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ON-POWER DETECTION OF PIPE WALL-THINNED DEFECTS USING IR THERMOGRAPHY IN NPPS

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Wall-thinned defects caused by accelerated corrosion due to fluid flow in the inner pipe appear in many structures of the secondary systems in nuclear power plants (NPPs) and are a major factor in degrading the integrity of pipes. Wall-thinned defects need to be managed not only when the NPP is under maintenance but also when the NPP is in normal operation. To this end, a test technique was developed in this study to detect such wall-thinned defects based on the temperature difference on the surface of a hot pipe using infrared (IR) thermography and a cooling device. Finite element analysis (FEA) was conducted to examine the tendency and experimental conditions for the cooling experiment. Based on the FEA results, the equipment was configured before the cooling experiment was conducted. The IR camera was then used to detect defects in the inner pipe of the pipe specimen that had artificially induced defects. The IR thermography developed in this study is expected to help resolve the issues related to the limitations of non-destructive inspection techniques that are currently conducted for NPP secondary systems and is expected to be very useful on the NPPs site.

KEYWORDS : IR Thermography, Wall-thinned Defects, IR Camera, Cooling Device, Finite Element Analysis (FEA), On-power Inspection

1. INTRODUCTION

The number of aging nuclear power plants (NPPs) has increased recently. Accordingly, the number of operational interruptions has increased due to malfunctions of the NPPs secondary systems. These cases occur in the secondary systems of NPPs with a range of structures due to fatigue, wall-thinned defects, corrosion, etc. Of these problems, wall thinned defects occur in the pipes by the diffusion of the corrosion with the flow of the fluids, and the defects frequently take place in carbon steel pipes with lower Cr content. Such wall-thinned defects can lead to damage without warning signs and they can be found frequently in the base material part. Therefore, they are one of the major factors that degrade the integrity of a pipe [1], [2].

Systematic management of wall-thinned defects requires regular inspections. In particular, systematic management requires a close inspection even when the NPP is in normal operation. The secondary system of a NPP is the place to which the operators or workers gain access for their work frequently. Unexpected damage to a pipe may have significant social impacts, which highlights the importance of systematic management of wall-thinned defects. Consequently, considerable attention has been paid to non-destructive inspections to examine the integrity of major facilities. In addition, there is increasing demand for non-destructive inspection methods that are relatively safe and enable measurement in a quick and easy manner [3].

Currently, a range of non-destructive inspections are conducted, such as ultrasonic testing (UT), eddy current testing (ECT), and magnetic particle testing (MT) [4], [5]. Non-destructive inspection techniques involve infrared (IR) thermography. IR thermography is expected to help resolve the issues related to the limitations of the existing non-destructive inspection techniques because it is used to examine defects based on measurements of the temperature difference between defective parts and non-defective parts. IR thermography is also expected to be useful on a NPP site [6].

IR thermography with a cooling device is a reliable technique for detecting wall-thinned defects in the inner pipes of NPPs that are in normal operation, and is expected to facilitate the maintenance of secondary systems of NPPs. The results of this study will be used as the basic material for the inspection of wall-thinned defects.

2. THEORETICAL BACKGROUND

2.1 IR Thermography

When a specific target is cooled from an outside cooler, thermal diffusion is disturbed on the surface of the target depending on the existence of defects inside the target. In this case, the insulation effect by defects inside the target induces temperature differences on the target surface. IR thermography is used to measure the temperature of the surface of the target and convert the measurement results to an image in real time. Based on a real-time image obtained using an IR camera, it is possible to measure the shape and location of the defects inside the target [7].

IR thermography has the following features [8]:
- Non-contact technique
- Full-field image of stress
- Energy measurement technique
- Easy visual interpretation of the results

Currently, IR thermography has been applied to the military field, stress analysis, welding monitoring, evaluation of heat transfer characteristics, deterioration diagnosis of power facilities, defect inspection in composites, and medical diagnosis [9]. Fig. 1 shows the principle of IR thermography.

2.2 Theory

All objects have a temperature that is above absolute zero and they emit radiant energy that corresponds to their temperature [10].

$$\frac{dR(\lambda,T)}{d\lambda}=\frac{2\pi hc^2\lambda^{-5}}{e^{hc/\lambda kT}-1}, \tag{1}$$

where

Plank's constant $h = 6.626\times10^{-34} J\cdot s$
Boltzmann's constant $k = 1.380546\times10^{-23}$
Speed of light $c = 2.998\times10^{8} ms^{-1}$.

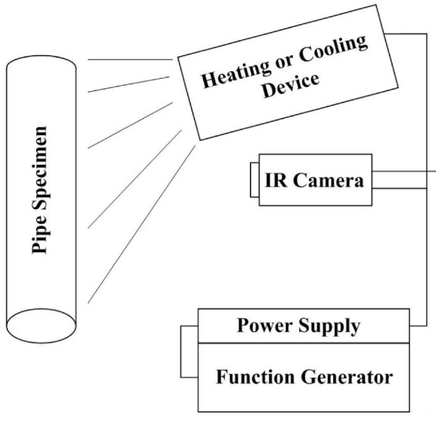

Fig. 1. Diagram of IR Thermography.

Eq. (1) describes Plank's theory of black body radiation. According to the theory, there is a simple relationship between the characteristics of black body radiation (energy intensity, R, and wavelength, λ) and its temperature, T. Moreover, the amount of radiation emitted from a black body radiator per unit time is determined only by temperature. The characteristics can be used to calculate the temperature of the black body. IR thermography provides a temperature image using the correlation between temperature and detected energy [10]. The integration of Eq. (1) over the total wavelength range $\lambda = 0$ to $\lambda = \infty$ gives:

$$R=\sigma T^4, \tag{2}$$

where

Stefan-Boltzmann's constant $\sigma = 5.67\times10^{-8} W/(m^2\cdot K^2)$.

Eq. (2) describes Stefan-Boltzmann's law. This theory states that the total energy radiated per unit surface area of a black body and per unit time is directly proportional to the fourth power of the absolute temperature, T. In this case, T represents the absolute temperature in Kelvin of an object and R_t is the reflection intensity of a black body. The IR camera can measure the temperature using Eqs. (1) and (2) [10].

An ideal black body emitter does not exist in reality. If the energy emitted from a real object is R_a and the energy emitted from a black body is R_b, the emissivity which is the ratio of energy radiated by an object to energy radiated by a black body at the same temperature can be expressed by Eq. (3) [10].

$$\varepsilon=\frac{R_a}{R_b} \tag{3}$$

In this case, if $\varepsilon = 1$, the object is called a black body. Therefore, for metal with low emissivity, the emissivity can be kept at 0.95 if a black matte color spray is applied, which is close to a black body.

3. OPTIMAL COOLING METHOD

In an NPP that is in normal operation, the pipes are covered with insulators and are at high temperature, transferring heat to the surface of the insulators. The thermal conduction in the specimen is related with the following equation where the heat flux is equal to the product of the thermal conductivity, k, and the negative temperature gradient, $-\nabla T$:

$$q=-k\nabla T \tag{4}$$

When a cooling device is used to cool the pipes at high temperatures, thermal diffusion is disturbed depending on the existence of defects inside the pipes. Insulation effects by defects induce local differences in temperature