# Improving Cold Protective Performance (CPP) of Graphene based Electrical Heating Garment (EHG) with Thermal Insulation Materials

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**Keywords:** Electrical Heating Garment, aerogel, HRM, Equivalent thermal conductivity

**Abstract:** In this paper, different thermal insulation materials including aerogel, PCMs and heat reflect material (HRM) are used to improve the cold protective performance (CPP) of the electrical heating garment (EHG). A heating experiment was designed and conducted to investigate the CPP of different thermal insulation units containing the thermal insulation materials at a low temperature of -20ºC. Results show that the combination of the aerogel and HRM can significantly reduce the equivalen thermal conductivity of the original textile by 24% while keeping the original textile light and flexible. And the thermal insulation unit consisting of the graphene heater, aerogel and HRM treated textile can provide excellent cold protection in extremely cold environment with low supply voltage and proper duty cycle.

## 1. Introduction

Prolonged exposure in cold environment may lead to severe cold injury, such as dehydration and numbness [1]. Thus protection of the human organisms against cold is highly necessary. Electrical heating garments (EHGs) are designed to provide heat to maintain an appropriate temperature between the body and the ambient environment using electrical energy. Graphene which is one-atom-thick, two dimensional material with excellent electrical conductivity, thermal conductivity and flexibility is a desired alternative to traditional heating materials such as metal wire. The application of graphene as the heating element now become a new research direction of EHG development [2-5]. However, the low energy efficiency of EHGs limits EHGs' further application because the EHGs are usually light and equipped with portable battery with low voltage and low capacity. Therefore, standard thermal insulation materials such as aerogel and PCMs which are applied to increase the cold protective performance (CCP) of clothing are now one of the promising solutions to solve such problems [6-8].

In this study, thermal insulation materials including aerogel, PCMs and heat reflection material (HRM) which may enhance the CPP of the textile are applied in graphene based EHG. A heating experiment is designed to evaluate the CPP of different thermal insulation units. Then the unit with the best CPP is tested at different ambient temperature with different supply voltage and duty cycle. The results can be promoted to the further research about EHGs.

## 2. Materials And Methods

### 2.1 Materials

Graphene is prepared by CVD on a PET substrate (FIGURE 1). The sheet resistance of the graphene film is about 150 Ω $sq^{-1}$. After pattern electrode treated, a 10cm×cm graphene heating film with the resistance of 3.3 Ω is fabricated. The aerogel used in this study is silica aerogel purchased from Shenzhen ZHONGNING Tech Co. The particle size of the aerogel is 15 um. The PCMs emulsion is purchased from Hebei RUOSEN Tech Co. And the core material and wall material of the PCMs are phase change wax and PMMA, respectively. The particle size of the PCMs is about 5~10 um, and the latent heat is 120 kJ kg-1. The PCMs change its phase at the temperature of about

26ºC. The PCMs was sprayed into the substrate of wool textile uniformly using a spray lance at the pressure of 400 kPa. The heat reflect textile was purchased from Kunshan ZHONGHENG Spin Co.

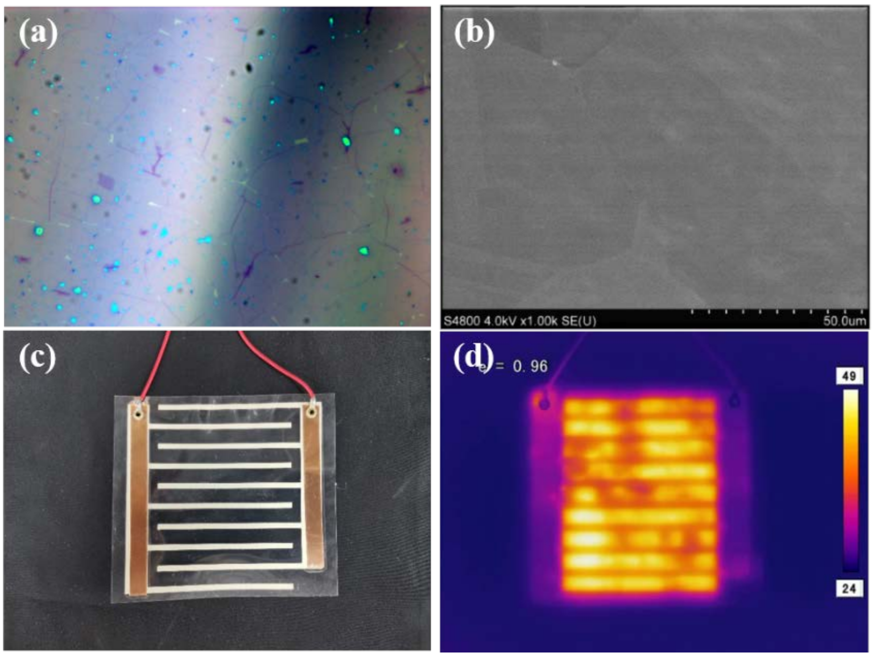


Figure 1. The graphene prepared by CVD. (a) Optical photomicrograph. (b) Scanning electron micrograph. (c) The flexible graphene heating film. (d) Infrared image of the graphene film.

## 2.2 Heating experiment

The heating experiment platform is made of three parts, the upper plate, the bottom plate and the heating part which is the main part. The heating part has a sandwich structure that two same thermal insulation units clamp the graphene heater. Three temperature sensors are placed on the surface of each layer centrally of the multilayer structure centrally. The thermal insulation unit consists of three layers, nylon as the outer layer to keep the thermal insulation materials (TIM) away from the heater surface, wool which is used to contain the TIM due to its high porosity, and the dacrons to prevent the TIM from being exposed to the ambient environment. A power of DC 5V is used to supply the graphene heater. The whole heating platform is placed in a low temperature chamber.

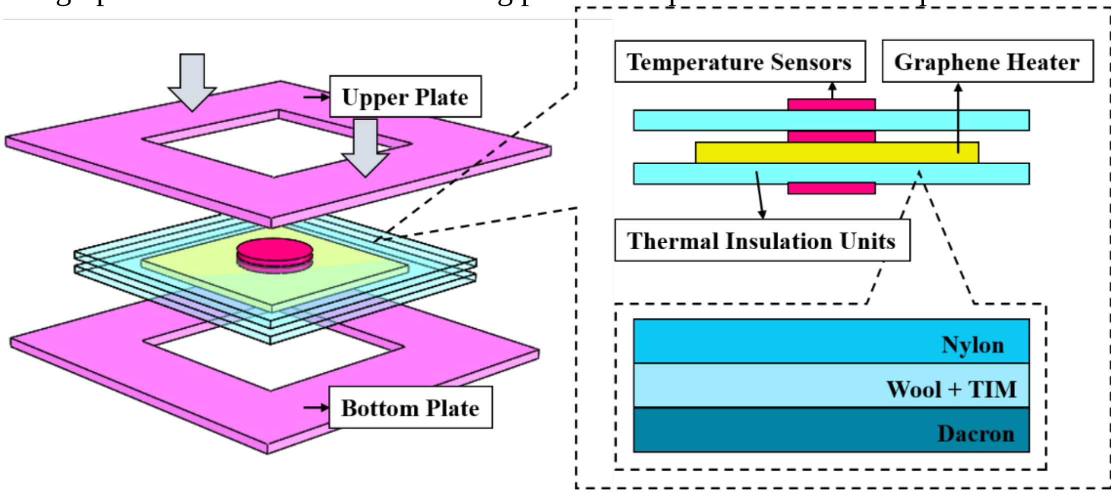


Figure 2. The structure of the experiment platform.

### 3. Results and Discussion

Firstly, three kinds of TIM including aerogel, PCMs and HRM are combined with the wool to explore the CPP of the treated textiles. All textiles are tested at the ambient temperature of -20ºC. As is shown in FIGURE 3(a), when starting heating, the temperature difference between surface of the heater and the TIM raises rapidly, and as the heating process going on, the raise rate of the temperature slows down and gradually reach a steady-temperature difference. On the contrary, when cutting off the power, the temperature difference change in an inverse way.

It can be seen from FIGURE 3 that, wool without any TIM can reach the steady-temperature difference of 21.36ºC while wool with aerogel can reach 40.56ºC, PCMs 34.26ºC and HRM 39.90ºC. The results indicate that TIM treated textile have better CPP. In other words, single TIM can improve the CPP of textiles such as wool.

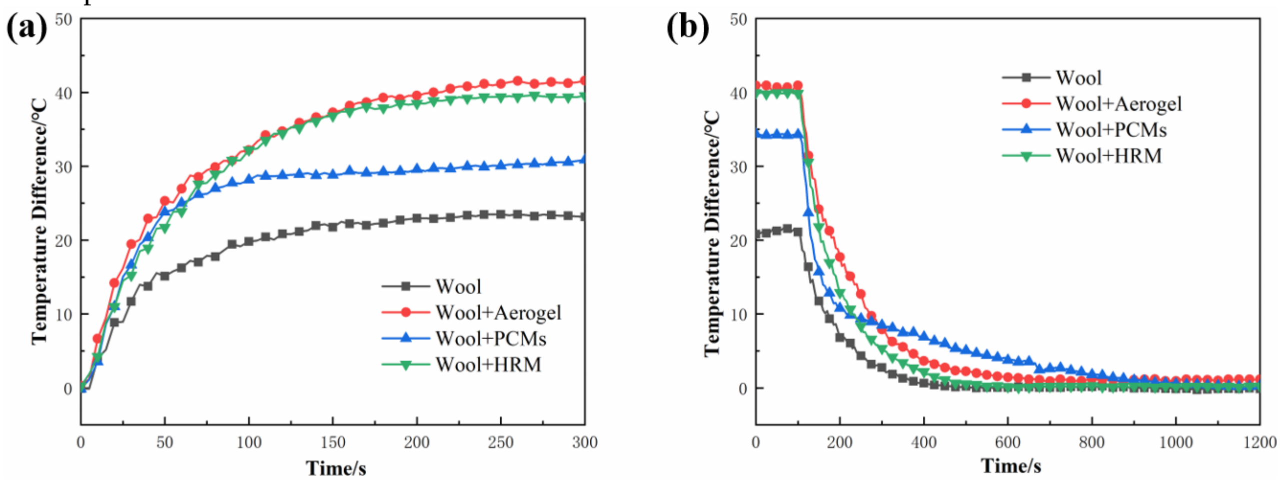


Figure 3. The temperature difference of different TIM. (a) Heating with a 5V DC power. (b) Turn off the power

Wang et.al found that heating elements perform better when placed in the interlayer of the EHG [1]. So for the sake of the application regarding to EHGs, thermal insulation units with multilayer structure which consists of layers mentioned before are investigated then. Clamped with nylon and dacrons, wool containing two kinds of different TIMs serves as the interlayer. Such thermal insulation units are placed at two sides of the heater. The experiment is conducted in the ambient temperature of -20ºC. To avoid the effect of the thickness of units, the thickness of all units are controlled at 4.4 mm ± 0.1mm.

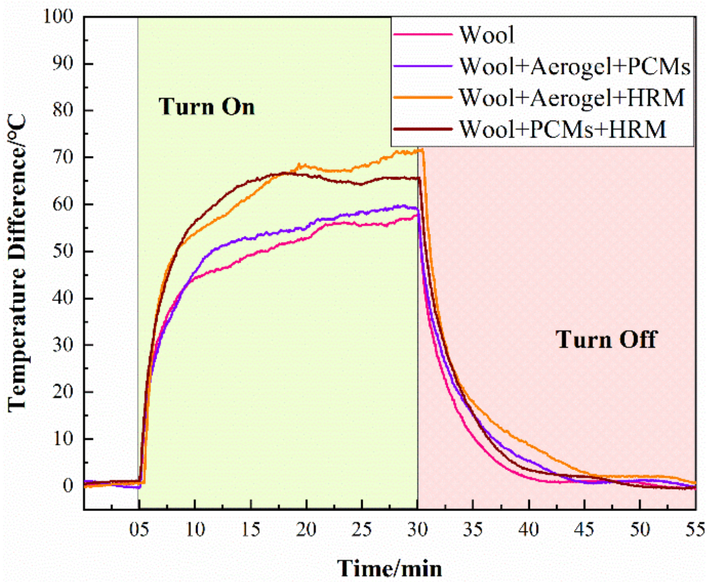


Figure 4. The temperature difference of kinds of thermal insulation units.

Table 1. Results of the heating experiment of kinds of thermal insulation units.

| ID | TIM | HT/ºC | TD/ºC | RR/(ºC/s) | FR/(ºC/s) | ETC/(m·W(m·K)$^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | W | 81.75 | 49.96 | 0.22 | 0.17 | 31.59 |
| 2 | W+A+P | 82.26 | 71.16 | 0.12 | 0.07 | 21.51 |
| 3 | W+A+R | 98.15 | 65.58 | 0.15 | 0.12 | 23.66 |
| 4 | W+P+R | 86.814 | 59.14 | 0.14 | 0.08 | 26.03 |

*HT: Heater Temperature. TD: Temperature Difference. RR: temperature difference Raise Rate. FR: temperature difference Fall Rate. ETC: Equivalent Thermal Conductivity. W: Wool. A: Aerogel. P: PCMs. R: heat Reflect materials.*

When the temperature difference between the heater and the unit reach stable, the steady temperature difference indicates the CPP of the unit. Formula (1) can be used to calculate the Equivalent Thermal Conductivity (ETC, λ) of the unit. In addition, because the rate of the temperature is time-varying, Formula (2) can get the raise rate approximatively and the fall rate in the same way.

$$\lambda = \frac{\eta U I \delta}{2A\Delta T} \quad (1)$$

η Is the efficiency of the electrothermal conversion which is 95% in this experiment. U (5 V) and I (1.5 A) represent the supply voltage and current of the graphene heater respectively. $\Delta T$ Is the temperature difference and $\delta$ is the thickness of the unit.

$$v_r = \frac{T_{0.95} - T_0}{t_{0.95} - t_0} \quad (2)$$

$T_{0.95}$ And $t_{0.95}$ are 95% of the steady temperature difference and the moment of such temperature. And $T_0$ and $t_0$ represents the temperature at beginning and the start moment, respectively.

TABLE 1 shows that, the combination of the aerogel and PCMs reduce the ETC of wool by 31.9%, while aerogel with HRM can reduce by 24.3% and PCMs with HRM can reduce by 17.6%.Also, after treated by kinds of TIMs, the temperature raise rate and fall rate decease obviously. Though the aerogel and PCMs perform best, the PCMs can harden the textile apparently as well. In all, the combination of the aerogel and HRM is the best choice for the application of the EHG. So the unit containing aerogel and HRM is chosen for the following tests.

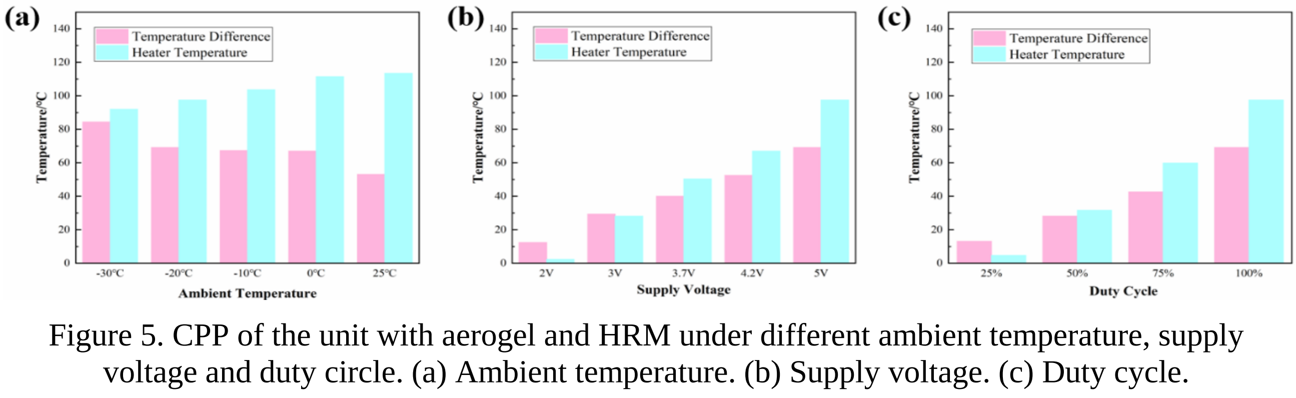


Figure 5. CPP of the unit with aerogel and HRM under different ambient temperature, supply voltage and duty circle. (a) Ambient temperature. (b) Supply voltage. (c) Duty cycle.

Since the thermal insulation is applied to improve the CPP of the EHGs, the unit with the combination of aerogel and HRM is then investigated under different ambient environment of low temperature, different voltage and duty cycle. The results are shown in FIGURE 5. When the ambient temperature is as low as -30ºC, the temperature difference can reach 84ºC, which indicates the thermal insulation unit has excellent CPP when faced with the extremely cold environment. When it comes to the low supply voltage, the unit and the heater can provide at least 50ºC to human body with the supply voltage of 3.7 V. Common temperature controller change the temperature via changing the duty cycle of the power. All experiments described previously are conducted using the 100% duty cycle, so the temperature is high. When changing the duty cycle of the power, the unit with the graphene heater can reach specific temperature as wish.

## 4. Conclusion

In conclusion, a heating experiment was conducted to explore the effect of aerogel, PCMs and heat reflect materials (HFM) to improve the CPP of textiles. The results show that all three kinds of materials can increase the CPP of the textiles. Three kinds of thermal insulation units which combine different materials were tested in a low temperature environment. Among the units, wool with aerogel and HRMs can reduce the equivalent thermal conductivity of the original textile by 24.3% while keeping the original textile light and flexible. Then this unit were tested under different ambient environment of low temperature, and the different voltage and duty cycle in consideration of the application of EHGs. In the results, textile treated with aerogel and HRM can provide excellent cold protection in cold environment with low voltage and proper duty cycle. The result of this work is an improvement to the further applications of EHGs.

## Acknowledgments

This work was financially supported by National Key Research and Development Project.

## References

[1] Wang F, Gao C, Holmér I. Effects of air velocity and clothing combination on heating efficiency of an electrically heated vest (EHV): a pilot study [J]. Journal of occupational and environmental hygiene, 2010, 7 (9): 501 - 505.

[2] Song W, Lai D, Wang F. Evaluating the cold protective performance (CPP) of an electrically heated garment (EHG) and a chemically heated garment (CHG) in cold environments [J]. Fibers and Polymers, 2015, 16 (12): 2689 - 2697.

[3] Wang F, Lee H. Evaluation of an electrically heated vest (EHV) using a thermal manikin in cold environments [J]. Annals of occupational hygiene, 2009, 54 (1): 117 - 124.

[4] Ma N, Lu Y, Xu F, et al. Development and performance assessment of electrically heated gloves with smart temperature control function [J]. International Journal of Occupational Safety and Ergonomics, 2018: 1 - 9.

[5] Shin S, Choi H H, Kim Y B, et al. Evaluation of body heating protocols with graphene heated clothing in a cold environment [J]. International Journal of Clothing Science and Technology, 2017, 29 (6): 830 - 844.

[6] Shaid A, Wang L, Islam S, et al. Preparation of aerogel-eicosane microparticles for thermoregulatory coating on textile [J]. Applied Thermal Engineering, 2016, 107: 602 - 611.

[7] Wang S X, Li Y, Hu J Y, et al. Effect of phase-change material on energy consumption of intelligent thermal-protective clothing [J]. Polymer Testing, 2006, 25 (5): 580 - 587.

[8] Bo-a Y, Yi-Lin K, Yi L, et al. Thermal regulating functional performance of PCM garments [J]. International Journal of Clothing Science and Technology, 2004, 16 (1/2): 84 - 96.