

Development of exothermic system based on internet of things for preventing damages in winter season and evaluation of applicability to railway vehicles

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Abstract. Gravel scattering that is generated during operation of high-speed railway vehicle is cause to damage of vehicle such as windows, axle protector and so on. Especially, those are frequently occurred in winter season when snow ice is generated easily. Above all, damage of vehicle windows has not only caused maintenance cost but also increased psychological anxiety of passengers. Various methods such as heating system using copper wire, heating jacket and heating air are applied to remove snow ice generated on the under-body of vehicle. However, the methods require much run-time and man power which can be low effectiveness of work. Therefore, this paper shows that large-area heating system was developed based on heating coat in order to fundamentally prevent snow ice damage on high-speed railway vehicle in the winter season. This system gives users high convenience because that can remotely control the heating system using IoT-based wireless communication. For evaluating the applicability to railroad sites, a field test on an actual high-speed railroad operation was conducted by applying these techniques to the brake cylinder of a high-speed railroad vehicle. From the results, it evaluated how input voltage and electric power per unit area of the heating specimen influences exothermic performance to draw the permit power condition for icing. In the future, if the system developed in the study is applied at the railroad site, it may be used as a technique for preventing all types of damages occurring due to snow ice in winter.

Keywords: brake cylinder; deicing technology; multi-layered paint-type exothermic coating; railway site; snow ice

1. Introduction

Across various social infrastructures, winter freezing incidents frequently occur (Kim and Cho 2017, Russell *et al.* 2018). In daily situations, ice occurs on sidewalks and stairs, which can cause falling, and icicle on buildings leads to safety accidents. Meanwhile, snow ice on airplanes occurs due to vapor contact during flights in the atmosphere and on airports due to heavy snow in winter (Karlsson *et al.* 2019). Snow ice may interrupt fluid flux while an airplane takes off, influence lift force, and threaten passengers' safety, so it must be removed before an airplane takes off. Moreover, black ice on roads occurs because of thin snow ice or snow in cracks of asphalt becoming ice, serving as a factor of traffic accidents (Han *et al.* 2006). In the case of railroads, snow ice occurring on railroad turnouts and lower parts of high-speed railroad vehicles is related to train accidents during operation (Cho 2016, Kim *et al.* 2017). Thus, snow ice is one of the main targets of winter maintenance by the railroad operation organization. Ice on lower parts of high-speed railroad vehicles drops due to vehicle vibration during operation, leads to gravel

scattering, and damages windows and protection material of vehicle axis. Damages on railroad vehicles incur more costs for changing breakdown parts and additional losses like sales loss due to the interrupted operation of vehicles. Among these situations, vehicle window damage in particular may make passengers emotionally anxious and become the main reason for the drop in the reliability of the operation organization. To prevent this, methods for removing snow ice include electrothermic system using copper wire, heating jacket, deicing with heat wind, and other related methods (Wang *et al.* 2018, Nilsson *et al.* 2019, Park *et al.* 2019). Note, however, that these are not efficient for large-area icing, taking a lot of time and depending on man power. Spraying deicing solution or warm water is one of the high-efficiency methods but is effective only for a short period of time, possibly giving rise to additional problems like freezing of remaining moisture and flow of moisture to electric devices. Furthermore, that the methods above are applied only during maintenance at a vehicle garage after operation, so there are basic limits in preventing real-time icing during vehicle operation. Therefore, there must be new methods to the real-time prevention of snow ice occurring during vehicle operation in winter.

Conventional deicing methods like deicing with heat wind and heating jacket use heat elements based on heat wires to heat air and remove ice (Lee *et al.* 2013, Ikeya *et*

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al. 2017). Line heating may cause heat wire shortage and fire, thereby requiring attention. Moreover, large-area heating requires a system designed considering the allowance power of heat wires, so it is hard to apply to a more complexed target. Therefore, area heating element that addresses the disadvantages of lineal heating element and reduces power consumption to 20~40% is being developed actively nowadays (Yoo *et al.* 2009). Most area heating elements can be flexibly applied in complex form, having the characteristic of conducting electricity on the area. Among surface heating elements, carbon-based heating element is a representative element and is developed in many forms like carbon fiber embedded pad and nano-based complex material (Bhattacharyya *et al.* 2007, Yang *et al.* 2016, Jayathilake *et al.* 2019, Yang *et al.* 2019, Arun *et al.* 2019, Kim *et al.* 2021). For example, application researches are widely conducted to protect social infrastructure and infrastructure from snow ice occurrence in winter at industrial sites.

Meanwhile, with the advent of the 4th industrial revolution, rapidly developing IoT (Internet of Things) and ICT (Information and Communications Technologies) techniques are largely impacting various fields including structural health monitoring (Ashima *et al.* 2021, Fatima *et al.* 2021). By combining wireless communication and sensor techniques (Guo and Li 2013, Li and Wang 2018), structures are monitored in real time and applied to system-automated maintenance of structure by feedback process. Especially, the technique above may be widely applied to remote sites that cannot be inspected directly by a manager or to highly dangerous sites.

A carbon-based large-area heating element was manufactured to solve snow ice problems occurring at a high-speed railroad vehicle in winter and developed a technique of remotely monitoring temperature and controlling heat in this study. To test the developed technique, paint-type area heating elements were applied to a brake cylinder of a train by using nano material-sprayed solution; to evaluate the applicability of the technique, it was applied to an actual railroad operation environment by wireless communication-based remote control module.

2. Multi-layered coating structure

The general paint structure is composed of primer, surfacer, base coat, and clear coat in that order. Among the many painting methods, a hand-spray method was used to coat the heating solution, which is useful for many forms of multi-layered heating coat and can be applied in small amounts. Based on a painting structure applied to an actual vehicle as in Fig. 1 (Kim *et al.* 2019), a multi-layered coating specimen was manufactured by applying heating solution to the middle part.

Specifically, multi-layered heating coat specimen was manufactured with mild steel (SS400, POSCO Co.) for base material, primer (KR-NUD-105, PPG Co.), nano solution (ACR70, FutureCarbon Co.), base coat (KR-NUN-794S, PPG Co.), and top coat (KA-900HP, GANGNAM CHEM. Co.). The heating area measured 50 mm × 50 mm, and copper tape (1181, 3M Co.) of width 5 mm and 0.04 mm thick was attached between primer and nano solution to form an electrode for electrical power supply.

The exothermic performance of the heating coat changes depending on the sprayed area, thickness, and electric power supply. Therefore, exothermic performance evaluation is required; according to its result, area heating design is available considering the application environment and condition. By considering the required conditions according to the application environment, for exothermic performance index, two types were selected that are heating rate and temperature change at the point where the temperature was saturated (steady state). Heating rate was defined with the temperature change ratio increased for 4 minutes from initial heating, with the maximum increase temperature drawn from the difference between the initial temperature and maximum heating temperature of specimen.

To evaluate the exothermic performance of the heating coat, a heating specimen (60 mm × 60 mm × 3 mm) was manufactured, and its composition was examined as in Fig. 2. The experiment used an environment chamber (TH-KE, JEIOTECH Co.) to recreate the surrounding temperature of -20 °C considering the climate condition in winter.

By using a power supply device (XFR100-12, Xantrex Co.), 4 types of voltages (6, 12, 18, 24 V) were supplied to

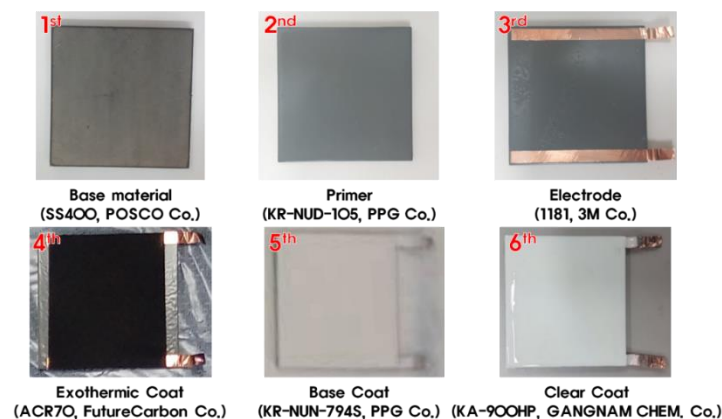


Fig. 1 Configuration of exothermic coating on base material

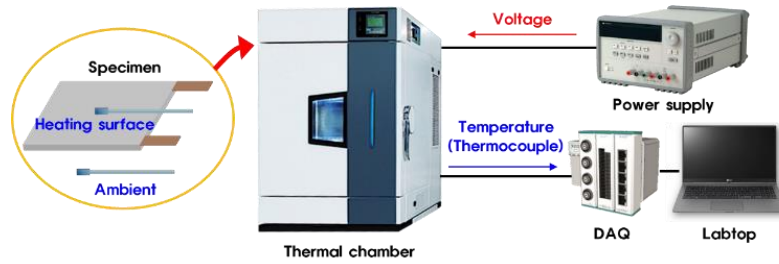


Fig. 2 Experimental setup for electrical and exothermic performance test exposed to periodic thermal cycles

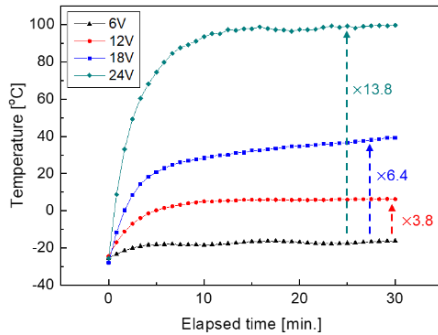


Fig. 3 Result of exothermic performance test with voltages

the heating specimen. To evaluate exothermic performance depending on input voltages, thermocouple (T-type) was attached to the center of the specimen surface, and DAQ (NI9213, National Instrument Co.) was used for measuring temperature with 1 S/s [Hz] sampling.

As a result, the heating specimen tended to increase in temperature sharply and then keep it constant as in Fig. 3, and its heating temperature increased as the input voltage increased. Exothermic performance drawn by using heating temperature data increased in quadric function according to input voltage as shown in Fig. 4. This can be understood through the relationship between the general heating amount and power amount expressed in Eq. (1).

$$Q = \int_t c_p m \cdot dT(t) \propto q = \int_t \frac{V^2}{R} \quad (1)$$

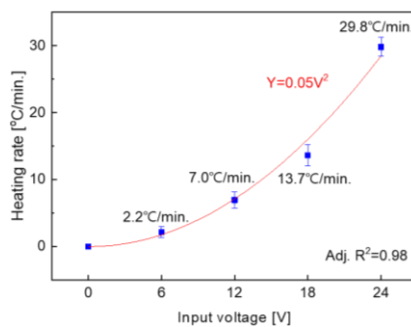
where, c_p is specific heat capacity, m is mass, ΔT is the amount of temperature change, q is electric power, V is

input voltage, R is the resistance of heating coat, and t is the heating time.

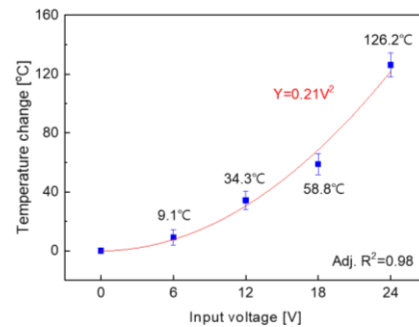
Specifically, as shown in Fig. 4(a), heating rate increased by 3.2 times more than the 6 V case when 12 V was supplied and by 13.8 times more than the 6 V case which was more than 30°C/min in condition of 24 V input. In addition, as shown in Fig. 4(b), the maximum increase temperature changed 3.8 and 13.8 times more than the 6 V case in condition of 12 V and 24 V input case, respectively. The study confirmed the relationship between exothermic performance and input voltage by Joule’s heat effect like Eq. (1) (Redondo *et al.* 2018).

Moreover, if temperature condition in winter is -20°C, to remove snow ice, more than 3 kW/m² of heating performance, in other words, more than DC 12 V of input voltage is necessary.

Based on the results, the study searched for a reasonable target to apply the technique for solving snow problems occurring at actual railroad vehicle sites in winter. Hydraulic line freezing occurs due to the inflow of moisture or snow ice in winter on the brake cylinder installed at a high-speed railroad vehicle, which causes problems in the brake system. Therefore, to fundamentally solve basic conventional problems at the brake cylinder, the study applied the developed large-area heating technique to the brake cylinder. Considering the performance acting condition of the deduced heating coat, heating paint was sprayed on the surface of the brake cylinder (CK10-90, YUJIN Machinery Ltd.) for high-speed railroad vehicle (KTX-Sancheon) as in Fig. 5. A heating paint layer was formed inside a conventional paint structure, so there was no exterior change before and after applying heating paint. Heating elements were sprayed on a width of 80 mm on a 50% area in the circumference direction of the head part of



(a) Heating rate with input voltages



(b) Temperature change with input voltages

Fig. 4 Exothermic performances of exothermic specimen based on mild steel

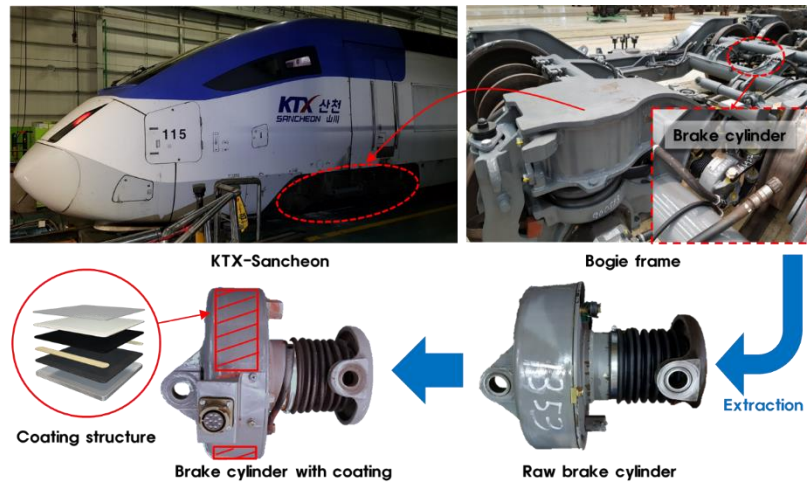


Fig. 5 Brake cylinder based on exothermic coating for exothermic system

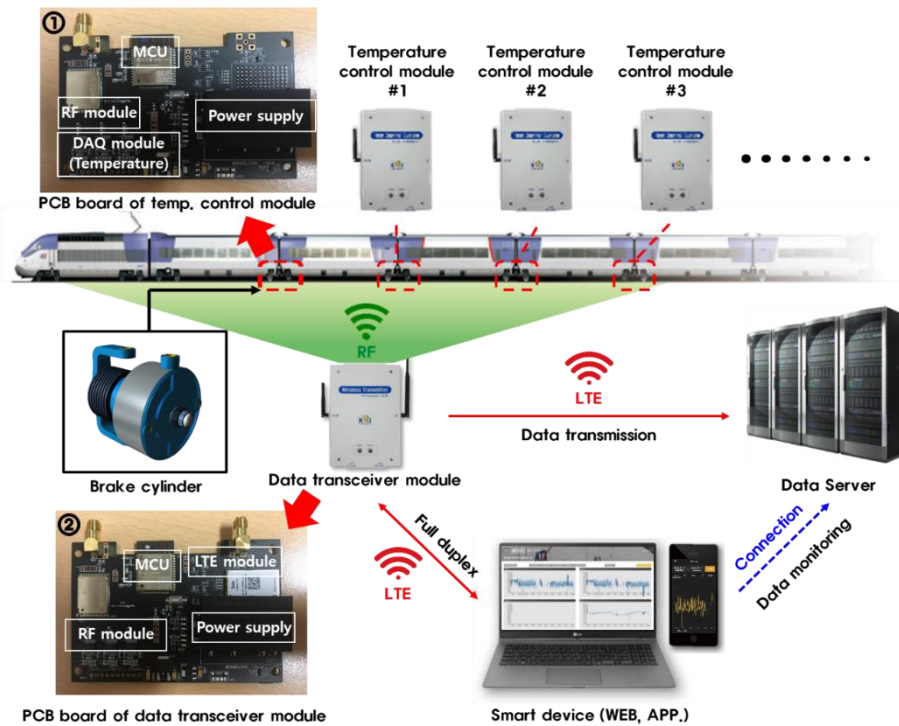


Fig. 6 Applications on various field using the exothermic system

the brake cylinder, which had a diameter of 250Φ and a width of 110 mm.

3. IoT-based temperature control

A high-speed railroad system operating at maximum speed of 300 km/h is controlled in real time at the central train control (CTC) with many operations information like the location of all trains. Therefore, the operation state of all systems installed on vehicles is managed at once at CTC, so it is also necessary for the technique of the large-area heating system developed in this study. To do so, a remote control technique for a large-area heating system with wide band communication technique is required, including

an efficient local communication technique-based data management technique between each unit considering the characteristic of high-speed train system of having 10 to 20 compartments as 1 unit.

Above all, to control the temperature of a constant heating area formed on each vehicle, a temperature control module (Fig. 6①) was developed that could measure the temperature of heating area and control electrical power supply. A local communication module was embedded in a temperature control module to provide temperature data in real time. The temperature control module installed in each vehicle communicated with the data combined module composed in one for a vehicle unit, and the gathered data was connected to a server in the remote central train control. As shown in Fig. 6②, it shows the data transceiver

module that combines local data and wide band communication.

Specifically, a temperature control module can set the target temperature of the heating element and temperature data cycle. A temperature sensor for temperature data measurement uses a K-type thermocouple. Likewise, through an RF (radio frequency) communication modem (A3025M, AUTOMAN Co.) embedded together, data transmission and reception and full duplex are available. RF communication uses 424.7 MHz frequency and has -118 dBm reception sensitivity and 2 km transmission and reception performance based on exposed state, so there are no problems in communication in unit of high-speed railroad vehicle within a maximum of 400 m.

Meanwhile, the data transceiver module builds a 4G band communication network by applying an LTE communication modem (LE866A1-KK, Telit Co.). Using this, a temperature control module installed at each vehicle acts as a repeater that combines a lot of data and transmits (uplink: 5 Mbps, downlink: 10 Mbps) to a remote data server.

On the other hand, a remote data server (NUC Kit NUC7i7BNH, Intel Co.) stores temperature data, so a user can check the temperature and heating control state upon logging. In addition, it has a mobile APP-based user

environment for users to control the system easily in a mobile environment such as mobile phone and tablets. A mobile APP was developed based on android by using Java software; it could set the operation condition of a temperature control module, and it had a function of monitoring the temperature data stored in a data server.

4. Applicability of exothermic system

4.1 Performance evaluation

The experiment was conducted by using an environment chamber as in Fig. 7 to evaluate exothermic performances in winter on the brake cylinder with heating coat applied. Specifically, a brake cylinder with heating coat applied was put in the chamber and cooled until -20°C to check the highest temperature available by supplying DC 24 V voltage. The temperature was then set at 10°C to see whether the heating area was controlled by temperature. Temperatures were measured using a thermocouple to compare the temperature change per location after measuring the heating surface, non-heating surface, and surrounding temperature at intervals of 3 seconds.

As a result, it took 3.3 hours (3 hours and 20 minutes)

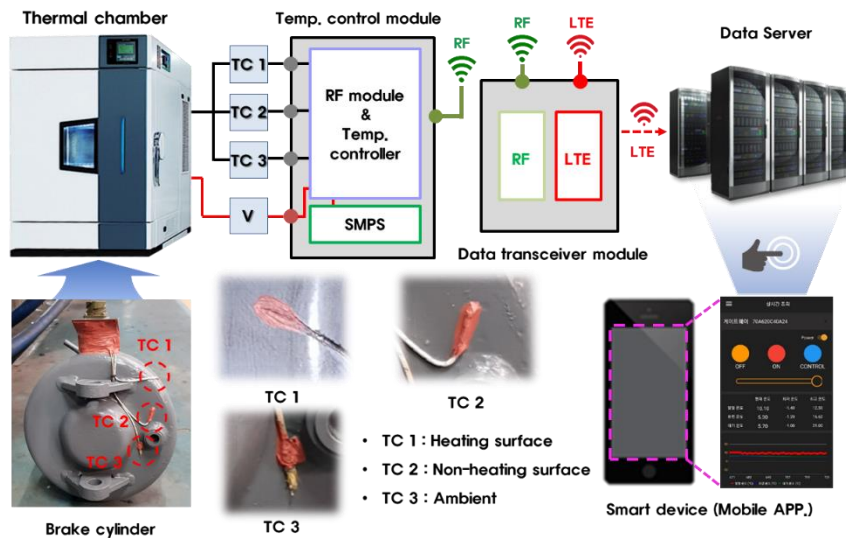


Fig. 7 Experimental setup for evaluating performance of exothermic system using thermal chamber

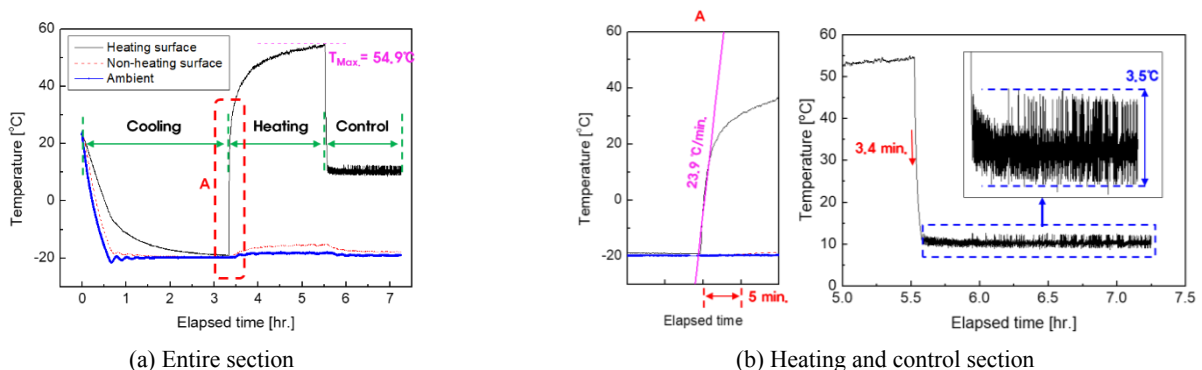


Fig. 8 Experimental results for evaluating performance of exothermic system using thermal chamber

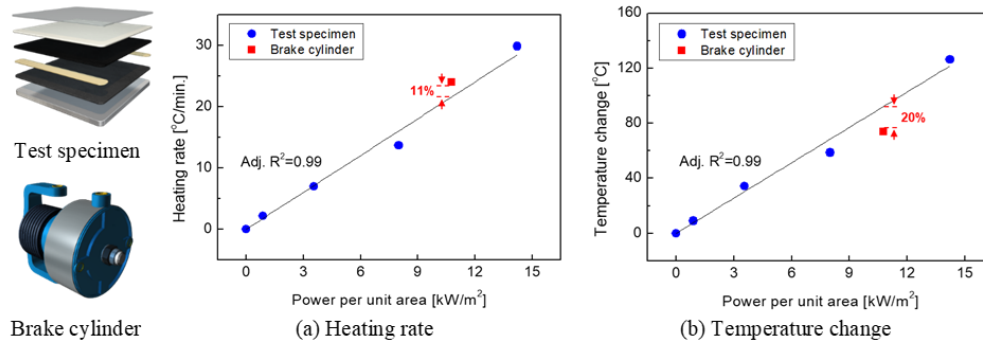


Fig. 9 Exothermic performance with input power per unit area of exothermic coating in brake cylinder

for the surface temperature of the brake cylinder to freeze to -20°C from room temperature as in Fig. 8(a). Then like area A of Fig. 8(a), after forcibly heating to 24 V, the heating rate became $23.9^{\circ}\text{C}/\text{min}$; after 5 minutes, the heating surface temperature of the brake cylinder became approximately 30°C or more. After 2.3 hours (2 hours and 20 minutes), the temperature increased to 55°C . The temperature of the non-heating surface was measured as approximately -15°C , and the surrounding temperature of the brake cylinder changed by 2°C to approximately -18°C . Temperature control was conducted after a forcible heating and cooling process to 10°C as in Fig. 8(b), which took 3.4 minutes. At the temperature-maintaining interval, temperature instantly increased by 2.5°C compared to the set temperature. Temperature increase and decrease repeatedly occurred after cooling by external convection. Change in temperature increase and decrease occurred in a 3-second period similar to the controlling time, shown as approximately 3.5°C temperature range based on 10°C .

To analyze the exothermic performance of the heating elements applied to the brake cylinder, brake cylinder performance was compared with the evaluated specimen like Eq. (2) and analyzed by using indexes such as power supply and heat flux related to heating area similar to the specimen.

$$q'' \propto \frac{V^2}{R} \cdot \frac{1}{A} \quad (2)$$

where, q'' is the heat flux, A is the heating area, and R is the resistance of heating coat.

By considering specimen resistance (16.2Ω) and heating material resistance (1.7Ω), and after analyzing heat flux according to the electric power per unit area, exothermic performances changed linearly as in Fig. 9.

The electric power per unit area of brake cylinder was approximately $10.8 \text{ kW}/\text{m}^2$; as a result of comparison, exothermic performance turned out to have a margin of error of 11% ($23.9^{\circ}\text{C}/\text{min}$.) for heating rate and 20% (73.9°C) for maximum increase temperature. Such margins of error were believed to have been influenced by the characteristic of the brake cylinder, which had larger mass and more complex structure compared to the specimen above. Note, however, that the performance of the brake cylinder in Fig. 9 generally followed the result of the specimen.

Based on the results above, the brake cylinder applied with heating coat was heated to 20°C for 1 minute after supplying DC 24V, and its surface temperature rose from 0 temperature to approximately 55°C . Therefore, heating coat sufficiently removes and prevents snow ice on the brake cylinder.

4.2 Field test in a railway vehicle

In the preceding section, the heating coat applied to the brake cylinder was shown to be applicable to the technique for removing and preventing snow ice through exothermic performance evaluation. In this section, field test was conducted to check the applicability of the developed techniques at an actual high-speed railroad environment. Specifically, a brake cylinder with heating coat applied was installed on the lower part of a high-speed railroad vehicle, and a heating test was performed during vehicle operation in a heavy snow situation in winter. The temperature of the brake cylinder was controlled based on 10°C while operating a high-speed railroad vehicle, and the state of brake cylinder was checked by using an infrared thermal camera (TESTO 882, TESTO Co.) after the vehicle finished operation and returned to a garage. As a result, snow ice occurred on the surfaces of two brake cylinders located on both sides with no heating coat, but snow ice was completely removed through heating on the center brake cylinder with heating coat applied as shown in Fig. 10. In addition, the surface of the cylinder was maintained at 10°C for a long period of time, so there was no remaining moisture. As a secondary effect of environmental temperature change, the hydraulic line with no heating coat was also in a good state to prevent ice. The infrared thermal image showed that the temperature of the non-heating area was approximately 0°C , and the brake cylinder with heating coat applied maintained a temperature higher than the set temperature of 10°C , i.e., approximately 11.6°C . Therefore, the heating coat applied to the brake cylinder is efficient in removing snow ice, and it can prevent icing accidents while operating in heavy snow.

5. Conclusions

The study developed a large-area heating technique to solve the snow ice occurring on the railroad vehicle in

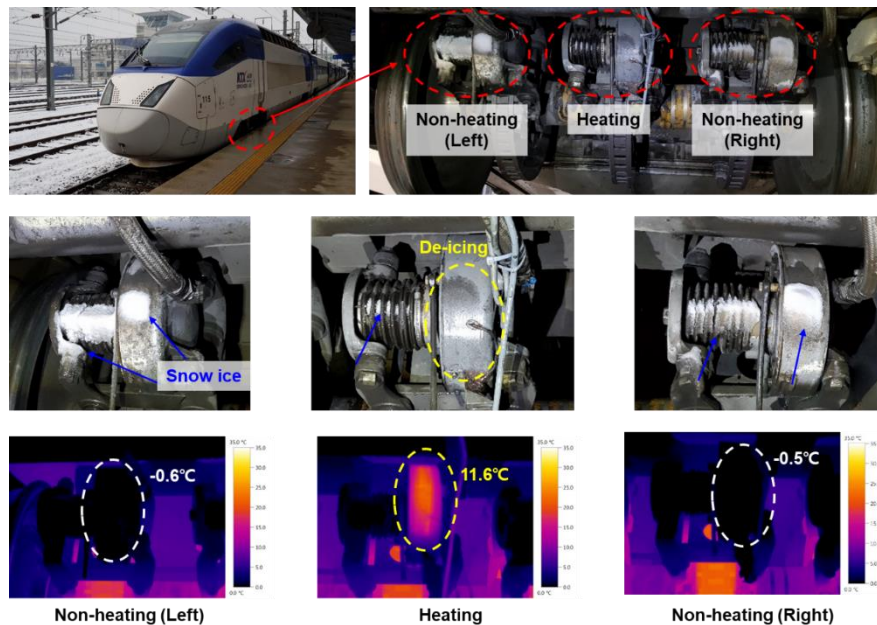


Fig. 10 Photographs and infrared thermal image of icing and de-icing regions on brake cylinder

winter and a heating system technique for real-time temperature control and monitoring with wireless communication. Moreover, a field test on an actual high-speed railroad operation was conducted by applying these techniques to the brake cylinder of a high-speed railroad vehicle to check the applicability to railroad sites. The following conclusions were drawn:

- It evaluated how input voltage (quadratic function) and electric power per unit area (linear) influence exothermic performances of the area heating specimen to draw the permit power condition for icing.
- It developed the wireless communication temperature control module and data transceiver module available for heating control and temperature monitoring. Additionally, it made available a mobile APP based on the user environment for easily controlling the system in a mobile environment such as mobile phone and tablet.
- It verified the feasibility of the technique of preventing snow ice by combining the area heating technique and wireless communication module to apply it to a high-speed railroad brake cylinder, evaluating its performance, and conducting field test on actual high-speed railroad operation.
- However, it is necessary to develop an insulation technology for preventing electrical shock, and the additional future work would be required for applying this system to operation lines.

In the future, if the large-area heating system developed in the study is applied at the railroad site, it may be used as a technique for preventing all types of damages occurring due to snow ice in winter.

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