HEAT STORAGE AND RELEASE CHARACTERISTICS OF CERAMIC-IMBEDDED WOVEN FABRIC FOR EMOTIONAL CLOTHING

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Abstract:

This study examined the heat storage and release characteristics of ZrC-imbedded woven fabrics by light emission and thermal manikin experiments. The surface temperature of the ZrC-imbedded fabric was higher than that of the regular PET fabric. Furthermore, the Clo values of both the total and torso of the ZrC-imbedded fabric by the thermal manikin experiment were higher than those of the regular PET fabric, which suggests that the heat release is caused by far infrared rays emitted from the ZrC particles imbedded in the yarns as they receive light. This was confirmed by the higher emissivity and emissive power of the ZrC-imbedded fabric. However, the tactile hand of the ZrC-imbedded fabric needs to be improved by adjusting the structural parameters of the fabric and finishing process factors.

Keywords:

conjugated spinning, heat storage and release, thermal radiation, far-infrared, Clo value

1. Introduction

The heat release property of fabrics used for warm-up suits has mainly been studied using three types of methods. Textile goods, such as Moiscare® (Toyobo) and Heattech® (Uniqlo), are made using the heat of wetting. Phase change materials (PCMs) undergo a change in physical state (liquid–solid) over a certain range of temperatures [5]. Therefore, nanocapsule PCM materials have been commercialized into different heat-release textile goods. In the recent years, Thermotron® (Unitika), Megatron® (Toray), and Reothermo® (Asahi Kasei) brands have been sold as fabrics composed of ceramic-imbedded yarns, which have the heat keepability as a result of their far-infrared emission characteristics. In previous studies [4, 7, 8, 9], the carbonized powder of the charcoal fibers was used to obtain the far-infrared emission characteristics [7]. On the other hand, Lin et al. [8] used Al2O3, TiO2, and SiO2 as ceramic powders for obtaining a far-infrared emissive polypropylene master batch. They reported the effects of the contents of the far-infrared master batches on the far-infrared emissivity using Al2O3, TiO2, and SiO2 ceramic powders. Kuo et al. [4] examined nanocomposite fiber process optimization for SiO2- and TiO2-imbedded polypropylene with antibacterial and far-infrared ray emission properties. They reported that the far-infrared ray emission of the SiO2- and TiO2-imbedded polypropylene fibers was 85%, and the temperature rise by far-infrared ray emission was 8.6°C, which was much higher than that of regular polypropylene fibers. Lin et al. [9] examined the far-infrared emissivity of PET filaments wrapped with bamboo charcoal nylon fibers. These studies investigated the far-infrared emissivity characteristics according to the contents of the different ceramic powders. Furthermore, the findings of these studies were focused on the far infrared emissivity and temperature rise because of the high far-infrared emissivity. On the other hand, the wear comfort properties, such as wicking, drying, water vapor permeability, and heat keepability rate, of the ceramic-imbedded yarns and their fabrics have been studied by many researchers. Furata et al. [2] reported an increase in the moisture permeability of the ZrC-imbedded PET fabrics. Bahng et al. [1] examined the superior moisture absorption and fast dry characteristics of the ceramic-imbedded PET fabrics, which were assumed to be caused by the rapid evaporation of perspiration from the human body by the heat produced from the ceramic-imbedded filament. Negish et al. [10] reported that the ZrC in the yarns absorbs the heat emitted from the human body and/or reflects far-infrared radiation, which prevents the heat from flowing out. Shim et al. [11] examined the heat-insulating water-vapor-permeable property of a warm-up suit with good thermal performance because of the application of ceramic powders. In addition, Kim et al. [3] reported the far-infrared emission characteristics and wear comfort property of ZrC-imbedded heat storage knitted fabrics for emotional garments. ZrC-imbedded PET was spun with high-viscosity PET imbedded with ZrC powder on the core part and low-viscosity PET on the sheath part by conjugated spinning. They measured the wicking, drying, and thermal properties of the knitted fabrics composed of this ZrC-imbedded yarn and compared them with the emissivity and emissive power of the ZrC-imbedded knitted fabrics. On the other hand, these studies did not provide objective measurement data of the fabric worn by a thermal manikin related to heat storage and release emitted from the ceramics imbedded in the yarns, that is, the heat keepability rate was only assessed by the fabric specimens. Therefore, a thermal manikin test as a quantititative evaluation of the actual wearing performance is required. In this study, ZrC-imbedded fabrics were prepared using the sheath/core composite yarns spun by a conjugated spinning and the temperature rise by heat emitted from ZrC in the yarns was measured using a light heat...
emission apparatus. In addition, a thermal manikin test was carried out, and the heat storage and release characteristics of the ZrC-imbedded fabrics were verified by the ClO value from the thermal manikin experiment. The results are discussed with the far-infrared emission property and compared with that of a regular PET fabric.

2. Experimental

2.1 Yarn preparation

ZrC-imbedded PET was prepared using a conjugated spinning method on a melt spinning pilot machine in Huvis Co. Ltd in Korea [3]. Partially oriented yarn (POY) 125d/36f with a low-viscosity PET on the sheath part and ZrC-mixed high-viscosity PET on the core part was spun on a bicomponent spinning machine. The spinning temperature was 285°C, and the spinning speed was 3000 m/min. The ZrC content in the yarn was 1.2 wt.%, which was mixed with high-viscosity PET at the core position in the extruder as a master batch chip. Figure 1 presents a schematic diagram of the conjugated spinning machine and cross section of the bicomponent yarn used in this study.

Figure 1. Schematic diagram of the conjugated spinning of ZrC-imbedded yarns

Table 1. Physical properties of the yarn specimens

| Specimens          | Specification | Measured yarn linear density (d) | Tenacity (g/d) | Breaking strain (%) | Initial modulus (g/d) | Thermal shrinkage (%) |
|--------------------|---------------|---------------------------------|----------------|---------------------|------------------------|-----------------------|
| ZrC-imbedded PET   | DTY 75d/36f   | 73.6                            | 4.368          | 48.9                | 10.2                   | 46.03                 |
| Regular PET        | DTY 75d/72f   | 73.8                            | 4.721          | 18.6                | 28.6                   | 12.71                 |

Table 2. Specification of the fabric specimens

| Specimens | Yarn linear density (d) | Warp | TPM | Fabric density | Thickness (mm) | Weight (g/in²) |
|-----------|------------------------|------|-----|----------------|----------------|----------------|
|           |                        |      |     | (ends/in) | (picks/in)    |                |
| 1         | 75d/72f PET SD         | 75d/36f ZrC-imbedded PET | 800  | 150          | 93             | 0.241          | 158          |
| 2         | 75d/72f PET SD         | 75d/72f regular PET       | 800  | 150          | 93             | 0.257          | 160          |
Figure 2. (a) Schematic diagram and (b) measuring images of the light heat emission apparatus

Figure 3. Prototype of the garments worn by thermal manikin. (a) Size specification and block patterns of the jacket and (b) size specification and block patterns of the trouser
experimental garments were made using two types of fabric specimens listed in Table 2. Figure 3 shows the jacket and trouser size specifications and their block patterns. The areas of the skin temperature measurements included 8 points (torso, forearm, thigh, calf, upper arm, hand, foot, and head) and temperature measuring sensors were attached to the 15 skin surfaces of the thermal manikin, as shown in Figure 4. The light emission apparatus was used for detecting the heat storage and release characteristics by far-infrared emission of the ceramic-imbedded yarns and fabrics. Figure 5 shows the garment worn by the thermal manikin with the light on and light off. The skin temperature of the manikin was set to 37°C for each body part. The ambient temperature (T_a) in the climatic chamber was 20 ± 0.5°C at 65 ± 2% RH and an air velocity of 0.1 m/s. The thermal manikin had no movement during the entire experiment. The average skin temperature (T_s) on 15 points was measured, and the total dry heat loss (H) from the manikin was also measured after 60 min since the thermal manikin was started. Thermal insulation value (I_t) was calculated using Eq. (1). Finally, the Clo value was calculated using I_t.

\[ I_t = \frac{A_s(T_s - T_a)}{H} \]  

where I_t is the total thermal insulation of the clothing and air layer, H is the total dry heat loss from the manikin, A_s is the surface area of the manikin, T_s is the mean skin temperature.

2.6. Tactile hand and measurement of the mechanical properties of the fabric

The mechanical properties of the ceramic-imbedded fabric specimens were measured using a fabric assurance simple testing (FAST) system [3]. The shear rigidity (G) was calculated using EBS, as shown in Eq. (2), which was measured using a FAST-3 measuring device.

\[ G = \left( \frac{123}{EBS} \right) \times 1 \text{ N/m} \]

Figure 4. Positions attached by sensors on the thermal manikin

Figure 5. Photograph of the thermal manikin measurement of the woven fabric garment. (a) ZrC-imbedded fabric and (b) regular PET fabric
The surface temperature of the ZrC-imbedded fabric specimen increased nonlinearly to 38°C during 10 min of light emission. When the light was off after 10 min, the surface temperature decreased rapidly to 24°C after 20 min. On the other hand, the temperature rise on the fabric surface of the regular PET fabric was increased to 34.8°C and decreased to 24°C, which showed a similar increasing and decreasing shape to the ZrC-imbedded fabric. In addition, the heat-release temperature of the ZrC-imbedded fabric after 10 min was higher than that of the regular PET fabric. This phenomenon was assumed to be caused by the heat released from the absorption or accumulation of far-infrared radiation emitted from ZrC in the yarn. According to a previous study [4], far-infrared textiles are effective in retaining heat because the energy absorbed by the far-infrared material contained in the fiber is converted to and emitted as far-infrared rays.

Table 3 lists the emissive power and emissivity of the ZrC-imbedded and regular PET yarns [3]. The sum of the emissive power of the ZrC-imbedded yarns between 5 and 20 µm of wavelength was $3.65 \times 10^2 \text{ W/m}^2$, which was larger than that of the regular PET fabric. This was attributed to the ZrC particles imbedded in the yarns. On the other hand, the emissivity of the ZrC-imbedded yarn between 5 and 20 µm was 0.906, which was higher than that of the regular PET specimens; this was also caused by the ZrC particles imbedded in the yarns. The higher emissivity and emissive power of the ZrC-imbedded yarns resulted in a higher surface temperature of the ZrC-imbedded fabric than the regular PET fabric, as shown in Figure 6.

3. Results and discussion

3.1 Heat release characteristics by light emission experiment

Figure 6 presents the light heat emission diagram of the ZrC-imbedded fabric and a regular PET fabric specimen as a control fabric. As shown in Figure 6, the temperature rise on the fabric surface of the ZrC-imbedded fabric was observed according to the time lapsed as light is emitted from a 50-cm distance, that is, the surface temperature of the ZrC-imbedded fabric specimen increased nonlinearly to 38°C during 10 min of light emission. When the light was off after 10 min, the surface temperature was decreased rapidly to 24°C after 20 min. On the other hand, the temperature rise on the fabric surface of the regular PET fabric was increased to 34.8°C and decreased to 24°C, which showed a similar increasing and decreasing shape to the ZrC-imbedded fabric. In addition, the heat-release temperature of the ZrC-imbedded fabric after 10 min was higher than that of the regular PET fabric. This phenomenon was assumed to be caused by the heat released from the absorption or accumulation of far-infrared radiation emitted from ZrC in the yarn. According to a previous study [4], far-infrared textiles are effective in retaining heat because the energy absorbed by the far-infrared material contained in the fiber is converted to and emitted as far-infrared rays.

Table 3. Emissivity and emissive power of the fabric specimens.

| Specimens       | Emissive power (W/m²) between 5 and 20 µm | Emissivity (–) |
|-----------------|------------------------------------------|----------------|
| ZrC imbedded    | $3.65 \times 10^2$                       | 0.906          |
| Regular PET     | $3.58 \times 10^2$                       | 0.836          |

Figure 6. Surface temperature of the woven fabrics specimens by light exposure
3.2 Thermal insulation by thermal manikin test

A quantitative evaluation of the thermal property of the ZrC-imbedded fabric was carried out using the thermal manikin experiment. The total Clo value from the 15 positions of the thermal manikin and the Clo value from torso area to which light is emitted were obtained from the ZrC-imbedded and regular fabrics. This assessment was carried out with the light on and off. Table 4 lists the Clo values of the ZrC-imbedded and regular PET fabrics worn by the thermal manikin at 15 positions and the torso position of the thermal manikin. As shown in Table 4, the total Clo value of the ZrC-imbedded fabric exhibited a higher value than the regular PET fabric specimen at the light on state. This means that the effect of the ZrC particles in the ZrC-imbedded fabric to the heat storage and release is superior to that of TiO₂ in the regular PET fabric, which is caused by the higher emissivity and emissive power of the ZrC-imbedded fabric than the regular PET fabric, as listed in Table 3. This finding is consistent with the result of a higher fabric surface temperature of the ZrC-imbedded fabric than the regular PET fabric, as shown in Figure 6. In addition, the Clo values of both the total and torso areas under the light on measuring condition were much higher than those under the light off condition. Moreover, the Clo value of the ZrC-imbedded fabric at the torso area was much higher than that of the regular PET fabric at the light on state. On the other hand, no significant difference in the Clo value between the ZrC-imbedded fabric and regular PET fabric was observed under the light off measuring conditions, as shown in Table 4. This suggests that less heat is released in the light off state than in the light on state, that is, the heat release is caused by the far-infrared rays emitted from the ZrC particles in the fabric, when they receive light. According to Lin et al. [6], the fabric with the function of the far-infrared ray absorbs the heat energy from sunlight and then releases it back to the human body in the form of far-infrared radiation, so that it can repeatedly reach the effect of the heat preservation of human body, that is, the ZrC-imbedded fabric can release the heat by far-infrared emission and preserve the heat of the human body. On the other hand, differences in the Clo values (total and torso) of the regular PET fabric between the light on and off states were also observed, which was caused by TiO₂ in the regular PET, that is, TiO₂ emits heat energy by far-infrared radiation from light emission (light on state), even though it is less than that of the ZrC ceramic powder in the yarns, which was obtained by the elemental analysis reported elsewhere [3]. The concentration of Zr and Ti (wt.%) in the ZrC-imbedded yarns and regular PET yarns was 19.29% and 4.43%, respectively [3].

3.3. Tactile hand estimation from fabric mechanical properties

Figure 7 shows the relative mechanical properties of the two types of woven fabric specimens measured using the FAST system. The extensibility (E20 and E100), compressibility (ST), bending rigidity (B1 and B2), and shear rigidity (G) of the ZrC-imbedded woven fabric were plotted as the ratio to those of the regular PET woven fabric. As shown in Figure 7, the compressibility (ST) of the ZrC-imbedded fabric was lower than that of the regular PET fabric. This means that the ZrC-imbedded fabric is less compressible than that of the regular PET fabric, which was assumed to be caused by the nano-sized ZrC powders imbedded in the yarns. The bending...
4. CONCLUSIONS

The heat storage and release characteristics of ZrC-imbedded woven fabric were examined by light emission and thermal manikin experiments. The results were compared with those of regular PET fabric. The surface temperature of the ZrC-imbedded fabric was higher than that of the regular PET fabric, which was caused by the heat released from absorption or accumulation of the far-infrared emitted from ZrC-imbedded in the yarns. This was verified by the higher emissivity and emissive power values of the ZrC-imbedded fabric than those of the regular PET fabric. Furthermore, the Clo values of both the total and torso of the ZrC-imbedded fabric by the thermal manikin experiment were higher than those of the regular PET fabric. In addition, the Clo values of both total and torso areas under the light on measuring conditions were much higher than those under the light off condition, but no significant difference in the Clo value between ZrC-imbedded and regular PET fabric under the light off measuring condition was observed. This means that the heat release is caused by the far-infrared radiation emitted from the ZrC particles imbedded in the yarns as they receive light. On the other hand, the extensibility (E20) was similar but the extensibility (E100) at 100gf/cm of the ZrC-imbedded fabric was slightly higher than that of the regular fabric. Furthermore, the shear rigidity (G) of the ZrC-imbedded fabric was lower than that of the regular PET fabric, which was assumed to be due to the thinner fabric thickness and less filament numbers in the yarn.

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Figure 8 presents SEM images of cross sections of the yarns and fabric of the ZrC-imbedded and regular fabrics. The ZrC-imbedded fabric was thinner than that of the regular PET fabric, which caused high extensibility and low compressibility. Moreover, Figure 8(a) shows larger ZrC nanoparticles than those of regular PET (Figure 8c) imbedded in the cross section of the yarn, which also resulted in low compressibility of the ZrC-imbedded fabric. Summarizing the tactile hand of ZrC-imbedded fabric from mechanical properties, the extensibility of the ZrC-imbedded fabric in the longitudinal and bias extension was not influenced by the ZrC nanoparticles imbedded in the yarns. On the other hand, the compressibility in the lateral direction was worse than that of the regular fabric because of the ZrC particles in the yarns. Therefore, the tactile hand property of the ZrC-imbedded fabric needs to be improved by lowering the bending rigidity and enhancing the compressibility through adjustments of the fabric structural parameters and finishing process control.

Figure 8. SEM images of cross sections of ceramic-imbedded and regular PET yarns and fabrics. (a) ZrC-imbedded yarn, (b) regular PET yarn, (c) ZrC-imbedded fabric, and (d) regular PET fabric
References

[1] Bahng, G. W., & Lee, J. D. (2014). Development of heat-generating polyester fiber harnessing catalytic ceramic powder combined with heat-generating super microorganisms. Textile Research Journal, 84(11), 1220-1230.

[2] Furata, T., Shimizu, Y. & Kondo, Y. (1996). Evaluating the temperature and humidity characteristics of solar energy absorbing and retaining fabric. Textile Research Journal, 66(3), 123-130.

[3] Kim, H. A., & Kim, S. J. (2017). Far-Infrared emission characteristics and wear comfort property of ZrC-Imbedded heat storage knitted fabrics for emotional garments. Autex Research Journal, 17(2), 142-151.

[4] Kuo, C. F. J., Fan, C. C., Su, T. L., Chen, S. H., & Lan, W. L. (2016). Nano composite fiber process optimization for polypropylene with antibacterial and far-infrared ray emission properties. Textile Research Journal, 86(16), 1677-1687.

[5] Lee, E., Han, S., Lee, K. H., Lee, J., & Cho, G. (2017). Thermal properties of combat uniforms treated with microencapsulated octadecane and change in clothing microclimate via thermal manikin. The Journal of The Textile Institute, 1-11.

[6] Lin, C. A., An, T. C., & Hsu, Y. H. (2007). Study on the far infrared ray emission property and adsorption performance of bamboo charcoal/polyvinyl alcohol fiber. Polymer-Plastics Technology and Engineering, 46(11), 1073-1078.

[7] Lin, C. M, & Chang C. W. (2008). Production of thermal insulation composites containing bamboo charcoal. Textile Research Journal, 78(7), 555-560.

[8] Lin, J. H., Huang, C. L., Lin, Z. I., & Lou, C. W. (2016). Far-infrared emissive polypropylene/wood flour wood plastic composites: Manufacturing technique and property evaluations. Journal of Composite Materials, 50(15), 2099-2109.

[9] Lin, J. H., Jhang, J. C., Lin, T. A., Huang, S. Y., Chen, Y. S., & Lou, C. W. (2017). Manufacturing techniques, mechanical properties, far infrared emissivity, and electromagnetic shielding effectiveness of stainless steel/polyester/bamboo charcoal knits. Fibers and Polymers, 18(3), 597-604.

[10] Negishi, N. & Kikuchi, M. (1988). Infrared ray effects in biological systems. Ceramics Japan, 23(4), 335-339.

[11] Shim, M. H., Park, C. H & Shim, H. S. (2009). Effect of ceramics on the physical and thermo-physiological performance of warm-up suit. Textile Research Journal, 79(17), 1557-1564.