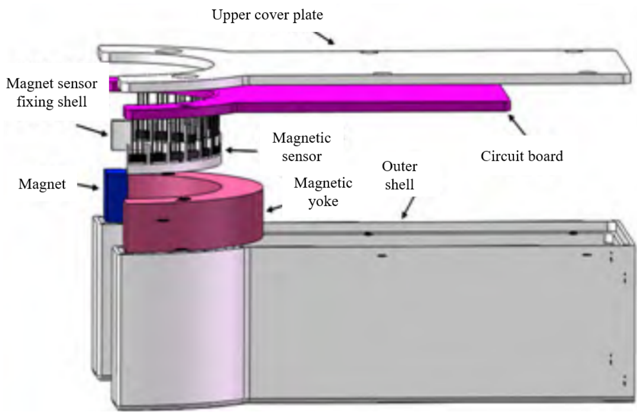
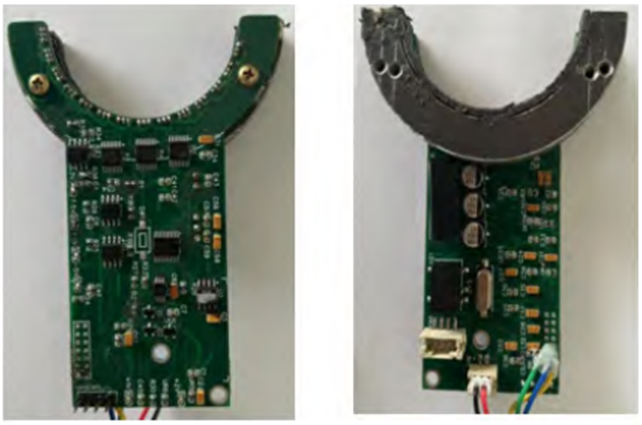


Figure 3. Three-dimensional diagram of the detection probe.

(2) Circuit hardware and signal output process: The overall PCB board diagram of the circuit is shown in **Figure 4**.



(a) Front (b) Back

Figure 4. PCB board diagram.

4. Composition and software function implementation of the oxide scale detection instrument

4.1. Composition of the oxide scale detection instrument

The main components of the detection instrument include the instrument host, detection probe, calibration sample, probe connection cable, charger, and built-in special software system.

(1) Instrument host. The instrument host is similar to a tablet notebook, lightweight, and portable, as shown in **Figure 5**.

(2) Detection probe. The detection probe is a multi-channel detection probe designed and developed for the above experiments, which can tightly fit the outer wall of the tested tube, as shown in **Figure 6**.

Figure 5. Instrument host diagram.

Figure 6. Detection probe diagram.

4.2. Software function implementation

The sample detection software is mainly programmed in C# language, and the main program flowchart of the detection system software is shown in **Figure 7**.

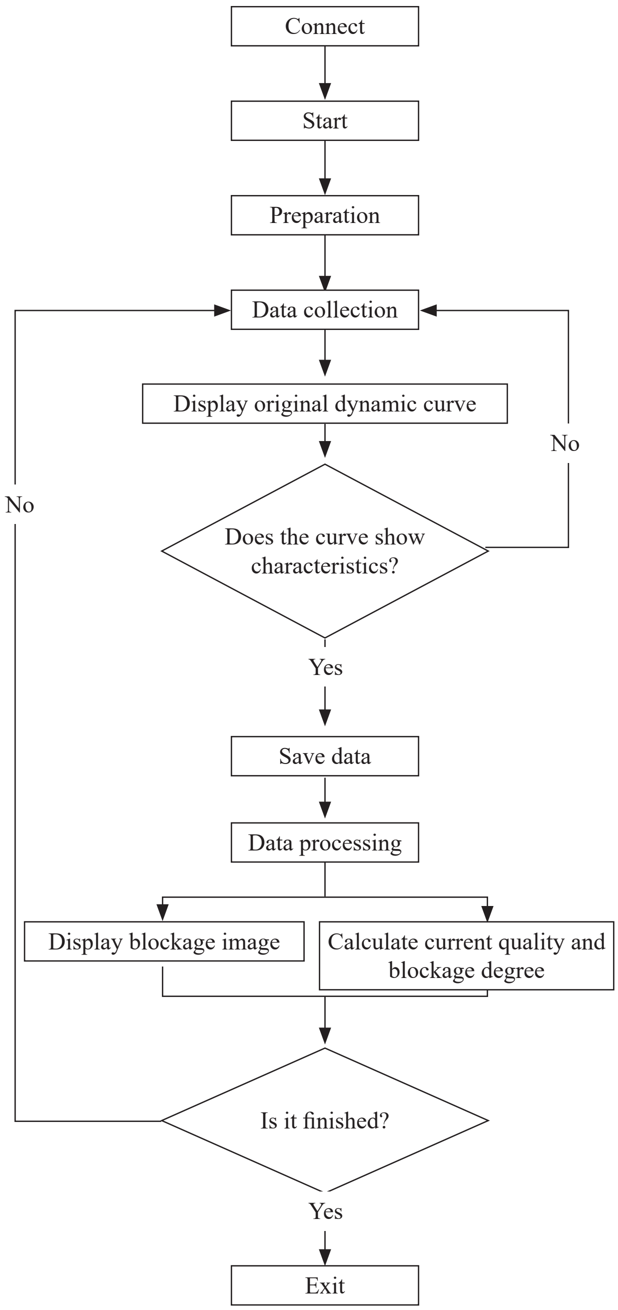


Figure 7. Main program flowchart.

The built-in detection software of the instrument consists of two interfaces: detection interface and statistics and report interface.

(1) Detection interface

The function of the detection interface is to set relevant parameters and perform detection tasks (as shown in **Figure 8**), which is mainly divided into two areas: the upper part is the display area, and the lower part is the setting area.

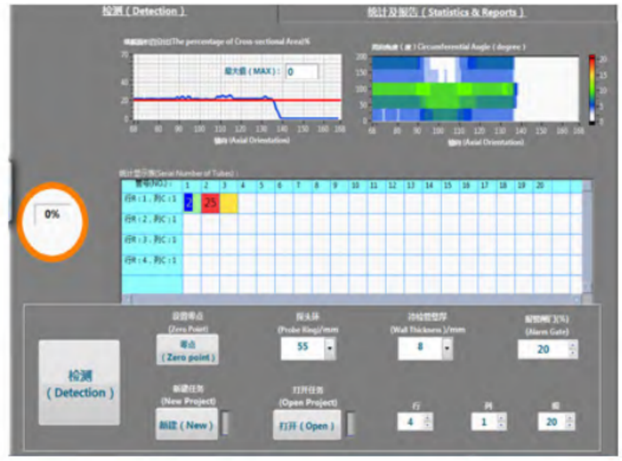


Figure 8. Detection interface.

(2) Statistical display table

The statistical display table displays all tube numbers in the tube bank in a tabular format. When the detection starts, click the corresponding tube number to be detected, and after the detection of that tube number is completed, click save. All detection information (blockage area percentage curve, real-time detection value, and maximum value) is stored by default. In the detection display diagram in **Figure 9**, the red square represents that the first row, first column, and first tube have been detected and completed, and the value in the square represents the maximum detection value of oxide scale blockage in that tube number. The yellow square represents that the first row, first column, and second tube are ready for detection.

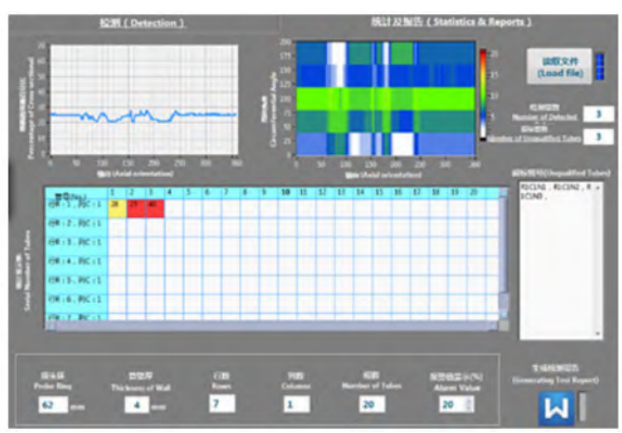


Figure 9. Statistics and report interface.

4.3. Experimental verification

Conduct on-site tube verification experiments, as shown in **Figure 10**.

Figure 10. Physical image of on-site tubes.

In thermal power plants, a common shape of bent tubes is the transition from a vertical direction to a horizontal direction. Using TP347H austenitic stainless steel magnetic tubes with an outer diameter of 45 mm and a wall thickness of 10.5 mm as the detection object, as shown in **Figure 11**, a long strip window is opened along the axial direction of the experimental tube to facilitate the placement of oxide scale with different blockage amounts. Since the measured difference in the oxide scale blockage area ratio is approximately proportional to the mass of the oxide scale, 10% to 30% of the oxide scale is weighed out using the weighing method and separately loaded into the on-site tubes to be detected.

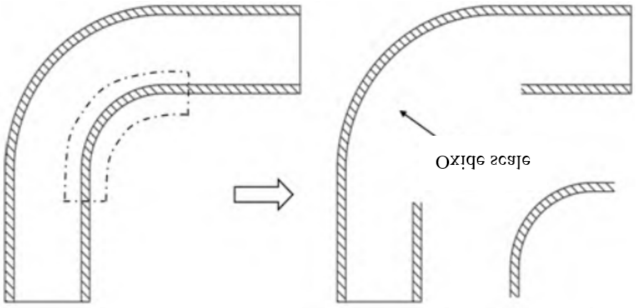


Figure 11. Schematic diagram of adding oxide scale to the bend.

Relevant data obtained from two repeated experiments are shown in **Table 1** and **Table 2**.

Then, an analysis of experimental results was done. From **Table 1** and **Table 2**, it can be seen that the measurement results of the two experiments have repeatability, and the sum of the measurement differences

Table 1. Relevant detection values of the first experiment

Detection location	Experimental data type	Oxide scale blockage area ratio (%)		
		10	20	30
Straight tube	Sum of measurement differences (mv)	38.3	64.4	83.8
	Calculated percentage (%)	11.6	23.2	33.6
	Absolute error (%)	1.6	3.2	3.6
Curved tube	Sum of measurement differences (mv)	44.8	69.1	87.9
	Calculated percentage (%)	14.2	25.5	36.1
	Absolute error (%)	4.2	5.5	6.1

Table 2. Relevant detection values of the second experiment

Detection location	Experimental data type	Oxide scale blockage area ratio (%)		
		10	20	30
Straight tube	Sum of measurement differences (mv)	37.9	63.1	83.5
	Calculated percentage (%)	11.4	22.5	33.5
	Absolute error (%)	1.4	2.5	3.5
Curved tube	Sum of measurement differences (mv)	44.5	69.3	88.3
	Calculated percentage (%)	14.1	25.6	36.3
	Absolute error (%)	4.1	5.6	6.3

in the straight tube section of the TP347H austenitic stainless steel boiler tube is close to that in the bend section, which verifies again the conclusion that the far-field magnetostatic method is less affected by tube magnetism. When detecting the oxide scale in the straight tube section, the absolute error range of the oxide scale blockage area ratio is 1.5–4.1%, which is relatively small, indicating that the above standard sample can be used to replace the bending sample for the curve calibration in actual detection. When detecting the oxide scale in the bend section, the absolute error range of the measured values is 4.1–6.4%. Therefore, the detection results of the on-site tubes meet the target expectations, verifying the effectiveness of the non-destructive detection system based on the far-field magnetostatic method designed in this paper.

5. Conclusion

Aiming at the difficulty of quantitative detection of oxide scale in weakly ferromagnetic boiler tubes using existing magnetic non-destructive testing methods, this paper has developed an oxide scale detection instrument based on the far-field magnetostatic method that can be applied on-site. The instrument's composition, the implementation of software functions, and the operation mode are introduced, and on-site tube experimental verification is conducted.

Disclosure statement

The authors declare no conflict of interest.

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