Eddy Current Thermographic Inspection of Weld Defects in Pressure Vessel Nozzles

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Abstract

Eddy current thermography is employed in this study for defect detection in small nozzle welds of pressure vessels. To address the challenges posed by miniature dimensions and the complexity of structure, an arc-shaped excitation coil was specifically designed. A three-dimensional model was constructed using SolidWorks, followed by numerical simulations in COMSOL Multiphysics to investigate temperature distribution around weld defects under arc-coil excitation. The thermographic inspection methodology utilizing intersecting line scanning mode along the weld seam is systematically explored in this simulation. Meanwhile, the feasibility of the method is further verified through experimental simulations,demonstrating preliminary capabilities for quantitative assessment of defect length.

1. Introduction

Small-diameter nozzles for pressure vessels serve as connecting components for accessory parts or material inlets and outlets of pressure vessels and pressure pipelines in refining and petrochemical plants and oil and gas field stations. With pipe diameters ranging from 20 to 100 mm and wall thicknesses exceeding 3.5 mm, small-diameter nozzles are numerous and widespread. Statistics indicate that a 5-million-ton refining unit may contain over 10,000 small nozzles, highlighting their immense quantity. Characterized by their small diameters and complex structures, most small-diameter nozzles are welded using fillet welds. However, there is a notable lack of quality inspection requirements for the connection structures and weld interiors during the design and manufacturing stages of pressure vessels, often resulting in cracking, leakage, and other issues during equipment operation[1]. Failures of small nozzles are frequent, as evidenced by multiple leaks in a chemical oil pipeline at a particular company[2]. Furthermore, an explosion occurred in a steam pipeline at a petrochemical plant in central China due to incomplete fusion defects in a small nozzle. Therefore, effectively conducting quality inspections and safety assessments of small-diameter nozzles, eliminating potential hazards, preventing accidents, and ensuring the safe operation and scientific supervision of refining and petrochemical plants and oil and gas field stations hold significant economic and social importance.

The particularity of the small-diameter nozzle structure and the complexity of the working conditions determine that the defect detection space is small, the operation is difficult, and the possible defect forms are multiple and complex. How to solve these problems is a huge challenge for small-diameter nozzle defect detection. At present, the detection technologies for small nozzles of pressure vessels mainly include penetrant testing, magnetic particle testing, eddy current testing, ultrasonic testing, etc. For example, Wei Rongshuai et al. [3] used phased array ultrasonic testing technology to simulate the corresponding conditions of various defects on the outer wall of the pressure vessel cylinder and the inner wall of the connecting pipe; Guo Zonghao et al. [4] developed a special ultrasonic testing technology based on the characteristics of the pressure vessel nozzle and cylinder weld of the HPR1000 reactor; Xie et al. [5] used pulsed eddy current nondestructive testing technology to detect defects in the welds of gas cylinders; Qi Zhengwang et al. [6] invented a radiographic inspection device for safety welds of pressure vessel nozzles; Shen Gongtian [7] proposed the acoustic emission testing and result evaluation methods for metal pressure vessels and atmospheric pressure metal storage tanks; Budimir M[8] et al. successfully detected defects ranging from 3.3 to 15.8mm in the head of the nuclear reactor pressure vessel using ultrasonic testing and eddy current testing; Karaduman D[9] et al. used acoustic emission method for nondestructive testing of buried pressure vessels for liquefied petroleum gas storage. However, these technologies are limited in their effectiveness due to the special structure of pressure vessels with small-diameter nozzles and high requirements for surface quality inspection. Therefore, it is important to develop inspection techniques that are suitable for small-diameter nozzles with complex structures, poor surface quality, and limited space, in order to effectively evaluate the safety status of these nozzles.

Eddy current thermography is a newly emerged non-destructive testing technology in recent years, integrating the benefits of traditional eddy current testing and thermal wave testing [10]. Zhang Yubin et al. [11] introduced an intelligent detection approach for subsurface defects in coated steel structures, leveraging YOLO v5 within pulsed eddy current thermography. Tu Yanxin et al. [12] employed dynamic scanning eddy current thermography to inspect artificially induced defects in carbon steel specimens. Wang Chuanzhao et al. [13] conducted research on diagonal weld cracks using eddy current pulsed thermography. Torane Vaibhav et al. [14] utilized scanning induction thermography for detecting rail cracks. Compared to conventional eddy current non-destructive testing techniques, this technology boasts enhanced detection depth and resolution, with minimal impact from the shape of the inspected object. Furthermore, the versatility in the design of excitation coils broadens its application potential, particularly in defect detection of small-diameter nozzles in pressure vessels.

This study investigates the temperature distribution around surface defects in small-diameter nozzle welds of pressure vessels under the excitation coils, employing both numerical simulation and experimental analysis based on eddy current thermography. Furthermore, the simulation incorporates the scanning motion of the excitation coil along the intersection curve to explore the application effectiveness of eddy current thermography in inspecting small-diameter nozzle welds in pressure vessels more comprehensively.

2. Theoretical basis

2.1. Basic principles of eddy current thermography detection technology

Eddy current thermal imaging detection is a form of active infrared thermal imaging detection, representing a novel detection technique that integrates eddy current detection with thermal imaging. It operates initially by leveraging the principle of electromagnetic induction, positioning an excitation coil or probe carrying alternating current close to the object under inspection capable of generating eddy currents. The alternating magnetic field emitted by the excitation coil or probe induces currents within the object, subsequently heating it, as illustrated in Figure 1.Eddy current thermal imaging detection is a form of active infrared thermal imaging detection, representing a novel detection technique that integrates eddy current detection with thermal imaging. It operates by initially utilizing the principle of electromagnetic induction, where an excitation coil or probe carrying an alternating current is positioned close to the object under inspection capable of generating eddy currents. The alternating magnetic field emitted by the excitation coil or probe induces currents within the object, subsequently heating it, as illustrated in Figure 1.

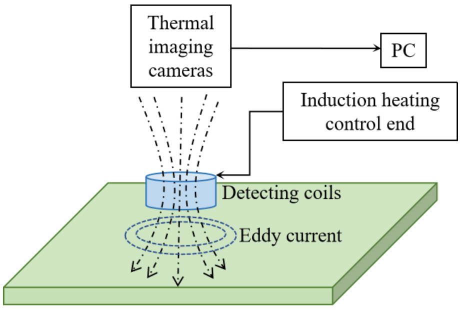

Fig. 1. *Eddy current thermography principle*

When there are defects on the surface or subsurface of an object, due to the anisotropy of the material, the eddy currents at the defect site change, resulting in abnormal temperature and a change in the temperature field of the object. At this time, an infrared detection device is used to receive the infrared radiation emitted by the detected object to obtain the temperature field. After processing, thermal imaging data is obtained to obtain defect features and achieve defect detection of the object.

Compared with other infrared thermal imaging methods, eddy current thermal imaging detection has significant advantages. This method uses excitation coils or excitation probes to heat the object being detected, which belongs to non-contact heating and avoids damaging the surface of the object being detected. During the detection process, local heating is performed, which effectively solves the problem of uneven heating of the excitation source. In electromagnetic excitation, excitation coils or probes are used as excitation sources, which have strong flexibility in selecting excitation parameters. Different frequency waveforms, output powers, etc. can be selected based on the different characteristics of the detected object. Different forms and shapes of excitation coils or probes can also be selected or designed for different shapes of the detected object.

2.2. Basic principle and excitation coil design

In the process of using eddy current thermal imaging technology to detect structural damage, the excitation coil plays a very important role as an external excitation carrier. During the operation of the excitation coil, the excitation effect is closely related to factors such as the matching degree between the coil and the tested workpiece, and the skin effect generated by the coil. Therefore, it is very important to select an appropriate excitation coil with suitable parameters for the tested workpiece. In both simulation and emulation, it is necessary to match appropriate excitation coils based on the shape of the tested workpiece and the state of defects.

2.2.1. Water-cooled coil

The excitation coil can be wound with different forms of materials, such as copper wire, copper tube, hollow copper tube, etc., all of which require current to be passed through the coil to generate a corresponding magnetic field. The current size ranges from tens of amperes to hundreds of amperes, and due to the existence of coil resistance, the excitation coil will inevitably generate a large amount of heat during operation. In order to prevent damage to the equipment caused by high temperature and ensure the normal operation of the coil, it is necessary to cool and cool the excitation coil. At present, the commonly used cooling methods include natural cooling, liquid cooling, etc. The excitation system studied in this article uses a hollow copper tube wound coil. Through a water cooling system, circulating water is circulated in the excitation coil to absorb and take away some of the heat generated by the coil, achieving the purpose of cooling and temperature reduction.

2.2.2. Excitation coil design

The small diameter connecting pipe of the pressure vessel provides limited space for the movement of the excitation coil. To accommodate this constraint, the excitation coil is designed as an arc-shaped double coil, as illustrated in Figure 2. This specially shaped coil is developed based on the principle of eddy current generation using U-shaped magnetic chokes, as well as the geometric characteristics of the small diameter connecting pipe.

The coil is capable of generating eddy currents similar to those induced by traditional U-shaped magnetic chokes within the test object. Compared with conventional U-shaped chokes, this design offers greater ease of installation, enhanced dimensional flexibility, and improved conformity to the geometry of the connecting pipe. These advantages allow the coil to more effectively approach the weld seam of the small diameter pipe. Additionally, the arc-shaped configuration improves the coverage area of the eddy current inspection.

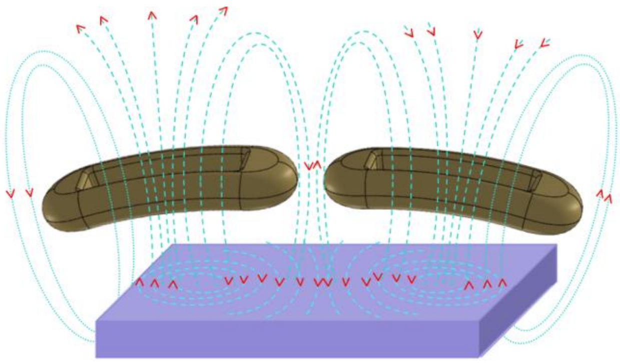

Fig. 2. *Coil design principles*

3. Numerical simulation

A one-to-one three-dimensional model was constructed based on the sample size of the small-diameter connecting piece of the laboratory pressure vessel. A simplified model was also developed using the coil configuration proposed above. The dimensions and defect specifications of the small-diameter nozzle model for the pressure vessel are provided in Table 1.

Table 1. *The pressure vessel has a small diameter to take over the relevant dimensions*

parts	Outside diameter /mm	Wall thickness /mm	Welding Feet /mm	Length /mm	Width /mm
Pressure vessels	293.0	10.0	/	/	/
Small-caliber tubes	60.3	5.0	/	/	/
Welding seam	/	/	6	/	/
Defect1 size	/	/	/	12	0.2
Defect2 size	/	/	/	8	0.2
Defect3 size	/	/	/	4	0.2

3.1.1. Static analysis

In the simulation, excitation currents with opposite directions are applied to the two coils to ensure that the induced currents between them flow in the same direction, thereby enhancing the detection performance. This configuration is illustrated in Figure 3.

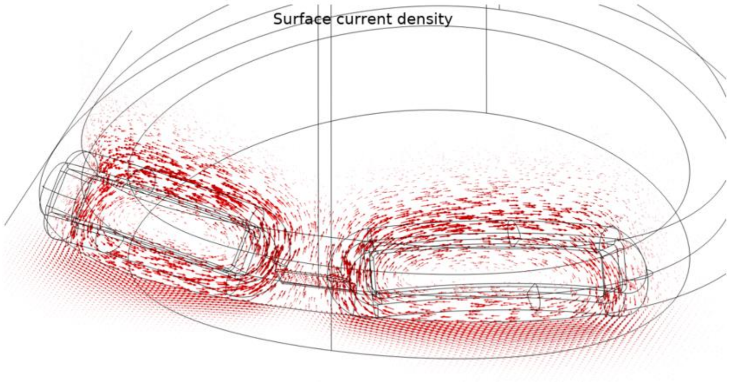

Fig. 3. *Surface current density*

COMSOL was used to analyze the temperature at the weld defect of the small-diameter nozzle of the pressure vessel. The resulting thermal image at the 8 mm defect is shown in Figure 4. It can be observed from the image that, under the excitation of the arc-shaped double coil, the eddy current heating effect on the weld surface exhibits a non-uniform distribution, primarily concentrated at both ends of the defect. This phenomenon aligns with the principle of eddy current thermography, which states that when defects exist on or beneath the surface of an object, the eddy currents at the defect site will exhibit noticeable changes.

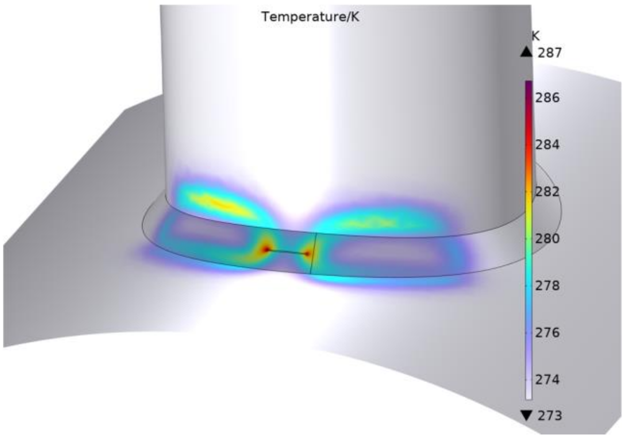

Fig. 4. *Temperature distribution map*

During static inspection, defects exhibit significant temperature variations. The maximum temperatures reach approximately 290 °C for 12 mm defects, 286 °C for 8 mm defects, and 280 °C for 4 mm defects, indicating that small-sized defects can be effectively detected.

3.1.2. Intersecting line scan analysis

In practical engineering applications, the detection process is not static but requires dynamic scanning along the weld seam. The weld seam of small-diameter connecting pipes in pressure vessels typically takes the form of intersecting lines. At present, dynamic scanning methods mainly include line scanning and surface scanning, while research on intersecting line scanning remains limited. Therefore, this study introduces and supplements the intersecting line scanning mode.

In the simulation, dynamic scanning along intersecting lines is implemented by applying displacement and rotational transformations. The arrow shown in Figure 5 indicates the motion trajectory of the coil as it moves around the weld seam.

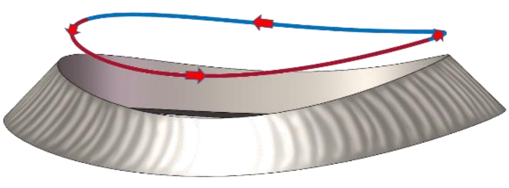

Fig. 5. *Intersection line scanning detection*

By simulating and analyzing weld defects using the intersecting line scanning mode, the detection performance of the coil for defects at different positions along the intersecting path can be evaluated. The specific temperature distribution is shown in Figure 6. From the dynamic simulation results, it can be observed that when the coil passes over different defects, elevated temperatures appear at the endpoints of the defects, with the maximum heating temperature reaching up to 290 °C. The locations of the defects can be clearly identified.

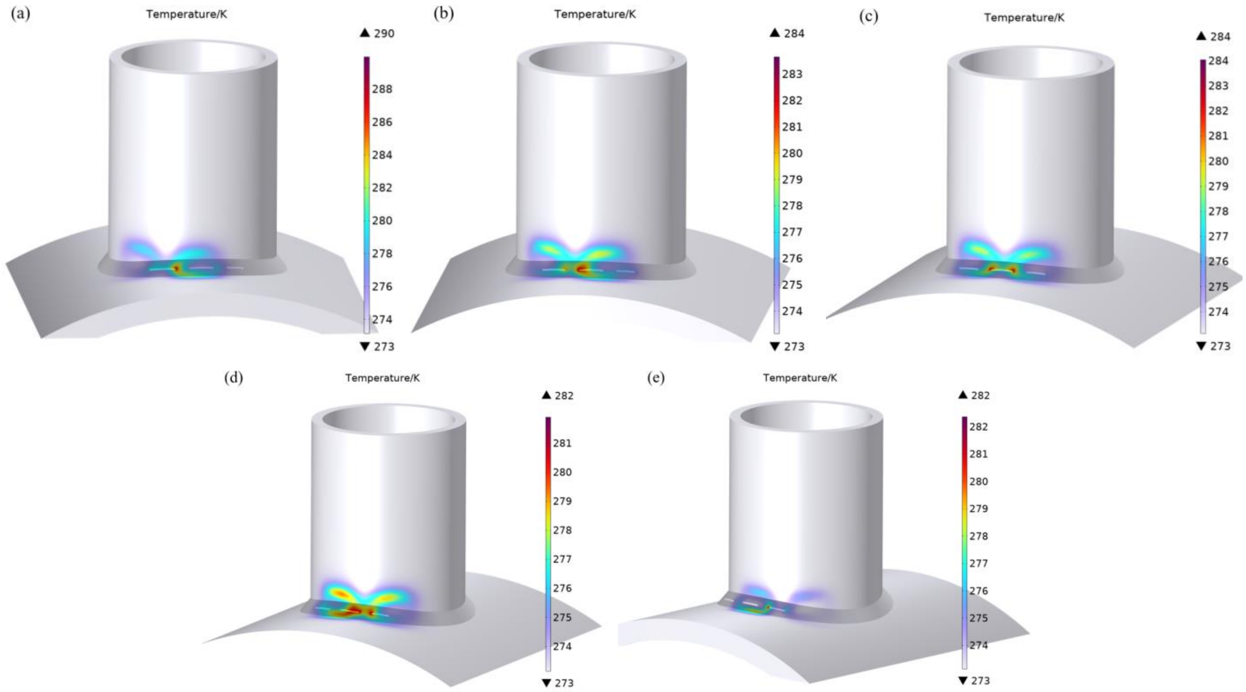

Fig. 6. *Weld surface temperature distribution when the coil moves to defect 1; (b) The coil moves to the weld surface temperature distribution between defects 1 and 2; (c) Weld surface temperature distribution when the coil moves to defect 2; (d) The coil moves to the weld surface temperature distribution between defects 2 and 3; (e) Weld surface temperature distribution when the coil moves to defect 3*

Through the simulation analysis conducted in this chapter, it can be concluded that eddy current thermography can be effectively applied to the detection of weld defects in small-diameter nozzles of pressure vessels, both in static inspection and dynamic scanning scenarios.

4. Empirical test

4.1.1. Experimental results

In this section, experimental studies were carried out on 8 mm and 4 mm defects located on the weld seams of small-diameter connecting pipes in pressure vessels. The experimental setup is shown in Figures 7 and 8.

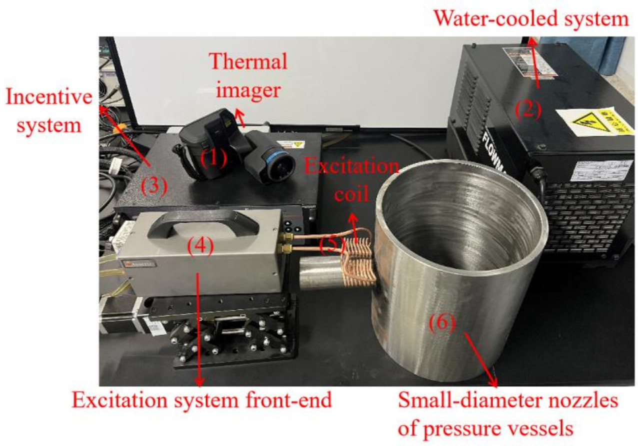

Fig. 7. *Experimental setup*

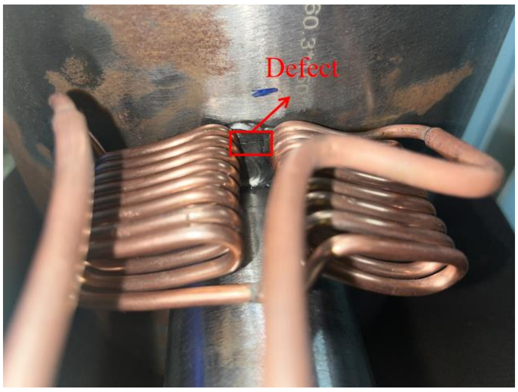

Fig. 8. *Coil and defect location*

In this study, the FLIR Research Studio software in high-sensitivity mode was used to observe and analyze the experimental results. By extracting thermal images during the defect heating phase from the recorded infrared thermography video, temperature changes in the defect area can be clearly observed, thereby enabling the identification of defect locations. The imaging results for the 4 mm defect are shown in Figure 9.

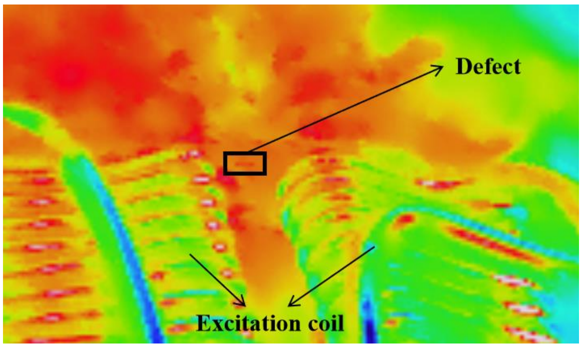

Fig. 9. *4mm defect temperature distribution image*

4.1.2. Quantitative evaluation of defect length

Defect length is a critical factor affecting structural integrity and safety. For the quantitative evaluation of defect length in small-diameter connecting specimens of pressure vessels, a width conversion coefficient (λ) between the specimen and the image is introduced. This coefficient is calculated by dividing the actual width of the inspected surface of the specimen by the pixel width occupied by the same surface after image processing. The specific quantitative calculation of defect length is as follows:

$$\lambda = \frac{L_1}{L_2} \tag{1}$$

$$L_3 = \lambda \times L_{PIX} \tag{2}$$

Among them, L_1 is the actual width of the tested surface, L_2 is the pixel width of the tested surface, L_{PIX} is the length of the defective pixel, and L_3 is the actual length of the defect.

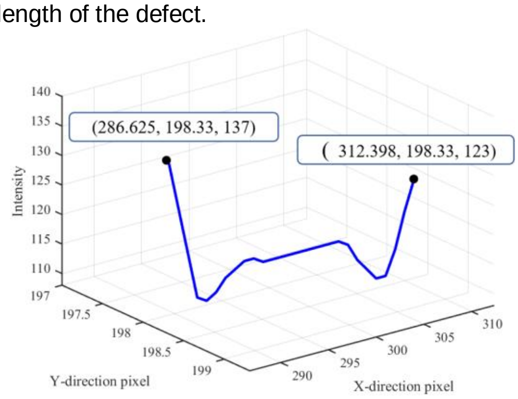

Fig. 10. *4mm defect pixel position and grayscale*

MATLAB was used to perform grayscale processing and pixel position extraction on the thermal images obtained from the experiment. The pixel positions and grayscale values corresponding to the 4 mm defect are shown in Figure 10, from which the pixel coordinates at both ends of the captured defect can be determined.

To improve data accuracy, the defect region in the image was captured multiple times, and the pixel width of the defect was measured in each case. The average value was then calculated. The detailed results are presented in Table 2.

Table 2. *The defective pixel being measured*

Defect	Pixel1	Pixel2	Pixel 3	Average pixels
8mm	20.15	21.71	21.30	21.05
4mm	23.33	23.77	23.37	23.49

By measuring the inspected surface of the specimen, the actual width of the surface containing the 8 mm defect is approximately 230 mm, while that of the surface containing the 4 mm defect is approximately 110 mm. The corresponding pixel widths in the thermal images are 630 and 714, respectively. Using equations (6) and (7), the calculated defect lengths are 7.68 mm and 3.62 mm, with respective errors of 4.0% and 9.5% compared to the actual lengths. The detailed results are shown in Table 3.This method enables the estimation of defect lengths at the weld seams of small-diameter connecting pipes in pressure vessels to a certain extent.

Table 3. *Calculation results*

Defect	Actual width of the tested surface	Pixel width of the tested surface	Calculate width	deviation
8mm	230mm	630	7.68mm	4.0%
4mm	110mm	714	3.62mm	9.5%

5. Conclusion

This study applies eddy current thermography technology to the detection of weld defects in small-diameter nozzles of pressure vessels and designs excitation coils that are structurally compatible. A model of the small-diameter nozzle weld and excitation coil was established in SolidWorks and simulated in COMSOL to study the heating effect at defect locations. The accuracy of the simulation results was verified through corresponding experiments. Based on the research, the following conclusions were drawn:

(1) Simulation analysis using COMSOL revealed that the temperature change in the defect area is significant when the excitation coil heats the defect. The defect disturbs the induced eddy currents, with the disturbance primarily concentrated at both ends of the defect, forming localized high-temperature zones. A dynamic intersecting-line scanning mode along spatial curves was implemented to detect small-diameter nozzle defects, providing preliminary validation of the effectiveness of eddy current thermography in detecting weld defects in pressure vessels.

(2) Experimental verification demonstrated that the excitation coil produces a pronounced heating effect on small-sized weld defects, allowing for effective defect detection. These results indicate that the arc-shaped double coil has good applicability for detecting weld defects in small-diameter nozzles and further validate the effectiveness of eddy current thermography for this purpose.

(3) Quantitative evaluation of defect length was achieved by using MATLAB to extract grayscale values and pixel positions from thermal images, enabling effective measurement of weld defect length in small-diameter nozzles of pressure vessels.

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