Detection of Hot Pipe Defects using IR Thermography

Kwae Hwan Yoo[1], Ju Hyun Kim[1], Man Gyun Na[1], Jin Weon Kim[1]
Kyeong Suk Kim[2] and Chang-Doo Kee[3]
[1]*Department of Nuclear Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju, Korea*
[2]*Department of Mechanical Design Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju, Korea*
[3]*School of Mechanical Engineering, Chonnam National Univ., 77 Yongbong-ro, Buk-gu, Gwangju, Korea*

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Abstract: Wall-thinned defects, which are attributable to acceleration of corrosion that is occurred by fluid flow in the inner pipe, appear in various structures of the secondary system in nuclear power plants (NPPs), playing a role as a major factor to degrade integrity of pipes. It is required to manage wall-thinned defects not only when the NPP is under maintenance but also when the NPP is in normal operation. To this end, this paper developed a test technique to manage such wall-thinned defects based on temperature difference on surface of hot pipe with use of infrared thermography and cooling device. Finite element analysis (FEA) was conducted to examine tendency of and test conditions for cooling experiment. Based on the FEA results, equipment was configured before the cooling experiment was conducted. Then, infrared camera was used to detect defects in the inner pipe of the pipe specimen that had artificially induced defects. The infrared thermography developed in this study is expected to help resolve issues related to limitations on the non-destructive inspection that is currently conducted for NPP's secondary system and expected to be very useful on the NPP site.

1 INTRODUCTION

Recently, an increasing number of nuclear power plants (NPPs) have deteriorated due to long-term operation, which has led to increase in the number of cases where NPP operation comes to a stop due to problems in facilities of NPP's secondary system. Such cases show that fatigue, corrosion and wall thinning cause problems in various structures of NPP's secondary system. Among these factors, wall-thinned defects are attributable to acceleration of corrosion that is occurred by fluid flow in the inner pipe. The wall-thinned defects can be found frequently in carbon steel pipe that has the low content of chromium (Cr). Such wall-thinned defects can lead to damage without warning sign in advance while they can be found frequently in base material part. Therefore, they are known to be one of the major factors that degrade integrity of pipe.

A systematic management of wall-thinned defects requires inspection that is conducted on a regular basis. In particular, the systematic managemet requires a close inspection even when the NPP is in operation. The secondary system of the NPP is the place to which operator or workers get an access for their work frequently. Unexpected damage to pipe may cause social impact that cannot be compared with loss of or damage to person, which demonstrates the importance of systematic management of wall-thinned defects. Consequently, much attention has been paid to non-destructive inspection in order to examine integrity of major facilities while there is an increasing demand on the non-destructive inspection that is relatively safe and enables conducting measurement in a quick and easy way.

Currently, various kinds of non-destructive inspections are conducted such as ultrasonic testing (UT), eddy current testing (ECT) and magnetic particle testing (MT). Such non-destructive inspections include infrared thermography. The infrared thermography is expected to help resolve issues related to limitations on the existing non-destructive inspection because it is used to examine defects based on measurement of temperature difference between defect part and non-defect part.

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The infrared thermography is also expected to be very useful on the site.

Against this background, this study used infrared thermography to develop cooling device and a reliable test technique in order to detect wall-thinned defects in the inner pipe of the NPP that was in normal operation, which is expected to facilitate maintenance of plumbing fixtures of NPP's secondary system. The results of this study will be used as basic data for inspection of wall-thinned defects.

2 THEORETICAL BACKGROUND

2.1 Infrared Thermography

When an object is cooled from the outside, thermal diffusion is disturbed on surface of target depending on existence of defects inside the target. In this case, insulation effect by defects inside the target causes temperature difference on the target surface. Infrared thermography is used to measure temperature on the surface of target and convert the measurement results to image before providing image in real time. Based on the real-time image obtained by using infrared camera (IR camera), it is possible to measure shape and location of the defects inside the target.

Infrared thermography has the following features:

- Non-contact technique
- Full-field image of stress
- Ability to measure energy loss
- Easy analysis of results thanks to visual effects

Currently, infrared thermography is applied to military field, stress analysis, welding monitoring, evaluation of heat transfer characteristics, deterioration diagnosis of power facilities, defect inspection in the composites, and medical diagnosis.

2.2 Theory

All of the objects have temperature that is above the absolute zero while they emit radiant energy that corresponds to their temperature.

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

Plank's constant $h = 6.626\times10^{-34} J\cdot s$

Boltzmann's constant $k = 1.380546\times10^{-23}$

Speed of light $c = 2.998\times10^{8} ms^{-1}$

The equation (1) describes the Plank's theory of black body radiation. According to the theory, a simple relationship is established between characteristics of black body radiation (energy intensity and wavelength) and temperature of black body. Moreover, radiation amount of wavelength that is emitted per unit time from black body radiator is determined only by temperature, which is characteristic of black body radiation. The characteristic can be used to calculate temperature of black body. Infrared thermography enables measuring amount of emitted energy to provide temperature image based on the correlation between amount of detected energy and temperature.

$$\int_0^{\lambda} \frac{dR(\lambda,T)}{d\lambda} \qquad R_t = \sigma T^4 \tag{2}$$

Steffan-Boltzmann's constant

$$\sigma = 5.67\times10^{-8} W/\left(m^2\cdot K^2\right)$$

The equation (2) describes the 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 absolute temperature T. In this case, T represents the absolute temperature K of an object in Kelvin temperature while Rt represents the reflection intensity of a black body. Based on the equation (1) and equation (2) mentioned above, IR camera is used to measure temperature.

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

Actual emissivity R_a

Blackbody emissivity R_b

Energy emitted from a black body is R_b. An ideal black body emitter does not exist in reality. If energy emitted from a real object is R_a, the emissivity of object to black body surface at the same temperature is expressed in the equation (3). In this case, if it is ε =1, an object is called a black body. Therefore, for metal that has low emissivity, the emissivity can be kept at 0.95 if matte colour spray, which is close to a black body, is applied.

3 OPTIMAL COOLING METHOD

3.1 Cooling Method

In an NPP that is in normal operation, pipes are covered with insulators and in high temperature, transferring heat up to the surface of insulators. When cooling device is used to cool the pipes in high temperature, thermal diffusion is disturbed depending on existence of defects in inside of the pipes. Insulation effects by defects cause difference in temperature locally on surface of the pipes. When IR camera is used to obtain thermal image of the pipes where such temperature difference occurred, defects in the pipes are shown in image depending on existence of defects. Therefore, after examining various cooling methods and investigating applicability of such methods, the authors found out the optimal cooling method to detect defects in NPP's pipes with use of infrared thermography.

3.1.1 Tube Air Cooler

A tube air cooler is a cooling device where pathway of air current is narrowed to increase fluid velocity as compressed air rotates in high speed, which aims at separating hot air current from cool air current. The tube air cooler uses compressed air in a general compressor to cool air readily. In addition, the cooler is fundamentally safe because refrigerant, electricity or any chemicals are not used for the cooler. The cooler is effective specially for local cooling even though it has low capacity. However, the cooler has some drawbacks because it requires an additional equipment to use compressed air and needs to be installed with equipment that produces compressed air in order to be used portably.

3.1.2 Air-cooling and Water-cooling Coolers

A cooler is a device that converts high-temperature high-pressure gaseous refrigerant to low-temperature liquid refrigerant. Gaseous refrigerant containing heat that is taken away from evaporator gets cooled as it passes through condenser. Therefore, heat is released to the outside as the gaseous refrigerant is turned to the liquid refrigerant. Cooler can be classified to air-cooling cooler and water-cooling cooler. The air-cooling cooler has the excellent cooling capability as it prevents degradation of cooling function that is attributable to increase in room temperature. Moreover, the air-cooling cooler enables keeping temperature constant precisely and can be adjusted in the wide range of use. The water-cooling cooler uses water from a cooling tower to work in the condensation cooling method. It minimizes indoor noise and shows the higher cooling efficiency than the air-cooling cooler.

3.1.3 Heat Pipe-type Cooler

A heat pipe-type cooler is a cooling device that transfers heat in large quantity to condenser prior to using the pin installed in the condenser for cooling through natural convection or forced convection. The heat pipe-type cooler uses working fluid of FC-27 in the maximum thermal load of 1.5 ㎾. In addition, it has the operating temperature of – 30~120℃ with the high cooling efficiency. Since water quantity in heat pipe can be adjusted, the heat pipe-type cooler can be manufactured in various forms. However, the heat pipe-type cooler has drawbacks that it takes longer time for cooling than other coolers and requires the installation of an additional fan to increase cooling efficiency.

3.1.4 Fan Cooler

A fan is a device that stirs up the wind as wings installed on the axis of electric motor rotate. The fan can be classified to desk fan, ventilating fan and stand fan depending on shape and purpose of use. Major parts of the fan include stand, pillar, motor, and wing. It can be adjusted quite freely according to angle and direction of movement (up and down or right and left). The pillar of the fan also can be adjusted upwardly or downwardly. The fan has the front-side control panel that enables an easy control as all of the devices are installed on the front side of stand. The fan can be also classified to turbo fan, limit fan and sirocco fan depending on shape of wing. The turbo fan has the wing that its tip is bent to the backward of rotation direction, which includes the one with curved wing and the one with straight wing. The turbo fan shows the high efficiency and can be operated relatively quietly even at a high speed. The limit fan is an upgraded version of the turbo fan and the sirocco fan. It has the streamlined wing that is manufactured by folding a thin plate. Therefore, the limit fan can be rotated in a high speed with low noise. The sirocco fan has a bent shape as the tip of wing is bent toward the rotation direction. Compared to other types of fans in the same capacity, the sirocco fan features the significantly low number of rotation.

3.2 Selection of a Cooling Method

In this study, the optimal cooling method was selected to obtain thermal image of defects in geometric shape in an easier and quicker way with a view to examining defect size and depth from surface. The previous cooling methods include the method for cooling a pipe with use of a cooler, a tube air cooler or a heat pipe-type cooler and the method for installation of a cooling device on the front side of a pipe with use of a fan. The authors investigated the characteristics of various cooling methods among the ones explained above in order to examine the applicability of such methods. The results are shown in Table 1.

As shown in Table 1, the cooling method with use of a fan was evaluated to be the best among the various cooling methods. The fan cooling method can be combined with other cooling methods or can be used independently. Therefore, the fan cooling method was used in this study to detect wall-thinned defects inside the pipe based on infrared thermography.

Table 1: Applicability of Cooling Methods.

Cooling Method	Applicability
Air Tube Cooler	As compressed air is used for cooling, the cooler is cheap and portable. The cooler has the low capacity, which is effective for cooling locally. However, it requires an additional equipment to use compressed air. Some limitations are expected when the cooler is used on the site of NPPs.
Air-cooling and Water-cooling Coolers	The coolers enable keeping temperature constant precisely and can be adjusted in the wide range of use. They show the excellent cooling capability with high efficiency. However, the initial cost of manufacturing is high. They are heavy and not suitable for being used portably.
Heat Pipe-type Cooler	The cooler has the high cooling efficiency while water quantity in heat pipe can be adjusted, which enables being manufactured in various forms. In addition, the interval of heat pipe itself can be adjusted. However, the cooler shows the high cooling efficiency when it is installed directly on the target. A fan needs to be installed additionally.
Fan Cooler	A fan is readily available. Its wing can be manufactured in various forms. The angle of the cooler can be adjusted while rotation speed of the fan can be adjusted continuously and freely. In addition, the cooler can be manufactured to be in light weight. Therefore, it is believed that the cooler will be easy to be used portably.

4 SIMULATION AND EXPERIMENT

In this study, the fan-type cooling device was selected as equipment to cool a pipe specimen. Prior to the testing, a finite element analysis (FEA) was conducted to investigate the cooling effect of the selected cooling device as well as the optimal test conditions. The FEA was conducted by using ANSYS FLUENT 13.0 while GAMBIT program was used for generating the mesh that was modelled to conduct the FEA. In addition, based on the FEA results, cooling tests were performed to detect defects inside the pipe specimen.

4.1 Specimen and Equipment

The pipe specimen used for this study has defects inside for the purpose of cooling test. For the test, the pipe specimen with 4 inch diameter was manufactured with the material of Shc.80 ASTM A106 Gr.B, which was similar to the actual pipe used in the NPPs. As shown in Figure 1, the pipe specimen has the total length of 500mm, the thickness of 7.5mm, and the external diameter of 113mm. On the inner surface, four defects were created in a constant length. The four defects have the depth that is 50% and 75% respectively of the thickness of the pipe specimen. Furthermore, matte colour spray was applied to the surface of the pipe specimen in order to ensure the surface emissivity of 0.95, which aimed at minimizing the reflection of light. Figure 2 shows the pipe specimen that was manufactured for this study.

A blower fan was used as a cooling device to cool the pipe specimen. The blower fan has 6 wings at the maximum wind speed of 16.5m/s. The size of its wing is 27cm. The blower fan features a uniform cooling of the pipe specimen.

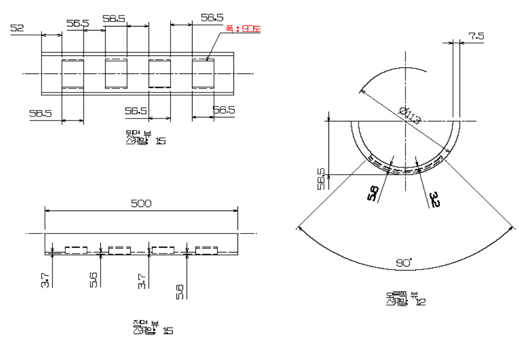


Figure 1: Design of a pipe specimen.

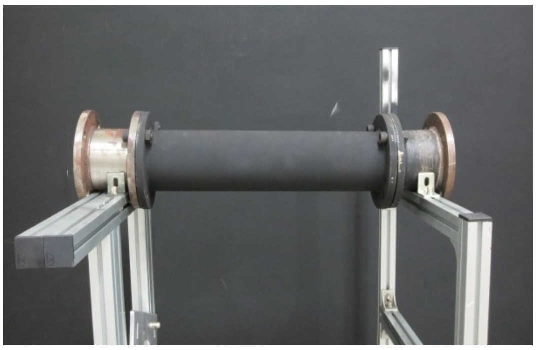


Figure 2: The pipe specimen.

4.2 Simulation Method

In regard to testing for wall-thinned defects inside the pipe, thermal analysis can be figured out based on the FEA that uses the numerical technique prior to experiments. The FEA provides the data to predict problems in thermal distribution of the pipe specimen based on analysis of simulation results, to configure the cooling device that can be applied to an actual environment, and to investigate the optimal test conditions.

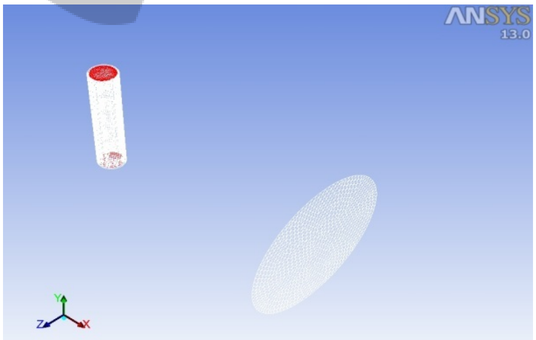
4.2.1 Specimen Modelling and Boundary Condition

In this study, the pipe specimen used for the experiment was ASTM A106 Gr.B that was frequently used for actual pipe of the NPP's secondary system, which was manufactured of carbon steel. Therefore, pipe modelling for the FEA was performed under the same conditions as the ones for pipe specimen that was used to test cooling devices. Modelling of the pipe specimen was performed in the total length of 500mm, the thickness of 7.5mm, and the external diameter of 113mm. Four defects in the two types were created inside to ensure that they had the depth that was 50% and 75% respectively of the thickness of the pipe specimen. Moreover, as matte colour spray was applied to the surface of the pipe specimen in order to minimize the reflection of light, reflection conditions were taken into consideration for the pipe modelling, which aimed at ensuring that the effects from emissivity were kept constant while the reflection of light was minimized.

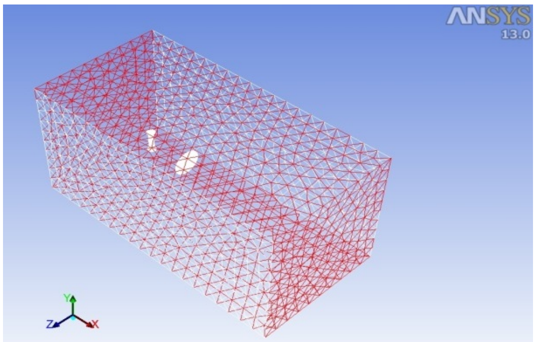
The basic boundary conditions for the FEA were established as follows. In order to simplify analysis, symmetric conditions were set to consider half of the pipe model. A large amount of thermal state and fluid conditions were entered for fluid that took each solid or air as thermal fluid medium. In addition, temperature (25℃) and humidity for the entire space were kept constant, excluding those for the pipe model and the cooling device model.

4.2.2 Cooling Method

This study used the cooling device based on the principles of a fan. Therefore, in order to conduct the FEA for the cooling device, the principles of a fan were applied to cool the pipe model through the forced convection that was occurred by pressure difference between surfaces of the fan model and the pipe model. In addition, as a way to describe a hot pipe in the NPP that was in normal operation, water was designed to flow inside the pipe model. Mass flow rate of water was set at 1kg/sec. Figure 3 (a) shows the diagrams of the pipe model and the fan model. Figure 3 (b) shows the meshes that were created to improve the accuracy of the analysis. ANSYS FLUENT was used to perform the simulation of the FEA for a cooling device. The distance between the fan model and the pipe model and the pressure difference in the fan model were adjusted. For simulation conditions, the distance between the pipe model and the fan model was adjusted to 1m, 2m and 3m while the pressure difference in the fan model was set at 100Pa and



(a) Diagrams of Pipe Model and Fan Model



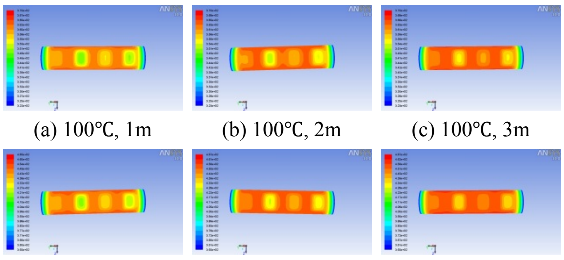
(b) Creation of Mesh

Figure 3: Configuration of Modelled Fan and Pipe Specimen.

150Pa. The temperature of water flowing inside the pipe model was adjusted to 100℃ and 200℃.

4.3 Simulation Results

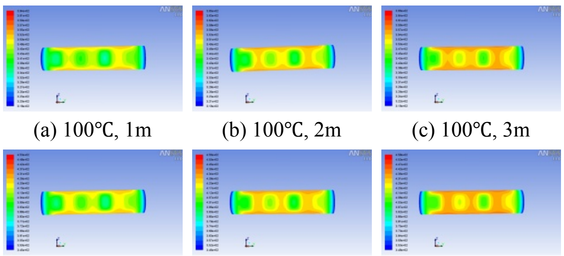
The FEA was made based on the image at 30 seconds that showed defects the most clearly among the results of simulation that was conducted for 60 seconds. Figure 4 shows the results of simulations that were performed when the surface pressure difference between the fan model and the pipe model was 100Pa, the temperature of the pipe model was 100℃ and 200℃, and the distance between the pipe model and the fan model was adjusted to 1m, 2m and 3m. The deviation of temperature in the defect part was observed to be conspicuous under all of the test conditions regardless of distance between the pipe model and the fan model. In addition, Figure 5 shows the results of simulations that were performed when the surface pressure difference between the fan model and the pipe model was 150Pa, the temperature of the pipe model was 100℃ and 200℃, and the distance between the pipe model and the fan model was adjusted to 1m, 2m and 3m. The shape of defects was observed with the naked eye while the defects looked clearer as the pressure difference in the fan model increased regardless of depth of defects. Moreover, as the distance between the pipe model and the fan model was shorter such as 1m and 2m, the defects became more distinct.



(a) 100℃, 1m (b) 100℃, 2m (c) 100℃, 3m

(d) 200℃, 1m (e) 200℃, 2m (f) 200℃, 3m

Figure 4: Pressure Difference of 100Pa in Fan Model.



(a) 100℃, 1m (b) 100℃, 2m (c) 100℃, 3m

(d) 200℃, 1m (e) 200℃, 2m (f) 200℃, 3m

Figure 5: Pressure Difference of 150Pa in Fan Model.

Consequently, the FEA simulation could confirm the cooling effects of the fan cooling device. The optimal test conditions include the pressure difference in the fan at 150Pa and the close distance such as 1m and 2m between the pipe specimen and the fan cooling device.

4.4 Experiment Method

The FEA that was conducted based on the numerical technique prior to the experiment could confirm the cooling effects of a cooling device. In this study, an IR camera and a cooling device were configured according to the test conditions that were established based on the FEA results with a view to detect wall-thinned defects inside the manufactured pipe specimen.

The temperature of pipes should be kept high since it is assumed that inspections are conducted for wall-thinned defects inside pipes of the NPP that is in normal operation. Therefore, the experiment for this study was conducted when the temperature of the pipe specimen was kept high. To this end, a heating device in the pipe was manufactured before it would be inserted to the inside of the pipe specimen. The inner heating device was manufactured to ensure that the support was close to the inner wall of the pipe specimen and that the support could be wrapped up with two heating tapes that could heat up to 400℃. Figure 6 shows the inner heating device that was used to implement a hot pipe.

In order to verify the heating performance of the inner heating device, the device was installed inside the pipe specimen before being heated up. Then, an IR camera was used to measure temperature distribution. The measurement results showed that the surface temperature of the 4-inch pipe specimen was kept at 142℃~150.35℃ depending on location when the temperature of two heating tapes was set at 320℃ for each. Figure 7 shows the surface temperature of the pipe specimen that was measured by using the IR camera when the maximum surface temperature of the pipe specimen was kept at 150℃. According to the measurement results, the highest temperature was observed in the center of the pipe specimen while the temperature tended to decrease as the distance from the center increased.

As shown in Figure 8, the authors configured the experimental equipment for detection of wall-thinned defects inside the pipe that included an IR camera, a fan, a pipe specimen, heating tapes, a heating tape controller, and a PC. The experiment

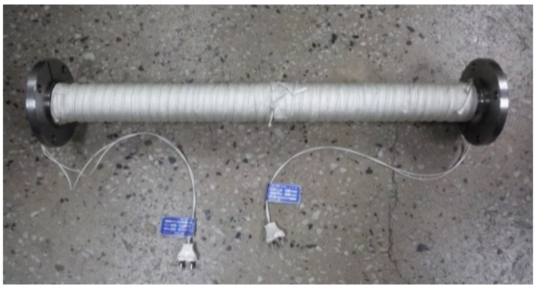


Figure 6: Inner Heating Device for a Pipe Specimen.

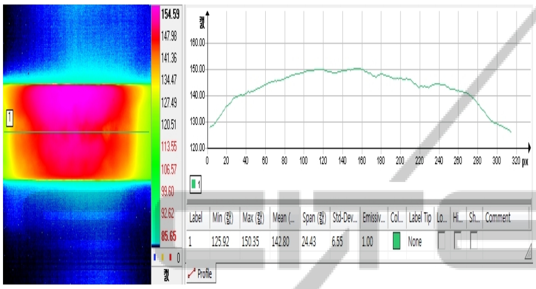


Figure 7: Temperature Distribution in an Inner Heating Device.

was conducted in a closed space while the temperature in the laboratory was kept constant at 25℃ with use of an air conditioner.

In order to describe the pipe of the NPP that was in normal operation, the inner heating device was used to maintain the temperature of the pipe specimen at 150°C while the experiments were conducted with variables that included the distance between the pipe specimen and the fan and the number of fans. The distance between the pipe specimen and the IR camera was fixed at 1m while the distance between the pipe specimen and the fan was adjusted to 1m and 2m. In addition, the number of fans was adjusted to 1 and 2 while each experiment was conducted for 120 seconds.

Figure 8: Experimental Equipment with Use of Cooling Device.

4.5 Experiment Results

Cooling tests for detection of wall-thinned defects inside the pipes of the NPPs that were in normal operation were conducted as an heating device was inserted to the inside of the pipe specimen at the temperature of 150℃, which aimed at implementing high temperature. In addition, the cooling tests were conducted as the number of fans was adjusted to 1 and 2 and the distance between the pipe specimen and the fan was adjusted to 1m and 2m based on the FEA results.

Figure 9 (a) and Figure 9 (b) show the experiment results when one fan was used with the distance between the pipe specimen and the fan adjusted to 1m, 2m and 3m. According to the experiment results, when the distance was 1m, the cooling effect was confirmed to be at around 34℃. When the distance was 2m, the cooling effect was confirmed to be at around 28℃. The defects created at the 75% depth inside the pipe specimen were detected at the distance of 2m. The defects were detected more clearly as the distance between the pipe specimen and the fan became shorter. Figure 9 (c) and Figure 9 (d) show the experiment results when two fans were used to cool the pipe specimen in the distance of 1m and 2m. When the distance was 1m, the cooling effect was confirmed to be at around 32°C. When the distance was 2m, the cooling effect was confirmed to be at around 27°C. In addition, it was possible to detect the defects that were artificially created not only with the 75% depth but also with the 50% depth inside the pipe specimen. The defects were detected more conspicuously as the distance between the pipe specimen and the cooling device became shorter.

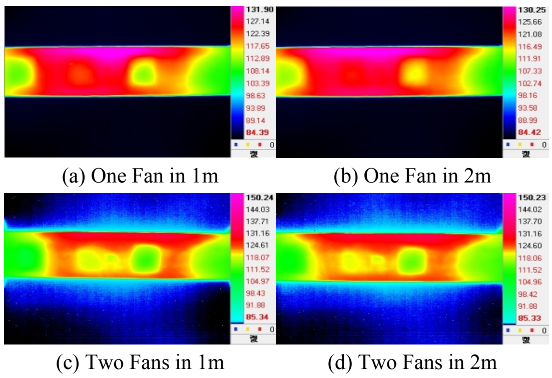


Figure 9: Pressure Difference of 150Pa in Fan Model.

5 CONCLUSIONS

In this study, infrared thermography was used to detect wall-thinned defects inside the pipe of the NPPs that were in normal operation. The pipe model and the pipe specimen that had the same physical properties as those for the actual pipe of the NPP were used for the FEA and experiment. Moreover, the size of defects applied to the pipe specimen was equal to that of defects applied to the pipe model for the FEA.

According to the results of the FEA that was conducted to examine the cooling effects of a cooling device and the optimal test conditions, the detection capability of defects was predicted to increase as the distance between the pipe and the fan decreased and the wind speed of fan increased. The prediction was applied to the experiment.

Defects could be detected partially in the test that was conducted by using the cooling device of a fan based on the FEA results. Unlike the analysis results, defects with the 75% depth of the pipe thickness could be detected clearly when the distance between the pipe specimen and the fan was 1m. In order to detect wall-thinned defects in the NPP that is in normal operation based on such results, the distance between the pipe and the fan should be short such as 1m while the wind speed and air flow of the fan should be high.

In conclusion, infrared thermography enabled detecting wall-thinned defects inside the pipe while it was expected to be very useful on the NPP site compared to the existing non-destructive inspection. Moreover, since the infrared thermography facilitates performing the maintenance of facilities of the NPPs that are in normal operation or the NPPs that are in maintenance period, it is expected to maximize the operation efficiency of NPP facilities and minimize the energy loss and economic loss that are attributable to the operation stop.

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