

Nondestructive Detection of Defect in a Pipe Using Thermography

Hee Seok Choi, Ok Jin Joung and Young Han Kim*

* Department of Chemical Engineering, Dong-A University, Pusan, Korea
(Tel : +82-51-200-7723; E-mail: yhkim@mail.donga.ac.kr)

Abstract: An infrared temperature sensor module developed for the detection of defects in a plate was modified to use in a cylinder. A set of optical fiber leads and a mechanism maintaining sensor-object distance constant were utilized for the modification of the IR sensor module. The detection performance was experimentally investigated, and the measured temperature was also compared with computed temperature distribution.

The experimental outcome indicates that the detection of a simulated defect is readily available. The temperature distribution is better for defect detection than that with the previous device. In addition, the measured distribution is comparable to the calculated one using a heat conduction equation. The developed device of defect detection is suitable to be utilized in chemical processes where most of vessels and piping systems are in the shape of a cylinder.

Keywords: Thermography, IR Sensor, Defect Detection, Nondestructive Detection, Numerical Analysis

1. INTRODUCTION

In chemical processes, the defected equipment and pipe often create large scale fire or explosion leading to operator casualty. Most of maintenance in the processes utilizes radioactive material or x-ray detection equipment. However, the instrument is expensive, and handling the hazardous material causes a variety of problems. In spite of the importance of defect detection in the industry, lack of proper detection technique incurs limited examination for defect detection. Recent development of thermographic defect detection systems is expected to solve the problem. For the instances of practical applications, the system has been utilized in the inspection of composite materials, laminated wood and thermal barrier coating.

In the chemical processes, vessels and pipes are often in service at high temperature, and therefore the thermographic measurement is useful because the process operation need not be interrupted for defect detection of the vessels and pipes. On the other hand, current nondestructive detection system employing x-ray or radioactive material requires the process shut down. That is not only inconvenient but costly and time-consuming procedure. A thermographic detection device is suitable to the application. An infrared (IR) camera utilized in the thermographic defect detection is expensive, and its limited imaging resolution makes the detection of small size defects difficult. A low-cost temperature measurement sensor, IR thermometer, is useful device for the thermographic detection system instead of the IR camera. Though its resolution is limited, cost benefit and ready availability are merits of the sensor. The IR thermometers were employed to locate a concealed groove as small as 1 mm wide in a metal plate and proved to be effective [1].

In this study, the previously developed IR thermometer sensor is modified to detect a concealed groove in aluminum pipe. For dense arrangement of the sensors giving narrow gap between sensors, optical fiber is attached to sensor window and contact rolls maintaining sensor-object distance constant are utilized. Experimental measurements are conducted to evaluate the modified device. In addition, the results of temperature measurement around the concealed groove are compared with the computed temperature distribution using a heat conduction equation.

2. NUMERICAL ANALYSIS

An aluminum pipe of 10 cm in diameter, 15 cm long and 5 mm thick is used in this experiment, of which the detailed dimension is given in Fig. 1. In the middle of the pipe a rectangular hole of 2 mm wide and 10 mm long is drilled and covered both sides with thin aluminum foil in order to conceal the groove. In order to provide a temperature distribution in the pipe a heater is placed on the top and a water cooler is at the bottom.

Considering the shape of the pipe, heater and cooler, a two-dimensional cylinder is utilized in the development of a system equation. For the computation of temperature distribution, a conduction equation is formulated based on the following assumptions:

1. steady state temperature profile
2. negligible temperature difference in the radial direction of pipe
3. constant temperatures at the top and bottom of the pipe
4. adiabatic at the concealed groove
5. constant thermal conductivity throughout the pipe

The assumptions results in a two-dimensional conduction equation written in cylindrical coordinate as

$$\frac{1}{r^2} \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} = 0 \tag{1}$$

B. C. $\frac{\partial T}{\partial r} = 0$ at $r = 0$

$$\frac{\partial T}{\partial z} = 0 \text{ at } z = 0$$

$$T = T_1 \text{ at } z = 0$$

$$T = T_2 \text{ at } z = Z \text{ for non-hole}$$

$$\frac{\partial T}{\partial z} = 0 \text{ at } z = Z \text{ for hole}$$

For the computational simplicity the pipe is separated into four sections by halving in both r and z directions. The cross point of two dividing lines passes the center of the groove. The boundary conditions are for the top section of left half of the pipe, and the origin is the top front corner of the section. The first two boundary conditions are of

symmetry. The conditions in z-direction are the constant temperature assumptions except the groove being adiabatic.

For the simplicity of analysis, the equation is rewritten in dimensionless form.

$$A^2 \frac{1}{r'^2} \frac{\partial^2 T'}{\partial r'^2} + \frac{\partial^2 T'}{\partial z'^2} = 0 \tag{2}$$

where the primes indicate the dimensionless variables as below.

$$T' = \frac{T - T_2}{T_1 - T_2},$$

$$r' = \frac{r}{R},$$

$$\theta' = \frac{\theta - \theta_2}{\theta_1 - \theta_2},$$

$$z' = \frac{z}{Z}$$

and

$$A = \frac{1}{R} \frac{Z}{R}$$

In the formulation of finite difference equation from Eq. (2), a two dimensional rectangular grid is employed. The finite difference equation derived from Eq. (2) is

$$A^2 \frac{1}{r'^2} \frac{T'_{m+1,n} - 2T'_{m,n} + T'_{m-1,n}}{\Delta r'^2} + \frac{T'_{m,n+1} - 2T'_{m,n} + T'_{m,n-1}}{\Delta z'^2} = 0 \tag{3}$$

The equation is applied to the inside nodes of the grid leading to a set of simultaneous equations which is solved to find temperature distribution. A matrix of coefficients is formulated from the set of simultaneous equations, and its inversion is directly computed using MATLAB.

The computed temperature distribution is of the upper left section having the boundary conditions of Eq. (1). Similarly the boundary conditions for the lower left section of the plate are formulated to derive a set of simultaneous equations using Eq. (3), which is also solved with matrix inversion. Then the solutions of the upper and lower sections are combined, and the temperature distribution of the right half of the plate is yielded using the symmetry of temperature distribution.

3. EXPERIMENTAL

3.1 Preparation of sensor module

The infrared sensor (Heimann Sensor GmbH, Germany, Model 3129) used in this experiment has a circular window of 2.5 mm in diameter detecting temperature. Five sensors are installed at the left end of the sensor module. The module has five sets of amplification circuit. The circuit has a variable resistor for the adjustment of base signal output. The sensor has an internal thermistor for temperature compensation.

Whereas the sensor case is 8.2 mm in diameter, the temperature detection window is only 2.5 mm leaving too much space between actual measurement positions. In order to reduce the distance, an optical fiber (Mitsubishi Rayon, Japan, SK-10) lead is attached. The 7 wires of the 1 mm fiber make a 3 mm circular window for each sensor leaving 1 mm space between the sensing windows. The 5 detection windows are placed in a vertical row, and the top and bottom of the windows two sets of rolls are installed. During measurements the rolls contact on the surface of the pipe maintaining the distance between the pipe and sensor window.

3.2 Experimental setup

The sample pipe described in the previous section is placed in the middle of experimental setup shown in Fig. 2. In order to obtain a uniform temperature distribution in the pipe an aluminum plate of 1 cm thick holding three electric rod heaters is placed on top of the pipe. The heater is 6 mm in diameter and 5 cm long of which heat generation is adjusted by controlling supply voltage with a sliders. In addition, a shallow container of cooling water is placed at the bottom of the pipe. The cooling water of 15 °C from a water circulation bath (Daeil Engineering, Korea, Model DTC-312) is supplied to the container and recycled. The whole system of the sample pipe, heater and cooler is placed on a turn table. The reference temperatures at the top and bottom ends of the plate are measured with a thin wire thermocouple and a temperature indicator. The IR sensors are calibrated with the thermocouple temperature measurement on other sample pipe heated using an electric rod heater.

While the sensor module is stationary, the sample pipe rotates manually. The rotating angle is monitored with a wheeled potentiometer as described in Fig. 2. The amplified voltage signal from the sensor module and the signal produced from the rotation detection circuit are fed to a PC through an A/D converter.

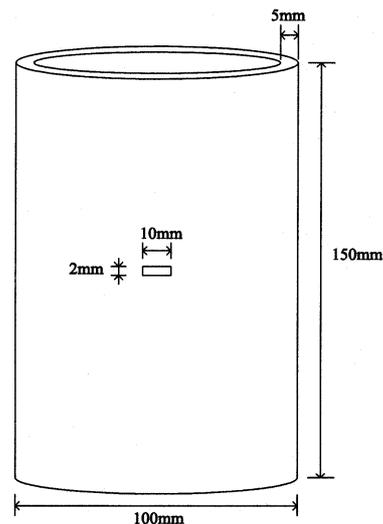


Fig. 1. Dimension of an aluminum pipe with a groove.

3.3 Experimental procedure

The experiment begins with supplying cooling water, and the heater is activated. In order to obtain a uniform temperature distribution on the sample plate in steady state, the heat supply and cooling are maintained with constant heat supply and cooling for an hour. During the period the temperature distribution on the plate is examined with a portable IR thermometer (Raytek, U. S. A., Model Raynger IP-K) for reference. When the distribution is stabilized, the turn table holding the sample pipe rotates at the speed of 30 degrees per minute and the data of temperature and sample rotation are fed to the PC. The data are stored during the measurement and retrieved for processing after the experiment.

4. RESULTS AND DISCUSSION

For the performance evaluation of the proposed detection device, two different settings of temperature distribution in the sample pipe were applied and the surface temperature was measured while it rotated. Fig. 3 shows the results of temperature measurement of the sample pipe having top end temperature of 95 C and bottom end temperature of 40 C. The numbers on the curves are sensor position counted from the top. Because the sensor 3 passes the concealed groove, it shows temperature decrease in the middle of the curve while other curves do not. This outcome clearly indicates that there is a temperature variation at the position of sensor 3 implying the existence of defect.

The experimental measurements are compared with the computational outcome of temperature distribution illustrated in Fig. 4. The numbers on the curves are normalized temperatures. The distribution is horizontally uniform except the center where the groove locates. Because no conduction occurs at the place, higher temperature gradient than other locations is observed and a large temperature drop across the groove is shown. The measured temperature at the position also indicates the temperature decrease like the computational outcome. This comparison of measured and computed temperatures was conducted with a rectangular plate, and a similar outcome was yielded [8]. For further performance evaluation, the experimental measurement was conducted with a different temperature profile in the sample pipe. The top end temperature of the plate is 110 C and the bottom end is 50 C. Again, the sensor 3 shows the same temperature variation at

the middle of the pipe as seen in Fig. 3 whereas rest of the sensors indicate no significant temperature fluctuation.

A similar application and analysis of IR thermometer defect detection device has been conducted with a metal plate [8]. The device is modified by attaching an optical fiber lead at the front of the IR thermometer. Placing the leads in a close row reduces the distance between sensors resulting denser scanning than the previous study. It eliminates the skipping possibility of detection from passing a defect between the sensor windows. One other improvement is maintaining a constant distance between the surface of measuring object and the tip of the optical fiber lead to yield stable temperature measurement. Comparing the outcome of temperature measurement with the previous one demonstrates the improvement. Because most of vessels and piping systems in chemical processes are cylinder shape, the proposed device is better to be utilized than the sensor module of the previous study.

In practical applications the temperature of a metallic object is often high enough, and therefore no external heating is necessary like this experiment. This gives convenience to utilize the proposed sensor system. Current techniques of nondestructive defect detection require total shutdown of a process to inspect vessels or reactors, which limits the application of the techniques.

CONCLUSION

A thermographic device for the detection of a groove in metal plate is modified to use in cylindrical objects. For the easy adjustment of sensor-object distance, an optical fiber lead is attached to the sensor window and rolls are installed on the sensor module maintaining the distance constant.

The temperature measurement results indicate that the modified device yields not only the location of the simulated defect but more stable measurement than the previous thermographic sensor. It is also shown that the measured temperature distribution is comparable to the calculated distribution. Because the proposed device is developed to detect defects in a cylinder, its wide application in chemical processes—in which most of vessels and piping systems are cylindrical shape—is expected.

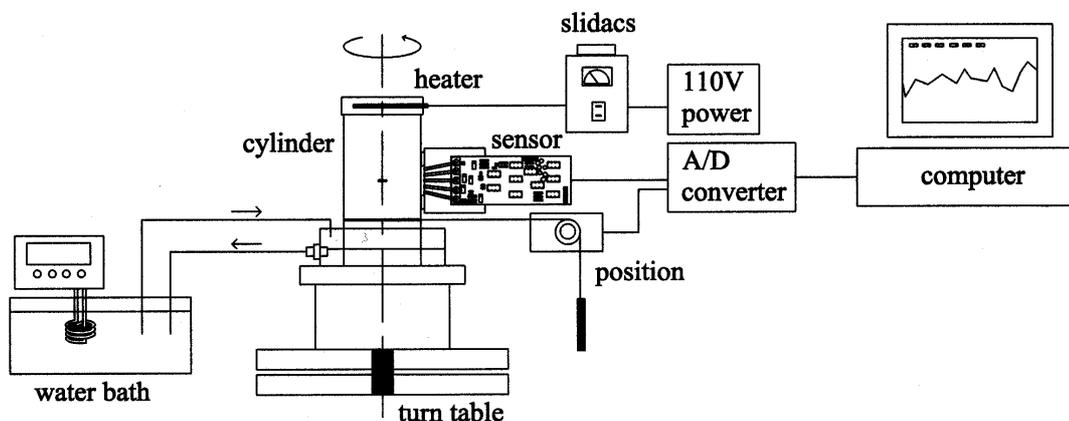


Fig. 2. A schematic diagram of experimental setup.

ACKNOWLEDGMENT

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NOMENCLATURE

- A = aspect ratio [-]
- T = temperature [°C]
- R = pipe radius [cm]
- r = radial coordinate [cm]
- Z = pipe length [cm]
- z = axial coordinate [cm]

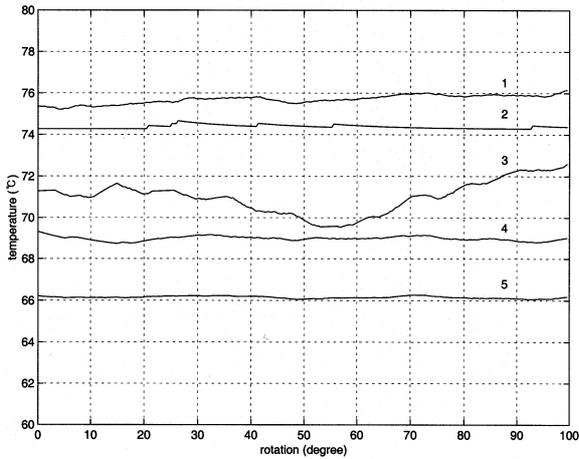


Fig. 3. Variations of measured temperatures in a low temperature pipe.

Greek

= angular coordinate [rad.]

REFERENCE

- [1] B. C. Kim, Y. H. Kim, J. S. Han, "A low-cost thermographic device for the detection of concealed groove in metal plate," *Sens. Actuators A*, vol. 118, no. 2, pp. 248-253, 2005.

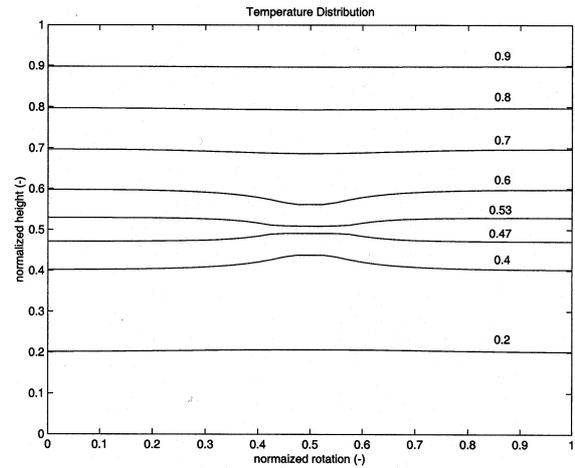


Fig. 4. Computation result of normalized temperature distribution.