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A Study on Thermal Characteristics of Carbon-Organic Surface Heating Element with Electrodeless Lamp of a Freezer

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냉동고 무전극램프 적용 탄소-유기소재 면상발열체의 열 특성에 관한 연구

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ABSTRACT

This study deals with the fabrication and thermal characterization of planar heating elements attached to the backside of the reflector used in the electrodeless lamp of a freezer. We tried to solve the problem of the local heat generation of the linear heating element that occurs about 50℃. The homogeneous dispersion and manufacturing excellence of the planar heating element produced were confirmed through SEM and EDS. In addition, the test specimens was prepared according to the change in the ratio of carbon fiber to the basis weight of the planar heating element, and a sample having a basis weight of 50g/m^2 having a content ratio of carbon fiber of 70% was selected. That sample showed low surface resistance of 4.3Ω/sq and high temperature of about 81℃ at 6V. Durability was confirmed by performing repeated bending evaluation of 3000 cycles for the sample. Large area test specimens were prepared to be applied to the actual reflector, insulated by EVA film and analyzed for their thermal characteristics. From 13V application, the temperature of the linear heating element was higher than 50℃ and the average temperature of 68℃ was maximum at 18V.

Key Words : Carbon Fiber(탄소섬유), Surface Heating Element(면상발열체), Thermal Characteristics(열 특성), Electrodeless Lamp(무전극램프)

1. Introduction

Recently, the market and consumer demands for freezers and frozen warehouses are increasing due to the diversification of food culture. Electrodeless lamps are being used in these freezers and frozen warehouses. The electrodeless lamps, which are a type of lighting system, have excellent economic efficiency of operation and maintenance costs. Furthermore, electrodeless lamps allow workers to immediately start working by fast lighting, and provide the advantage that lamp replacement is unnecessary due to semi-permanent life.

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However, the electrolytic condenser does not work properly at low temperatures, and the characteristics change severely according to the environment, which affects the product performance. Furthermore, electrodeless lamps activate the internal gas through amalgam, and at high temperatures, the power consumption and optical power decrease in almost identical rates, while the optical power decreases more significantly at high temperatures[1~3].

To address this problem, in the case of existing products, linear heating wires with a temperature of about 50°C are used in reflecting plates inside lighting systems equipped with electrodeless lamps in freezers and low-temperature warehouses. However, in the case of linear-shaped lighting products, the heating wires should be repeatedly bent to transfer heat as evenly as possible inside the lighting system. This not only makes them difficult to manufacture, but also can cause the problem of local heat generation.

Therefore, this study fabricates a surface-heating element mixed with carbon fiber and organic composite, and selects the optical conditions by analyzing the surface resistance and thermal properties according to the carbon fiber content and the total basis weight of the surface heating element.

Furthermore, the robustness of the product against bending is analyzed through durability assessment. A large area sample is prepared and an insulating material is attached to the front surface of the surface heating element through autoclave molding.

Finally, the temperature level of the linear heating wire is satisfied by analyzing changes in thermal properties generated for the prepared samples. At the same time, the heat is generated evenly over the entire surface by improving the overall thermal uniformity. Through this process, the applicability of electrodeless lamps for the reflecting plate of the freezer is determined.

2. UV Thermal Imaging Theory

An object that completely absorbs infrared light and has an emissivity of 1 is generally referred to as a black body, and it has a larger radiant energy than any other object.

The relationship between the infrared radiation of a black body and temperature can be examined by the Planck law as shown in Eq. (1). However, commonly used objects are expressed as gray bodies, and most gray bodies have an emissivity of less than 1.0 [4~7].

Hence, the radiant energy at the absolute temperature T of a gray body can be obtained by substituting the emissivity of $0 < \varepsilon < 1$ in Eq. (1).

$$W_A = \frac{c_1}{\lambda}(e^{\frac{C_2}{\lambda T}} - 1)^{-1} \qquad (1)$$

W_A : Monochrome radiant emittance $[W/cm \cdot um]$
λ : Wavelength of Emitted Radiation $[um]$
T : Absolute Temperature of Black Body $[K]$
c_1 : 3.702 × 10 $[W \cdot cm^2]$
c_2 : 1.4388 × 10 $[cm \cdot K]$

Furthermore, the energy radiated to a hemisphere of a black body at the absolute temperature, T, can be obtained by integrating W_A from λ = 0 to λ = ∞ in Eq. (1).

Eq. (2) expresses the Stefan–Boltzmann law for calculating the total radiation from a black body with an area of 1 cm^2 in the hemisphere direction. This equation shows that the radiation energy is proportional to the four square of the black body temperature.

W_A is unrelated to the wavelength and is determined by the four square of the absolute temperature. Thus, the temperature of an object can be determined by measuring the radiation energy, W_A[8-11].

$$E_t = \sigma T^4 \qquad (2)$$

E_t : Radiant Energy $[W/m^2]$
σ : Stefan-Boltzmann's Constant $5.67 \times 10^{-8} Wm^{-2}K^{-4}$
T : Temperature $[K]$

In addition, lenses and infrared thermal imaging cameras manufactured on the basis of infrared theory and radiant energy characteristics detect infrared wavelength energy, which is a kind of electromagnetic waves emitted from the surface of the subject, and measure the intensity of radiant heat on the surface of objects. Each color can be expressed according to the intensity of radiant heat, providing the user with a visualized image, and can be output as temperature data [12~14].

3. Sample Fabrication and Test Method

3.1 Manufacturing surface heating element using carbon-organic materials

The carbon fiber used in the fabrication of surface heating elements made of carbon-organic materials is a short fiber with dispersion sizing of approximately 6-mm length and 8-um diameter, and the organic material polyethylene (PE) has 4-mm length and 10-um diameter. In addition, Xanthangum was used as a thickener to bind the two materials [15-17].

Furthermore, for the insulation material, a sheet-type ethylene-vinyl acetate (EVA) film with a vinyl acetate (VA) content of 33%, a thermal conductivity of $0.28\,W/m \cdot K$, and a thickness of 0.45mm was used.

Xanthangum is a hydrophilic polymer that has excellent reproducibility and is easy to manufacture due to the small amount of bubbles generated during manufacturing. The EVA film has excellent bending characteristics even after molding and is easy to use to implement shapes.

A total of 10 samples with the same ratios of carbon fiber and PE were fabricated: samples with the basis weights of $10g/m^2$, $20g/m^2$, $30g/m^2$, $40\,g/m^2$, and $50g/m^2$, and samples with carbon fiber contents of 30%, 40%, 50%, 60%, and 70% at 30 basis weight. In addition, a sample with the highest base weigh of $50g/m^2$ and the highest carbon fiber content of 70% was fabricated for each type.

Finally, a sample with the highest carbon fiber content for a large area was additionally fabricated. This sample was subjected to insulation molding and analyzed for changes in thermal properties.

For sample fabrication, the first dispersion was performed in distilled water with carbon fiber and PE fiber, respectively. Xanthangum was fully dispersed using an agitator for about 5 h at the rate of 600rpm at 50℃.

The second dispersion was performed in the mixture of dispersed carbon fiber, PE, and Xantahngaum. This mixture was flowed into a wet paper machine. Then the third dispersion was performed by adding distilled water at 0.8 bar vacuum pressure, during which Xanthangum was maintained at 20ppm.

After complete dispersion, the vacuum tank open/close valve was opened to flow the mixture into the tank. The surface heating element of a carbon-organic material bound by Xanthangum was filtered through 70 mesh dense round net. This was dried in an oven at 50℃ for about 1 h to fabricate 50mm*50mm samples.

3.2 Insulation material molding

The size of the surface heating element applied to actual reflecting plate was 200mm×300mm. The connection was implemented using a high-conductivity copper tape, and for insulation molding, one ply each of EVA film was attached to either side.

Molding was performed using an autoclave. For the molding conditions, considering the melting point of the EVA film, the temperature was rose to 110℃ for 30 min and maintained for 10 min. Then it was naturally cured for 30 min at -1 bar vacuum pressure of and 4 bar autoclave pressure of to finally fabricate the surface heating element.

3.3 Test method

The fabricated surface heating element of the carbon-organic material was subjected to SEM analysis using the CS-200TA model of COXEM Co., Ltd. (South Korea), to analyze the morphological arrangements and observe manufacturability. Furthermore, energy dispersive spectroscopy (EDS) analysis was performed for elemental analysis and impurity detection using the EAX model of METEK Co., Ltd. (Germany).

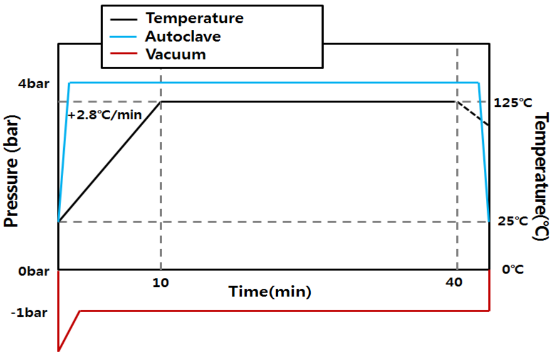


Fig. 1 Autoclave molding conditions

Fig. 2 EVA film forming of plane heating element using autoclave

The surface resistance was measured 10 times by the four-probe method using the MCP-T700 model of MITSUBISHI Co., Ltd. (Japan), and then the results were analyzed. The thermal imaging measurement was performed using A655SC of Flir Co., Ltd. (Germany), with a resolution of 640×480 LWIR, 17-micron pixels, and full frame 16 bits. For the 50mm×50mm sample size, the sample was attached to a jig produced using a 3D printer, and DC power of 1V to 6V was supplied.

For durability evaluation of the finally selected sample, repeated bending of 3,000 cycles was performed using the TS-150-MC model of Namil Optical Instruments co., Ltd. (South Korea). In addition, the large-area (200mm×300mm) heating element applied to reflecting plates before and after insulation and the existing heating cable were measured by mounting them on an insulation foam using the same thermal image camera at sequential voltages of 1V to 18V.

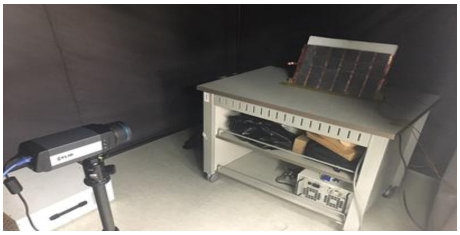


Fig. 3 Thermal image measurement of large area carbon planar heating elements

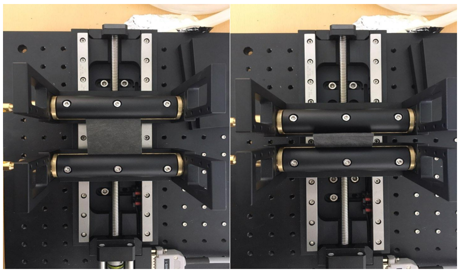
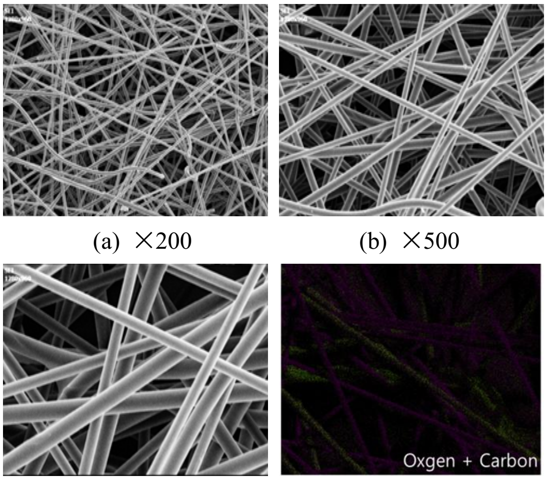


Fig. 4 Durability assessment through repeated bending test

Fig. 5 Thermal image measurement after attaching the reflector of planar heating element



(a) ×200 (b) ×500

(c) ×1,000 (d) EDS mapping image

Fig. 6 SEM and EDS mapping image of carbon plane heating element

Table 1 Results of surface resistance

Specimen Type	10 g/m^2	20 g/m^2	30 g/m^2	40 g/m^2	50 g/m^2
Surface Resistance (Ω/sq)	22.8	10.7	7.3	5.8	5.3
Specimen Type (Carbon : PE)	3 : 7	4 : 6	5 : 5	6 : 4	7 : 3
Surface Resistance (Ω/sq)	17.9	9.9	7.0	6.7	5.3

Finally, the back side of the reflecting plate used in the lighting systems of actual electrodeless lamps was insulated and attached with a type and then the front, which was black body-treated to improve emissivity, was measured. Sequential measurement and analysis was performed from 13V to 18V by reflecting the result values of the existing post-insulation type.

4. Results and Discussion

4.1 SEM and EDS analysis

The surface of the surface heating element of the carbon-organic material was observed through SEM. It was confirmed that carbon fiber and PE were uniformly dispersed throughout the surface of the heating element, and the pores of the heating element decreased as the basis weight increased. Moreover, it was confirmed that there was no abnormality in the manufacture of the surface heating element, with no element other than carbon and oxygen detected through EDS.

4.2 Surface resistance and thermal imaging of the basic sample

The surface resistances of the samples fabricated with different basis weights and ratios were measured using the four-probe method. The higher the carbon fiber content, the lower the surface resistance was measured. The samples of 50g/m^2 and 70% for basis weight and ratio with the highest content of carbon fiber showed the same values of 5.3Ω/sq. The surface resistance of the samples showed a low value, of 4.3Ω/sq.

The mean temperatures were measured by sequentially applying voltages of 1V to 6V to the 50mm×50mm samples at different carbon fiber contents and basis weights. The sample with a basis weight of 50g/m^2 and a carbon fiber content of 70% showed a high temperature of approximately 75℃.

Table 2 Results of average temperature according to basis weight

Specimen (g/m^2)	2V	3V	4V	5V	6V
	Avg Temp. (℃)	Avg Temp. (℃)	Avg Temp. (℃)	Avg Temp. (℃)	Avg Temp. (℃)
10	21.3	24.8	27.8	32.0	37
20	24.7	30.2	37.4	44.6	55.2
30	26.8	33.2	42.9	51.8	61.2
40	29	36.1	47.2	60.7	65.4
50	29.1	36.9	47.1	60.8	74.8

Table 3 Results of average temperature according to carbon fiber content

Specimen (g/m^2)	2V	3V	4V	5V	6V
	Avg Temp. (℃)	Avg Temp. (℃)	Avg Temp. (℃)	Avg Temp. (℃)	Avg Temp. (℃)
3:7	24.9	27.8	32.6	37.7	43
4:6	26.2	32.1	42.0	51.4	53.8
5:5	26.4	33.4	42.9	51.7	60
6:4	28.1	37.2	49	60.2	64.4
7:3	30.2	39.8	52	64.6	76.2

As with the surface resistance, the thermal imaging temperature was measured for the sample with basis weight of 50g/m^2 and a ratio of 70% with the highest carbon fiber content. The measured temperature was approximately 27℃ for 1V, 31℃ for 2V, 39℃ for 3V, 50℃ for 4V, 66℃ for 5V, and 81℃ for 6V. Thus, the higher the carbon content, the higher the temperature.

4.3 Durability evaluation by repeated bending

To evaluate the durability of the finally selected sample with a basis weight of 50g/m^2 and a carbon fiber content of 70%, 3,000 bending cycles at the moving rate of 1000 mm/min. Then the thermal properties when voltages of 1V to 5V were applied before and after the test were analyzed.

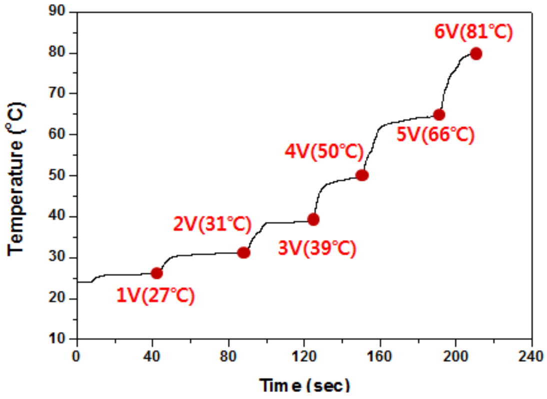


Fig. 7 Graph of average temperature (50g/m^2, 70%)

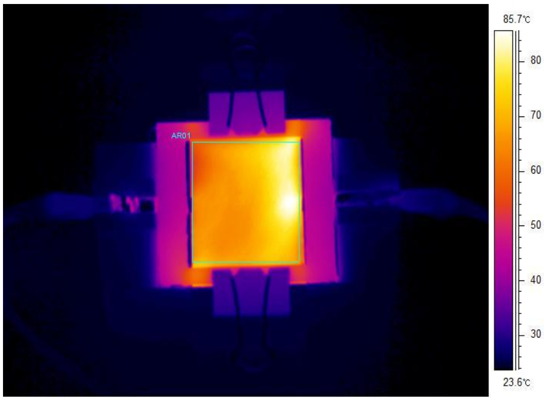


Fig. 8 Thermal image of average temperature (50 g/m^2, 70%)

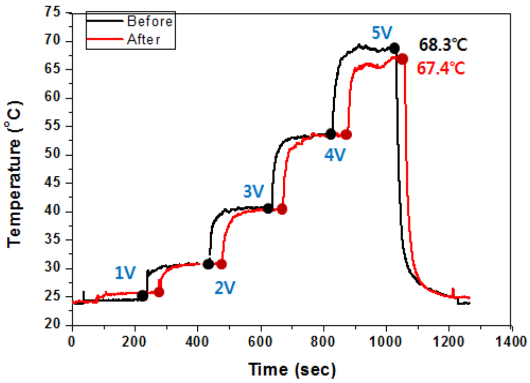
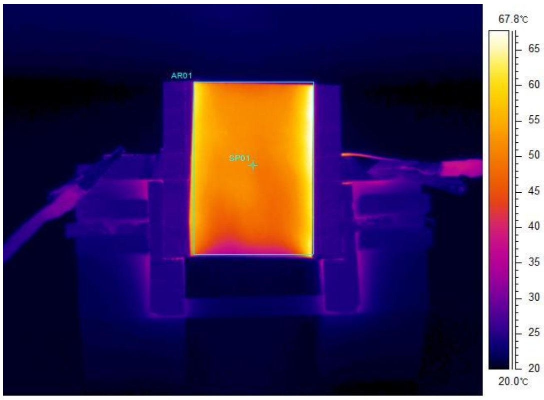
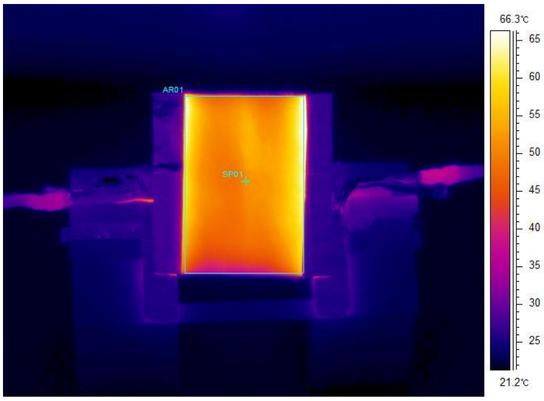


Fig. 9 Graph of average temperature results before and after bending test



(a) before



(b) after

Fig. 10 Thermal image of average temperature about before and after bending test

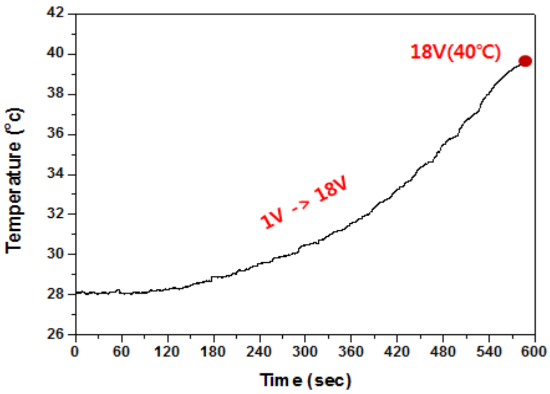


Fig. 11 Temperature result graph of large area heating element before insulation

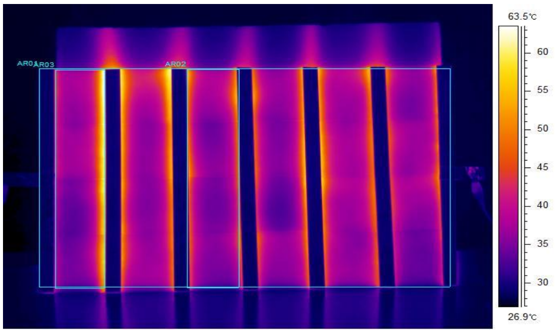


Fig. 12 Thermal image of large area heating element before insulation

The measurement result showed that almost no difference in mean temperature occurred and the temperature decreased by around 0.9℃ at 5V, suggesting durability for repeated bending. The thermal image showed that the temperature was slightly higher in the bending part than the other parts.

4.4 Thermal image measurement of large-area sample before and after insulation

The thermal properties of a 200mm×300mm large-area surface heating element, which is applicable to electrodeless lamp reflecting plate for freezers, using EVA before insulation (molding). The voltages of 1V to 18V were sequentially applied in 30-sec periods considering the rising resistance with the increasing sample size.

The mean temperature when 18V was applied was approximately 40℃, much lower than that of the 50mm×50mm sample. It is also lower than the currently used thermal wires (50℃).

Thus, to analyze the thermal properties after insulation, the same sequential voltages were applied in 400 sec period. The temperature rose above 50℃ from the moment that 13V was applied. When the final voltage of 18V was applied, the temperature was approximately 68℃.

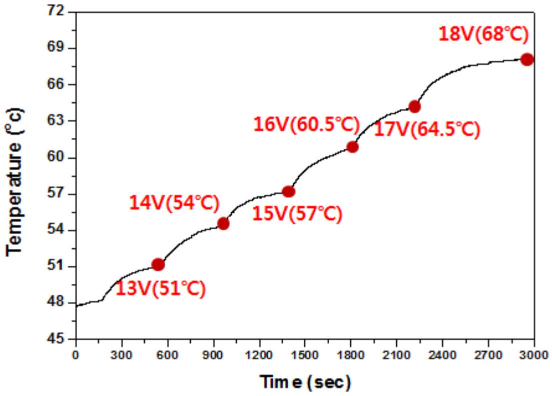


Fig. 13 Temperature result graph of large area heating element after insulation

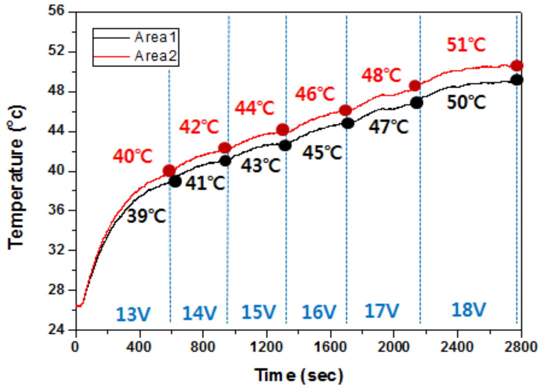


Fig. 15 Temperature result graph of after reflector attachment

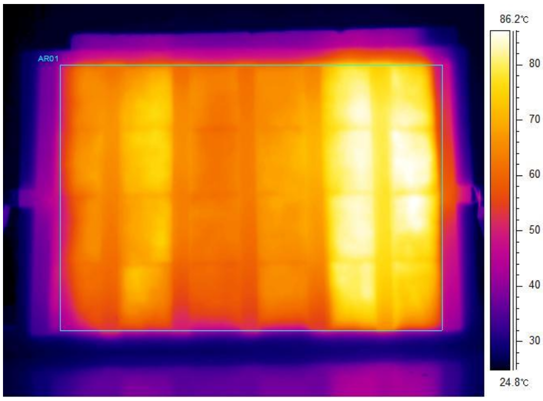


Fig. 14 Thermal image of large area heating element after insulation

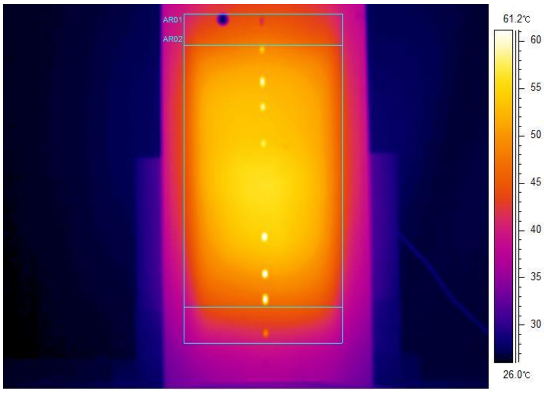


Fig. 16 Thermal image of after reflector attachment

4.5 Thermal image measurement after attaching reflecting plate for freezer electrodeless lamps

The insulated surface heating element was attached to the back of the reflecting plate for electrodeless lamps and the temperature properties transmitted to the reflecting plate were analyzed. The voltages of 13V (50℃) to 18V were applied, and Area 1 (200W-class lamp) and Area 2 (150W-class lamps) were analyzed separately according to the specifications of the attached lamp (attached positions are changed).

The analysis result showed a linear rising trend in mean temperature differences of around 1℃ from 13V to 18V. Finally, the temperature rose to around 50℃ in Area 1 and around 51℃ in Area 2. Thus, the temperature was higher in Area2, which has a smaller area, but the difference was small at around 1℃.

5. Conclusion

This paper fabricated a surface heating element attached to the back of reflecting plate used in electrodeless lamps for freezers and analyzed its thermal properties. We attempted to solve the problem of local heat generation of approximately 50℃ in existing linear heating elements.

1. The uniform dispersion and excellent manufacturability of the surface heating element fabricated through SEM and EDS were verified. Finally, a sample (50mm×50mm) with a carbon fiber content of 70% and a basis weight of 50 g/m^2 was selected. It showed a low surface resistance of 4.3Ω/sq and a mean temperature of 81℃ at 6V.
2. A repeated bending durability evaluation was performed for 3,000 cycles with the same sample. Thermal imaging indicated generation of a somewhat high heat where bending occurred, but the mean temperature difference was 0.9℃ at the maximum, suggesting excellent durability.
3. A large area (200mm×300mm) sample was fabricated for application to an actual reflecting plate, and the thermal properties before and after insulation were analyzed., As the sample size increased, resistance increased, and the voltage was sequentially applied up to 18V. The maximum temperature before insulation was 40℃, which is lower than the temperature of existing linear heating element before insulation.
4. After insulation, the compressed surface of the copper electrode and the surface heating element increased through the molding process, and the contact points between the PE fiber and carbon fiber increased. As a result, the temperature rose above 50℃, and the temperature of the existing linear heating element and the mean temperature rose to 68℃ at 18V. This result verified the possibility of using it at low temperatures in place of the existing linear heating wire.

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